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Abstract

How exercise intensity targets, calibrated according to oxygen consumption, relate to vertical

impacts during weight bearing exercise is currently unknown. We investigated the

relationship between vertical peaks (VPs) and metabolic equivalents of oxygen consumption

(METs) in 82 women during walking and running. The magnitude of VPs, measured using a

hip-worn triaxial accelerometer, was derived at recommended aerobic exercise intensity

targets. VPs were 0.63 ± 0.18g at the lower recommended absolute exercise intensity target (3

METs), but >1.5g at the upper end of moderate intensity activities ($1.90 \pm 1,13$g at 6 METs).

Multilevel linear regression analyses identified speed and type of locomotion as the strongest

independent predictors of vertical peaks, explaining 54% and 11% of variance respectively.

We conclude that, in contrast to lower intensities, exercising close to or above the 6-MET

threshold generates VPs of osteogenic potential, suggesting this could provide simultaneous

benefits to decrease all-cause mortality and osteoporosis risk.

Keywords: Accelerometry, postmenopusal women, physical activity, metabolic equivalent,

lactate threshold.

Investigation of the Relationship between Peak Vertical Accelerations and Aerobic

Exercise Intensity during Graded Walking and Running in Postmenopausal Women

Physical activity (PA) constitutes an important strategy against premature death and

chronic disease (Arem et al., 2015). Observational prospective cohort studies using self-

reported questionnaires suggest that meeting current PA guidelines (Riebe, Ehrman, Liguori,

& Magal, 2017) of 150 min·wk^{-1} of moderate-to-vigorous physical activity (MVPA) reduces

all-cause mortality risk by 26-31% (Arem et al., 2015). In addition, the beneficial effects of

mechanical loading on the skeleton are well recognised (Katarina T. Borer, 2005). The US

National Health and Nutrition Examination Survey (NHANES 2007-2010) showed that

women who reported PA levels 2-4 times higher than the amount of PA recommended by

guidelines (Riebe et al., 2017) had higher hip bone mineral density (BMD) (Whitfield, Kohrt,

Pettee Gabriel, Rahbar, & Kohl, 2015). People reporting greater vigorous intensity activities

show even higher benefits in mortality and bone outcomes compared to the same volume of

moderate intensity activities, suggesting that PA intensity contributes to such benefits

(Johansson, Nordstrom, & Nordstrom, 2015; Wen et al., 2011).

Physical activity intensity is generally defined in terms of absolute rates of energy

expenditure (3-6 METs for moderate intensity) (Garber et al., 2011). However, with

increasing age or decreasing cardiorespiratory fitness (CRF), an activity at a given absolute

intensity (MET) requires a greater percentage of the maximum oxygen uptake or $\dot{V}O_{2max}$ (*i.e.,*

relative intensity) (Garber et al., 2011; Howley, 2001). Therefore, using the absolute intensity

approach may not be the most accurate option for exercise programing or measuring PA

outcomes in samples varying in age or CRF (Miller, Strath, Swartz, & Cashin, 2010; Ozemek,

Cochran, Kaminsky, Strath, & Byun, 2013). Alternatively, the relative intensity approach

measured either through a percentage from the $\dot{V}O_{2max}$ or cardiac response (*i.e.,* heart rate,

HR) achieved during an exercise test to volitional fatigue, or throught the measurement of physiologic breakpoints of energy supply as lactate thresholds (LT) during submaximal exercise, are preferred for a tailored exercise intervention, and they provide a more homogeneous exercise dose among a group of individuals (Binder et al., 2008; Faude, Kindermann, & Meyer, 2009; Meyer, Gabriel, & Kindermann, 1999).

However, though useful in describing metabolic and cardiovascular benefits of PA, this may be less tractable when examining skeletal health. For example, PA is thought to improve skeletal health by producing deformations ('strains'), to which the skeleton responds in a dose-response manner (Clinton & Lanyon, 1984). Therefore, to evaluate potential benefits for skeletal health, it may be more appropriate to measure PA exposure in terms of the level of impact. Traditionally, accelerometers, which are widely used to provide objective measures of PA, are calibrated in terms of METs, however more relevant parameters for skeletal health, such as vertical impacts (VPs), can also be derived. Using this approach, cross sectional studies have identified relationships between the number of VPs, including higher impacts achieved during weight bearing exercise, and measures of skeletal health. For example, VPs which are four times above gravitational force (corresponding to running at or above 10 km·h^{-1} or jumping exercises) show the strongest relationships with hip and lumbar spine BMD in children (Deere, Sayers, Rittweger, & Tobias, 2012) and adult women (Stiles, Metcalf, Knapp, & Rowlands, 2017; Vainionpää et al., 2006; Winters-Stone et al., 2011). In addition, habitual exposure to lower VPs (~1.5g-s) can contribute to greater bone size and strength in older women (Hannam et al., 2017). This evidence suggests that impact exercise is site-specific and that the optimal dose may vary between different bone sites, sex and age groups.

