Reassembling the Field-based Applicability of the Lactate Threshold for Old Age

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ABSTRACT

This study aimed to investigate the applicability of the Lactate Threshold (LT) to predict maximal oxygen uptake ($\dot{V}O_{2max}$) and demarcate the boundary between the *moderate*- to *heavy*-intensity domain ($HR_{m\text{-}h}$) in old age in comparison to the most utilized methods. A cross-sectional validation study was conducted. Participants aged 61 to 77 performed a familiarization procedure, an incremental maximal exercise treadmill test (CPX) for $\dot{V}O_{2max}$ determination, the *Six-minute Walk Test* (6MWT), and a discontinuous incremental field test for LT determination. Lower ($P<0.01$) internal effort was required for LT testing (76 ± 8 %HR_{max}) compared to 6MWT (92 ± 9 %HR_{max}). The application of the 6MWT reference equations overestimated $\dot{V}O_{2max}$ by 10–23 %. LTs better estimated the $\dot{V}O_{2max}$ ($r\approx0.90$, SEE: ≈3.0] compared to the 6MWT ($r=0.68$, SEE $=5.5$). $HR_{m\text{-}h}$ determined by the CPX differed (20 %; $P=0.001$) from that obtained by LT. $HR_{m\text{-}h}$ stratification indicated participants fall into the very *light* to the *vigorous* intensity domains. LT testing is more submaximal than the 6MWT, and is a valuable tool to estimate the $\dot{V}O_{2max}$ in older male adults. Implementation of LT testing in physical activity programs might help improving the quality of aerobic exercise training in older men.

Introduction

Aerobic capacity is one of the most powerful independent predictors of risk of death among older healthy males [1]. Maximal oxygen uptake ($\dot{V}O_{2max}$), one of the strongest physiological markers of cardiorespiratory fitness, is considered the gold-standard approach for aerobic exercise prescription, monitoring exercise training-induced adaptations, guiding treatment in patients with chronic cardiovascular diseases, determining the health status of the patients, and prognosis of mortality [2]. Although direct $\dot{V}O_{2max}$ evaluations during incremental exercise testing (CPX) to the limit of tolerance are common in laboratory settings, there are practical limitations with this approach. Among others, 1) gas analyzers are expensive and require qualified personnel for the correct collection and interpretation of data [3, 4]; 2) $\dot{V}O_{2max}$ might not be well-tolerated in some patients [5]; 3) attainment of maximal effort depends on individual subjective motivational factors [6] and thus $\dot{V}O_{2max}$ is sometimes indeterminable; 4) although minimally, maximal testing increases the risk of adverse cardiovascular events, which can be a concern when testing some groups [5]; and 5) the usefulness of evaluations of maximal anchors, such as $\dot{V}O_{2max}$ and maximal heart rate (HR_{max}), for precise prescription of endurance exercise is limited [7].

To overcome some of the drawbacks of $\dot{V}O_{2max}$ testing, efforts have been made to establish and validate simpler and low-cost functional field walking tests (FWTs) to evaluate aerobic capacity [5, 8]. The *Six-minute Walk Test* (6MWT) is one of the most popular exercise tests used in clinical practice in healthy older participants [9]. This test is easy to administer, well-tolerated, and does not require sophisticated equipment or a high level of training. Although the distance covered during the 6MWT is *moderately* correlated with $\dot{V}O_{2max}$ [10, 11], there is a ceiling effect at about 650 m as patients with > 20 mL · kg^{-1} · min^{-1} of $\dot{V}O_{2max}$ cannot walk faster due to biomechanical limitations [5], and jogging or running is forbidden during the test [9]. Therefore, $\dot{V}O_{2max}$ estimation using the 6MWT is likely to underpredict the real value, even in older participants as many of them possess a $\dot{V}O_{2max}$ greater than 20 mL · kg^{-1} · min^{-1} [9]. Thus, precise assessment, guidance, and monitoring of the aerobic exercise capacity in this population through the 6MWT are challenging.