In the present study, we wished to examine whether targets for PA intensity, defined in terms of METs, are also likely to confer benefits for skeletal health. We were particularly interested in postmenopausal women because they usually report lower MVPA compared to men (Kujala et al., 2017; Tucker, Welk, & Beyler, 2011), and because they have an increased risk of osteoporosis and cardio-metabolic diseases related to menopause, lower fitness and inactivity (Kanis et al., 2012; Kannel, Hjortland, McNamara, & Gordon, 1976). Therefore, we aimed to relate recommended absolute rates of energy expenditure and relative intensities (Garber et al., 2011; Riebe et al., 2017) (i.e., relative to $\dot{V}O_{2max}$ and to lactate thresholds), to VPs, determined in postmenopausal women walking and jogging at a range of velocities. Furthermore, we aimed to identify factors predicting amplitude of VPs achieved during testing. In this way, we aimed to provide a basis for individualized PA recommendations in postmenopausal women, intended to achieve a wide range of health benefits including reduced risk of osteoporotic fracture.

Method

Participants

Eighty-eight postmenopausal women who were recruited via advertisements placed in health medical centers performed; 1) a submaximal incremental shuttle test (IST), and 2) several (two to seven) constant velocity tests using a hip-worn triaxial accelerometer with measures of impact loading, HR and blood lactate, and 3) additional cardiopulmonary exercise tests including measures of oxygen uptake ($\dot{V}O_2$). Inclusion criteria were: 1) age <75 years, and 2) surgical or natural menopause (no menstrual periods during previous 12 months). Participants were excluded from the study if they had any of the following conditions that might interfere with exercise testing: 1) presence of spine or low-trauma fractures or severe arthrosis at the hip, knees or feet, 2) functional limitation to walk for 20

minutes, 3) presence of any chronic disease that would impair the cardiorespiratory system during testing. The local hospital´s ethical committee approved the study (Pyto2011/71) and written informed consent was obtained from all participants before any study procedures were undertaken. The procedure of the study was in accordance with the Declaration of Helsinki and was registered in *ClinicalTrials.gov PRS* (NCT02984553).

Exercise testing

Submaximal Incremental shuttle test (IST). Prior to the first visit, participants were instructed to abstain from caffeine and stimulants for at least four hours and strenuous activity for ≥24 h before testing. Before starting the test each participant´s HR (Polar V800, Polar Electro Oy, Kempele, Finland) and blood lactate concentration ($[La^-]$) (Arkray KDK Corporation, Lactate Pro LT-1710, Shiga, Japan) were measured on a standing position. Capillary blood samples (0.3 µL) were taken from a hyperemic earlobe. Testing was performed in a laboratory setting in a controlled temperature environment (~20º) over a 20 m indoor track. The distance of the course was extended to 20 m from the original test (Singh, Morgan, Scott, Walters, & Hardman, 1992) to keep the pace constant avoiding excessive turns that might increase the energy cost and musculoskeletal demand, potentially leading to premature fatigue, discomfort or even injury. The exercise test protocol has been previously described and can be consulted elsewhere (Gil-Rey, Maldonado-Martín, Palacios-Samper, & Gorostiaga, 2018). Briefly, five cones were positioned at 0.5–5–10–15 and 19.5 m and participants had to walk in a straight line until the last cone, then turn around and return to the start.The speed was dictated by an audio signal. The IST started at 2.4 km·h^{-1} (~2.1 METs). The intensity was progressively increased by 0.61 km·h^{-1} (Singh et al., 1992) at each 2-min stage with 1-min rest in between. At the end of each stage, HR and $[La^-]$ were recorded.

Each participant was free to start running from the 7th stage onwards (6.1 km·h^{-1}), or the operator suggested to do so when the participant was not able to match the required speed. The test was stopped when: 1) [La$^-$] values were ≥3.0 mmol·l^{-1} to avoid excessive fatigue, and/or 2) participant repeatedly (if they were one cone behind in two successive occasions) failed to match the pace programmed, and/or 3) participant was exhausted. The first lactate threshold (LT1) was defined as the highest velocity above which [La$^-$] increased by an amount of ≥0.1 mmol·l^{-1} in the following stage and ≥0.2 mmol·l^{-1} in the subsequent stage.

Constant velocity tests (CVT). Participants completed two to seven 20 min CVT on the same 20 m track used for the IST. Each participant performed the corresponding tests on separate testing days (one week in between). Each CVT consisted of two stages of 10 min at a constant pace with a two minutes interruption for blood sampling. Heart rate was continuously recorded, and capillary blood samples were obtained before at rest, at the 10th min and the end of exercise (22nd min). Walking or running velocity of the first CVT was programmed as the velocity at which blood lactate increased by 1 mmol·l^{-1} above the blood lactate value at LT1 during the IST. In the following tests, the velocity was increased or decreased by ~0.30 km·h^{-1} until the maximal lactate steady state velocity (*i.e.*, LT2) could be determined (Billat, Dalmay, Antonini, & Chassain, 1994). This is the reason why the participants had different number of CVTs. An increase in [La$^-$] ≤0.4 mmol·l^{-1} during the final 10 min of exercise was defined as steady state (Beneke, 2003).

Cardiopulmonary exercise tests with gas exchange analysis. A sub-group of randomly selected 30 participants performed two additional exercise tests. First, they repeated the IST wearing the same accelerometer on a treadmill ergometer (Kuntaväline, Hyper Treadmill 2040, Finland) with continuous gas exchange analysis in order to relate recommended exercise intensities (in METs) with VPs. At the end of each stage, capillary

blood sampling from hyperaemic earlobe for $[La^-]$ analysis was performed until the velocity of LT2 from the track test was overcome. With a minimum of one week in between, participants performed a maximal cardiopulmonary exercise test on the same treadmill ergometer for the determination of $\dot{V}O_{2max}$. After 3-min rest, participants walked at 4.9 km·h^{-1} for a minute. Then, the speed was increased and maintained in 5.5 km·h^{-1} and the inclination of the treadmill was increased by 0.5% and by 1.3% in the first and next 1-min stages, respectively, to induce a ~0.6METs increment per stage until volitional fatigue. The perceived exertion was rated by a modified Borg´s scale (Borg, Ljunggren, & Ceci, 1985). A capillary blood sample was taken for lactate analysis at the termination of exercise, and 1, 3 and 5 minutes later when the blood lactate continued increasing. All metabolic data were averaged over 30-second periods with the highest 1-min $\dot{V}O_2$ recorded as $\dot{V}O_{2max}$. Achievement of $\dot{V}O_{2max}$ was assumed in the presence of a minimum of three of the following criteria: (1) failure of $\dot{V}O_2$ and/or HR to increase with further increases in workload, (2) individual´s volitional fatigue, rating a perceived effort of a minimum of 8 points out of 10 (Borg et al., 1985), (3) elicited an exercise maximum HR (HR$_{max}$) that exceeded 85% of the individuals age-predicted maximum based on the HR$_{max}$ estimated by 208-0.66·age (Edvardsen, Hansen, Holme, Dyrstad, & Anderssen, 2013), (4) RER $\geq$1.10, and (5) Maximum $[La^-]$ (BLC$_{max}$) >8 mmol·L^{-1} (Mezzani et al., 2013).

Inmediatelly after cessation of each exercise test, gas analysers drift was verified and $\dot{V}O_2$ values were corrected following procedures previously described (Garcia-Tabar, Eclache, Aramendi, & Gorostiaga, 2015).

Accelerometry data

Each participant wore a triaxial accelerometer (Actigraph wGT3X-BT Pensacola, FL, USA) over the right iliac crest in the mid-axillary line throughout the tests, as vertical as

possible attached to an elastic belt around the waist. Each monitor was previously initialized at 50Hz frequency and raw acceleration files were downloaded in Actilife 6® full software (Actigraph, Pensacola, FL, USA). The acceleration of gravity (9.81 m/s2 = 1g) was subtracted, expressed as Euclidean Norm minus One (ENMO) and initial values of the three axes in a static standing position during three minutes were corrected to eliminate any inclination of the device. The average of the 20 highest acceleration peaks, identified based on accelerations that were higher than preceding and subsequent reading, on vertical (V), anterior-posterior (AP) and media-lateral axis (ML) were selected to represent acceleration magnitudes of each speed (Hannam et al., 2017).

Other measures

Stature was measured using a wall stadiometer (Seca, Germany) and body mass was measured using a scale to the nearest 0.1kg (Seca, Germany). Leg strength was measured using the leg press (Technogym, Italy) one repetitium maximum (1-RM) test. Participants started performing 5-6 repetitions with a mass of 40kg and the load was progressively increased until the participant was not able to lift one repetition. During the test, speed and power of each lifting was monitored with T-Force dynamic measurement system (Ergotech, Spain) and was used to determine the number of repetitions with each load. In the case of two consecutive dropping repetitions (speed decrement), lifting was stopped to avoid excessive fatigue (Pareja-Blanco et al., 2017).