The lactate threshold (LT) represents the exercise intensity above which blood lactate concentration ([BLac]) increases beyond resting values during incremental exercise [12, 13], and it is considered an important component of aerobic capacity that can be used to design endurance exercise training programs [2, 14, 15]. The LT represents the first exercise-intensity threshold, i. e. the boundary demarcating the *moderate* to *heavy* exercise intensity domain transition [4, 7]. This is an important demarcation point, as crossing this boundary has important implications in terms of metabolic stress and fatigue development [16, 17]. The determination of the LT allows investigators to quantitatively evaluate aerobic capacity, exercise training-induced adaptations, and to design endurance exercise training intensities [15, 18]. A notable advantage of the LT compared to the evaluation of $\dot{V}O_{2max}$ is its submaximal and objective nature, the possibility to evaluate it without performing other metabolic measures, and as a consequence its considerably lower cost. Furthermore, although LT and $\dot{V}O_{2max}$ are physiologically different, the LT measured during a submaximal incremental test can be utilized to estimate the $\dot{V}O_{2max}$ [19]. Despite the first exercise-intensity threshold and $\dot{V}O_{2max}$ being fundamental concepts within exercise physiology, further exploration of the relationship between the classical and objectively determined LT [12] and $\dot{V}O_{2max}$ is deemed necessary [8, 19]. To the best of our knowledge, whether the classical LT predicts $\dot{V}O_{2max}$ in older adults has not been fully explored and deserves further attention.

This study aimed to: 1) investigate the applicability of the LT to predict $\dot{V}O_{2max}$ in comparison with one of the most popular functional submaximal FWTs (6MWT), and 2) compare the delimitation of the boundary between the *moderate*- to *heavy*-intensity domain determined by the conventional and most utilized method (CPX) against the LT. The results of this study might help to improve the quality of professional assistance in the assessment, guidance and monitoring of aerobic capacity in older male adults.

Materials and Methods

Participants

Twelve 61 to 77 year-old males accustomed during the last few (> 3) years to 2 days per week of supervised physical activity were recruited in 2012 from a Physical Activity Program for persons over the age of 55, which was partially funded by the regional government. The sample size was calculated based on the LT vs. $\dot{V}O_{2max}$ relationship. Assuming a power of 80 % and a type I error of 0.05 for a minimum value of a *very large* correlation (r = 0.80), the estimated sample size for this study was 11 participants. Eligibility included: 1) ≥ 60 yrs, 2) not to have suffered a cardiovascular or respiratory event, and 3) available for four testing sessions within 4 wks. ▶ **Table 1** includes the descriptive anthropometric and medication characteristics of the participants.

Prior to participation, participants gave written informed consent. Procedures were approved by the Local Institutional Review Board and conformed to the Declaration of Helsinki. The study meets the ethical standards of the journal [20].

Study design

A cross-sectional study was conducted to: 1) assess the applicability of the LT to predict $\dot{V}O_{2max}$ in comparison with the 6MWT, and 2) compare the CPX with the LT at the time to demarcate the boundary from the *moderate*- to the *heavy*-intensity domain. Only males were recruited due to the sex-dependent physiological characteristics [21] that requires the development of sex-specific prediction models, as previously observed [22]. Four testing sessions were conducted. During the first testing session, anthropometrical measurements were taken [23] and familiarization with the exercise testing protocols took place. During the second visit, participants underwent a CPX for $\dot{V}O_{2max}$ determination. During the re-

▶ **Table 1** Participants' anthropometric and medication characteristics (n = 12).

Anthropometrical data (Mean ± SD)	
Age (years)	69 ± 6
Body mass (kg)	85.9 ± 13.3
Height (m)	1.67 ± 0.04
BMI (kg · m^{-2})	30.7 ± 4.9
Body fat (%)	27.3 ± 4.3
Medications (number of participants)	
Beta-blockers	2
Angiotensin-converting enzyme inhibitors	2
Statins	2
Angiotensin receptor antagonist	1
Acetylsalicylic acid	3
Antidiabetic medication	4

maining sessions, participants performed two FWTs in a randomized counterbalanced order. FWTs were the 6MWT [5] and a discontinuous version [8] of the *Modified Shuttle Walk Test* (D-MSWT) [24] enabling LT determination.

Testing procedures

Testing sessions were integrated in the participants' physical activity training program, were conducted one week apart, at the same time of the day, and were preceded by two days of rest or very light exercise (slow walking). Participants fasted for at least 2 h before each testing session and abstained from caffeinated and alcoholic beverages during the testing days. All procedures were conducted under controlled laboratory conditions for temperature (19.5 ± 1.8 °C), humidity (30 ± 5 %), and barometric pressure (720.5 ± 6.7 mmHg).