Statistical analysis

Means and standard deviations (SD) were determined for participant demographics. Repeated measures ANOVAs were used to assess whether acceleration peaks were different across axes at each speed, across lower and upper moderate intensity boundaries according to absolute (METs) or relative (LT and %$\dot{V}O_{2max}$) intensity criteria, as well as across the range

of walking and running velocities at each axis. The magnitude of the differences were assessed with Cohen´s effect-sizes (0.2 = small, 0.5 = medium, ≥0.8 = large). Where sphericity was violated, the Greenhouse-Geisser correction factor was applied. Post-hoc analyses were carried out using pairwaise comparisons with alpha (0.01) adjusted using Bonferroni correction.

A subgroup of 30 participants performed an additional IST on a treadmill to measure the rates of metabolic energy expenditure (METs). A 3rd order (cubic) polynomial equation (R^2 = 0.998) between vertical acceleration peaks (y) and METs (x) was used to determine the corresponding magnitude of VPs at the recommended exercise intensities (*i.e.,* 3 and 6 METs) by standard public guidelines (Garber et al., 2011). The level of significance was set at $p <$ 0.05. Statistical analyses were performed using SPSS statistical software (version 22.0, IBM SPSS Statistics, Chicago, IL) and GraphPad Prism 7 was used for figures.

To identify factors which predicted maximum VP, relationships between speed, type of locomotion, physical fitness exposures (aerobic fitness and leg strength), anthropometric characteristics (age, body mass and stature) and VPs were examined using univariate linear regression analysis. To identify the independent effect of each variable, all factors (speed, type of locomotion and footwear) and covariates (age, body mass, stature, leg strength and aerobic fitness), were adjusted in the same multivariate model. Partial Eta-square (η^2) represents the explained proportion of the variance of the dependent variable after controlling for other factors. Coefficients represent the percentage change in outcome per SD change in exposure. Multilevel linear mixed-effect analysis was used to determine and estimate the effect of independent variables on VPs, as it can handle unbalanced data sets and take into account individual trends for regression analysis. Vertical peak measures are grouped per participant considering a multilevel data structure. As the number of velocity stages and

locomotion varied across individuals (participant´s dependent), participant, speed, locomotion (0 = walking, 1 = running) and the interaction between speed and locomotion were entered as random-effects factors. The models included participant-related characteristics which were found to be independently associated with VPs (age, leg strength and aerobic fitness) as fixed–effects factors. Non-significant factors ($p > 0.05$) were excluded from the model.

Model fit was subsequently evaluated (R^2 and Akaike´s Infromation Criterion) and cross validated in a randomly selected 80% of the sample. This training data set was subdivided in five groups who were used to develop the models, leaving the remaining 20% assigned to the test dataset to be used to cross validate the models (Neugebauer, Collins, & Hawkins, 2014). Model assumptions (linearity of the relationships, normality and homoscedasticity of residuals) were checked via residual analysis (Q-Q plots and summary diagnostics) to ensure that both the prediction equation and the single-number summaries of the prediction accurately represent the full dataset. SAS/STAT statistical software (version 14.3) was used for linear mixed-effect analysis.

Results

Among 102 interested participants who were screened by telephone for eligibility, 14 were excluded. Reasons for exclusion were; 1) not meeting inclusion criteria/reported any of the exclusion criteria (n = 12), and 2) declined to participate (n = 2). Among 88 participants who were invited to the Medicine Center, 82 completed the exercise tests and were included in the study for data analysis (Table 1). Reasons for exclusion in data analysis were inability to walk-run for 20min due to musculoskeletal pain or discomfort that interfered with exercise tests (n = 5), and diagnosed cardiovascular disease (n = 1). One of the sub-group study participants was excluded from data analysis due to not-meeting maximal exercise criteria. The final 29 participants had a $\dot{V}O_{2max}$ of 10.0 ± 4.2 METs (Table 2).

Figure 1 shows triaxial acceleration peaks of the whole group during the IST. Across all walking stages, V and AP acceleration peaks showed a similar pattern, although higher acceleration peaks were observed in the V axis ($p < 0.01$, ES = 0.42–0.62). Beyond 6.7 km·h^{-1}, when the majority of participants were running, greater inter-subject variability was observed, with a stepper increase in the magnitude of VPs compared to AP peaks ($p < 0.01$, ES = 1.36–2.02). Medial-lateral peaks remained lower ($p < 0.01$) than the other two axes across all velocities. A similar pattern was observed when only participants completing the 8.5 km·h^{-1} stage (n = 18) were considered.

Figure 2 shows the $\dot{V}O_2$ (in METs) and the VPs across the velocity stages of the IST performed on the treadmill by the sub-group of study participants (n = 29). Mean VP magnitudes at the recommended absolute moderate intensity thresholds were 0.63 ± 0.18g at 3 METs (corresponding to a velocity of 3.2 km·h^{-1}), and 1.90 ± 1.13g and at 6 METs (6.61 km·h^{-1}). The magnitudes of the VPs achieved at the lower boundary of moderate intensity according to relative intensity criteria (*i.e.,* 46% $\dot{V}O_{2max}$ or at LT1) were significantly higher compared to the clasiccal 3 METs boundary according to absolute intensity criteria (1.20 ± 0.09g at 46% $\dot{V}O_{2max}$, $p < 0.01$; 95%CI: 0.364 to 0.790; ES: 8.91, and 1.16 ± 0.08g at LT1 which corresponded to 4.6 ± 0.7 METs or a velocity of 5.5 km·h^{-1}, $p < 0.01$; 95% CI: 0.359 to 0.710; ES: 8.91). Measured VPs at the upper boundary of moderate intensity were highest at their maximal lactate steady-state velocity (*i.e.,* LT2) (2.47 ± 0.20g) compared to the classical absolute intensity 6 METs boundary (1.90 ± 1.15g, $p < 0.05$; 95% CI: -0.179 to 1.317; ES: 0.69) or the relative intensity boundary anchored at 63% $\dot{V}O_{2max}$ (1.88 ± 1.14g, $p < 0.01$; 95%CI: 0.213 to 0.978; ES: 0.72). The corresponded velocity at LT2 was 7.3 km·h^{-1} or an energy expenditure of 7.3 ± 1.9 METs during the 2-min exercising at that velocity during the IST.

In subsequent analyses intended to identify the determinants of maximum VPs, all factors (speed, type of locomotion, footwear) and covariates (age, aerobic fitness, leg strength, body mass) except stature were found to be related maximum VPs in univariate analyses (Table 3). Age was the only factor showing an inverse association with VPs [β (95% CI) = -0.03 (-0.05, -0.02), $p < 0.01$]. In multivariate analyses, speed [β (95% CI) = 0.29 (0.27, 0.31), $p < 0.01$] and type of locomotion [0.70 (0.55, 0.86), $p < 0.01$] were independently positively related to VPs, explaining 54% and 11% of the variance in VPs after adjusting for all factors and covariates ($p < 0.01$) . Leg strength, aerobic fitness and age also showed a weak independent association with VPs explaning less than 5% of their variation ($p < 0.01$) (Table 3). The multilevel linear mixed model identified speed, locomotion and age as the best fitting variables in terms of AIC and log likelihood estimates (equation 1).

$$VP = 1.2911 - 0.00642 \cdot (age - 58.77) + 0.2999 \cdot (speed - 5.16) + 0.5333 \cdot (locomotion) -$$
$$0.03445 \cdot locomotion \cdot (age - 58{,}77) + 0.1613 \cdot (speed - 5.16) \cdot locomotion \ (eq. \ 1)$$

Where: a value of 0 is assigned if the mode of locomotion is walking and a value of 1 is assigned to running.

The Bland-Altman method between predicted and actual VPs against their mean for eq. 1 showed good agreement and moderate 95% individual limits of agreement [-0.12 (0.71)g-s]. The slope of the regression line was significantly different from zero ($p < 0.05$), showing higher bias at higher VPs (particularly above 2g-s) (suppl. Figure 1).

Discussion

Our results suggest that the 3-MET threshold, classically established as the minimum exercise intensity required for reducing all-cause and cardiovascular mortality risk, is

unlikely to decrease osteoporosis risk in postmenopausal women; the associated level of vertical impacts (0.63 ± 0.18g) is well below that previously found to be positively related to indices of bone strength (~1.5g), including in older postmenopausal women (Ahola, Korpelainen, Vainionpää, Leppäluoto, & Jämsä, 2009; Bassey, Rothwell, Littlewood, & Pye, 1998; K. T. Borer, Fogleman, Gross, La New, & Dengel, 2007; Hannam et al., 2017; Vainionpaa et al., 2007). On the other hand, walking or jogging at higher intensities, closer to the lower boundary of vigorous intensity (6 METs or 6.6 km·h^{-1}) are associated with higher vertical impacts (1.90 ± 1.15g) that might reduce the risk of osteoporotic fractures.

Information about musculoskeletal loading during usual walking and running speeds in adults is important for designing exercise training programs aiming to reduce the risk of osteoporotic fracture through increased BMD and related measures of bone strength, without exposing the individuals to higher risk of falls and osteoporotic injuries. Mean VP values were higher compared to AP and lateral axes, increasing from 0.9 ± 0.2g at 4.3 km·h^{-1} to 1.5 ± 0.4g at 6.1 km·h^{-1} during velocities associated with walking. In line with Giarmatzis and colleagues (Giarmatzis, Jonkers, Wesseling, Van Rossom, & Verschueren, 2015) running VPs were approximately 38% higher compared to walking at the same speed (6-7 km·h^{-1}). One of the most noticeable differences is the existence of a flight phase in running, rather than the double support phase that occurs in walking, which suggest that muscles generate greater tensile forces in running (Sasaki & Neptune, 2006). During running, VPs increased markedly to 3.1 ± 0.8g at 7.9 km·h^{-1}. The difference in VPs between walking at 6.1 (1.32 ± 0.3g) to running at 7.9 km·h^{-1} (137%) was higher than that reported by Giarmatzis (Giarmatzis et al., 2015) (57%), based on measurement of hip contact forces (normalized to body mass) through calculation of muscle forces along the gait cycle using integrated motion capture, but lower than after transitioning from brisk walking to jogging (~320%

higher magnitude of the VPs) in a small group of young students and recreationally active people based on measurement of 3-dimentional tibial acceleration during eigth gait cycles in each condition (Montgomery, Abt, Dobson, Smith, & Ditroilo, 2016; Rowlands & Stiles, 2012). Sample size and participant characteristics (<20 young males and females in the previous three studies *vs.* 82 postmenopausal females in our study), surface (motor driven treadmill or 40-m track *vs.* 20-m track in our study, including turns, accelerations and decelerations), footwear (barefoot *vs.* usual footwear) and data processing and methods of measuring impacts between studies might explain some of these inconsistencies in the magnitude of the VPs.

One of the aims of the present study was to identify the factors which predict VPs during walking and running, of which the most important were speed and type of locomotion. In addition, we observed relatively high variability between individuals (CV = 18-29%), consistent with the 20-25% variability in hip contact forces at a wide range of walking and running speeds found by Giarmatzis and colleagues (Giarmatzis et al., 2015). The large variability in VPs between individuals was more pronounced during running at high velocities ≥ 6.7 km·h^{-1}, suggesting that individual running characteristics also play an important role. For example, participant´s age had a significant but small predictive value, in line with previous findings suggesting that shorter stride length observed in elderly individuals may result in reduced VPs (Stansfield & Nicol, 2002). Other parameters which we evaluated, including body mass and leg strength, were weakly related to VPs in multivariable models. In the case of leg strength, attenuation was observed after adjustment for velocity, suggesting that leg strength affects VPs through the ability to achieve a certain velocity.

In a previous study, body mass, type of locomotion and hip V acceleration were postulated as significant factors for predicting VP ground reaction forces (Neugebauer et al., 2014). However, speed had a stronger influence on hip contact forces compared to ground reaction forces during walking and running, suggesting an influence of muscle activity on vertical hip contact forces with increased speed (Giarmatzis et al., 2015). In fact, electromyography activity of the rectus femoris and semitendinosus increased almost three-fold from walking to running (Montgomery et al., 2016; Sasaki & Neptune, 2006). Moreover, the results of Giarmatzis and colleagues (Giarmatzis et al., 2015) showed that hip adduction moment best predicted both walking ($R^2 = 0.53$-0.78) and running ($R^2 = 0.63$-0.73) hip contact forces. Thus conceivably, incorporation of information about biomechanics, and more specifically hip abductor function, could further improve the prediction of VPs.

Observational prospective cohort studies using self-reported questionnaires (Arem et al., 2015; Wen et al., 2011) suggest that people meeting current PA guidelines (Garber et al., 2011; Physical Activity Guidelines Advisory Committee, 2018; Riebe et al., 2017) of 150 min·wk^{-1} of MVPA (>3 METs) have reduced risk of all-cause mortality. However, bone responds differently to daily PA exposure and current evidence suggest that VPs generated by PA play a significant role in bone preservation in postmenopausal women (Katarina T. Borer, 2005; K. T. Borer et al., 2007; Hannam et al., 2017; Hatori et al., 1993). The present results suggest that V acceleration peaks at 3 METs intensity (0.63 ± 0.18g) are well below the suggested 1.5g threshold for preserving bone in pre and post-menopausal women (Hannam et al., 2017; Stiles et al., 2017; Vainionpää et al., 2006), whereas walking or running at 6 METs threshold (corresponding to 6.6 km·h^{-1}) or above may provide bone-protective benefits due to higher vertical impacts (1.90 ± 1.15g). However, elderly and populations at higher risk of osteoporotic fractures (e.g. severe osteoarthritis,

postmenopausal women, people with impaired balance and higher risk af falls, hormone

deficiencies and treatments with glucocorticoids) should progressively increase the

frequency and the magnitude of the impacts beyond what they can obtain by walking (which

we showed that is <1.5g) by adding small jumps or short running intervals to their regular

walks alongside resistance training, considering the U-shaped relationship between physical

activity, fall risk and osteoporotic injury.

When mechanical loading is associated with the release of endocrine and muscle-

derived peptides such as oestrogens and growth factors that are released as a function of

exercise intensity above LT1 (Urhausen, Weiler, Coen, & Kindermann, 1994) it may

maximize its effects on bone (Edwards, Dennison, Aihie Sayer, Fielding, & Cooper, 2015;

Pedersen, 2013). In fact, Borer and colleagues (K. T. Borer et al., 2007) and Hatori and

colleagues (Hatori et al., 1993) showed that fast walking above LT1 (~6.1-7.2 km·h^{-1} in their

participants) was effective in increasing BMD and reducing bone resorption markers in

postmenopausal women in a dose-dependent manner. In our study, LT1 (5.5 ± 0.6 km·h^{-1}

corresponding to 4.6 ± 0.7 METs or 46.7 ± 8.2%$\dot{V}O_{2max}$, which matched on average their

usual walking speed) was still below (1.16 ± 0.08g) the bone protective threshold of 1.5g.

Exercising at higher intensities (above the 6-MET threshold or ≥ 6.6 km·h^{-1}) might provide

further benefits for the bone, since accumulating 1-2 minutes/day of vigorous intensity PA,

equivalent to running close to 10 km·h^{-1} in pre-menopausal women and jogging at 8 km·h^{-1}

in post-menopausal women was associated with better bone health, but there was no

evidence that time spent at lower intensities was related to BMD (Stiles et al., 2017). Based

on these findings, fast walking or slow jogging that produce vertical impacts beyond 1.5g

might provide adequate bone protective stimuli for postmenopausal women with similar

characteristics, since this magnitude of VPs represented an exercise intensity 13% higher

than the mean LT1 of the study participants (6.24 km·h^{-1} or 5.38 METs). Progressing to higher VPs (~4g) such as jumping exercises might induce even greater benefits in hip BMD and architecture (Ahola et al., 2009; Vainionpää et al., 2006; Vainionpaa et al., 2007), wihout having to engage in moderate aerobic exercise. This findings will complement the tailoring of more complete individualized exercise programs for reducing fracture risk, that includes resistance training and balance training activities.

To the best of our knowledge, this is the first study comparing the accelerations produced at a range of walking and running velocities to absolute measures of $\dot{V}O_2$. Secondly, the measurement of acceleration peaks in the same way as in population-based studies, make results easier to translate to clinical recommendations. Some important limitations of the study should also be noted. First, we did not measure muscle activity during walking and running that might have contributed to improve the prediction of VPs. It has to be also acknowledged that the mechanical loading presented in this study might not apply to younger women or men, since body mass, age and muscle activity have been suggested as significant predictors of the magnitudes of vertical impacts. Finally, we did not directly measure $\dot{V}O_2$ during CVTs for the determination of the LT2. The gold standard method for the determination of LT2 requires at least two or three CVT; consequently, increasing the time and cost related to cardiopulmonary exercise testing. Instead, we accurately determined LT2 velocity from CVTs on the track to derive it´s mechanical loading and corresponding energy cost from individual regression equations between VPs and measured $\dot{V}O_2$ values at each velocity during the graded test.

Conclusions

We found that the magnitude of VPs corresponding to walking at the lower end of the recommended moderate intensity target (3METs) by international PA guidelines is well

below the level previously suggested to be beneficial for BMD and other measures of bone strength related to risk of osteoporotic fracture. In contrast, exercising at an intensity close to or above the 6-MET upper threshold of moderate intensity (corresponding to brisk walking or slow jogging at 6.6 km·h^{-1}) could provide combined benefits in terms of reducing all-cause mortality and osteoporosis risk. The equation provided in this study to predict VPs from speed, type of locomotion and age may guide exercise professionals in the prescription of activities intended to reduce the risk of osteoporotic fractures.

Acknowledgements

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Table 1. Descriptive characteristics of study participants (n = 82).

Characteristics	
Age (years)	59.1 ± 5.4
Stature (cm)	158.3 ± 5.5
Body mass (kg)	65.5 ± 11.2
BMI (kg/m^2)	26.1 ± 4.2
Physical fitness	
Leg press 1RM (kg)	129.7 ± 29.6
LT1 (km·h^{-1})	5.1 ± 0.6
LT2 (km·h^{-1})	7.1 ± 0.9
Footwear	
Sport trainers/shoe cushioning	50 (61)
Standard shoe/no cushioning	32 (39)

Note: Values represent mean ± SD. footwear is described as number and (percentage) of participants.

BMI = body mass index, 1RM = 1 repetition maximum strength in kg, LT1 = first lactate threshold determined through an incremental shuttle test on track, LT2 = maximal lactate steady-state determined through constant velocity tests on track. LT2 velocity represents aerobic fitness level of each participant.

Table 2. Descriptive characteristics of the sub-group of participants who performed additional cardiopulmonary exercise testing (n = 29).

Characteristics	
Age (years)	57.2 ± 5.0
Stature (cm)	158.3 ± 5.5
Body mass (kg)	65.4 ± 12.2
BMI (kg/m^2)	26.0 ± 4.2
$\dot{V}O_{2max}$ (METs)	10.0 ± 4.2
[La$^-$]$_{max}$	7.8 ± 3.2
RER$_{max}$	1.22 ± 0.07
RPE$_{max}$	8.8 ± 1.9
HR$_{max}$	172.7 ± 11.3
LT1 (km·h^{-1})	5.5 ± 0.6
LT1 (METs)	4.6 ± 0.7
LT2 (km·h^{-1})	7.3 ± 1.1
LT2 (METs)	7.3 ± 1.9

Note: Values represent mean ± SD.
BMI = body mass index, MET = rates of energy expenditure (1 MET is equivalent to 3.5 ml·kg^{-1}·min^{-1}, [La$^-$]$_{max}$ = maximal blood lactate concentration at the end of the test, RER = respiratory exchange ratio, RPE = rating of perceived effort (0-10 scale), LT1 = first lactate threshold determined through an incremental shuttle test on treadmill, LT2 = maximal lactate steady-state velocity obtained on the track. $\dot{V}O_2$ was measured on the treadmill at the corresponding LT2 velocity (2-min stages) from the constant velocity tests on the track (2 stages of 10min).
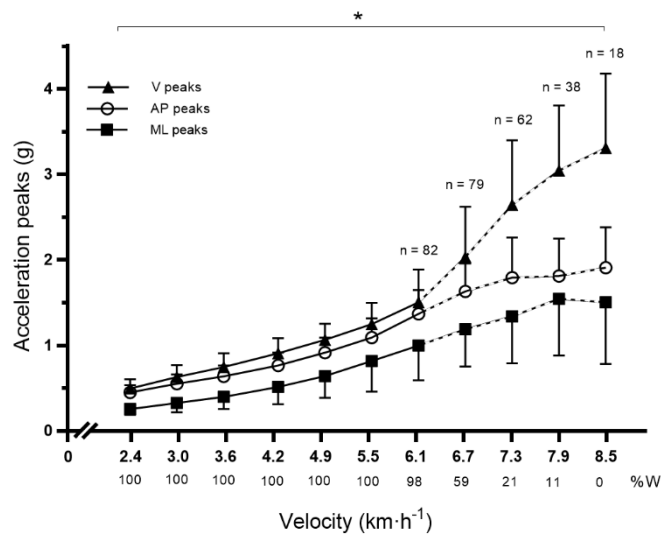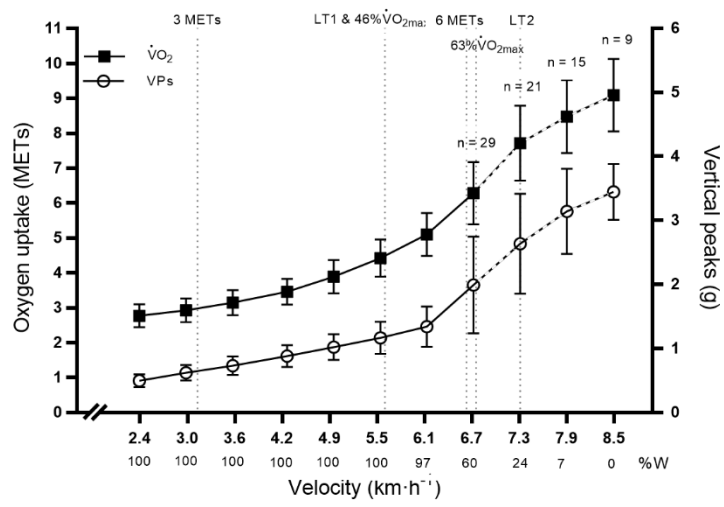
Figure 1

Figure 2

Supplementary Figure 1