Familiarization and determination of the walk-run transition speed

The individual walk-run transition speed was determined by the incremental continuous *Modified Shuttle Walk Test* (C-MSWT) [24] and used to design the CPX protocol according to the established guidelines [25]. After a 10-min rest, participants were asked again to perform the same test protocol until they reach their individual walk-run transition speed. This time the test was performed on a treadmill (Kuntaväline, Hyper Treadmill 2040, Finland) to get accustomed to treadmill walking and avoid any potential learning effect. A familiarization session for the 6MWT was considered unnecessary as this test was routinely performed in the Physical Activity Program for persons over 55 years of age [6].

Maximal cardiopulmonary treadmill exercise test (CPX)

$\dot{V}O_{2max}$ was determined by an incremental maximal CPX test on the abovementioned treadmill. The exercise test was designed to reach volitional exhaustion within 8–12 min using intensity increments of estimated 0.6 metabolic equivalents (METs) per min [25]. METs were estimated following the formulas proposed by the American College of Sports Medicine (ACSM) [26]. Thus, the exercise test started at 4.9 km · h^{-1}. After one min the speed was increased to 6.1 km · h^{-1} (i. e. the maximum walking speed commensurate with each individuals' ability) for another min, and thereafter the grade was increased by 1.1 % every min until volitional exhaustion.

A 12-lead electrocardiogram (GE Healthcare, CASE Marquette, Germany) was continuously displayed and the health status of the participants was examined by a cardiologist. Metabolic data were recorded using a Vista Mini-CPX (Vacu-Med, Silver Edition 17670, Ventura, CA, USA). Calculation of the maximal metabolic data by the use of the individual pre- (calibration) and post-test (verification) values was performed according to Ward [3] following the procedures described elsewhere [27] HR_{max} and $\dot{V}O_{2max}$ were determined following criteria previously detailed [27]. $\dot{V}O_{2max}$ was also estimated based on speed and grade obtained at the end of each CPX test [26] HR_{max} obtained was utilized to determine the heart rate (HR) corresponding to the boundary between the *moderate*- and the *heavy*-intensity domain (HR-CPX_{m-h}) according to the current established guidelines for exercise testing and prescription [26].

Six-minute walk test (6MWT)

Two 6MWTs were performed and the records of the best trial were used for further analysis. Both 6MWTs were performed on a 20-m indoor track following standard recommendations [28]. Participants were instructed to walk as fast as possible back and forth during the test. Peak heart rate (HR_{peak}) obtained during the test was defined as the highest 30-s averaged HR value [29] and named HR-$6MWT_{peak}$.

Discontinuous modified shuttle walk test (D-MSWT)

The LT [12] was determined by a discontinuous version [8] of the C-MSWT [24] (i. e. D-MSWT). The test was performed on an indoor athletic track located inside our laboratory. The exercise test protocol was the same as the C-MSWT described elsewhere [24] but with rest intervals between stages enabling [BLac] assessment. The test required participants to walk up and down 20-m. The distance of the course was extended to 20 m from the original test to keep the pace constant avoiding excessive turns that might increase the energy cost and musculoskeletal demand. 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 [8]. The pace was set by a self-customized (MATLAB R2015a, The MathWorks Inc, Natick, MA) audio protocol file emitted by an audio-emitting computer (MALIBU-212P; Fonestar, Revilla, Cantabria, Spain). Starting speed was 0.50 m · s^{-1} (1.8 km · h^{-1}), which was increased by 0.17 m · s^{-1} (0.61 km · h^{-1}) every 2 min, with 1 min rest between stages. From the 8th stage onwards (6.1 km · h^{-1}, i. e. the maximum walking speed commensurate with every individuals' ability) participants were commanded to jog. The test finalized when [BLac] increased over two consecutive exercise stages as follows: an increase in [BLac] of ≥ 0.1 mmol · L^{-1} followed by an increase of ≥ 0.2 mmol · L^{-1} in the subsequent stage. HR_{peak} obtained during the test was defined as the highest 30-s averaged HR value and named HR- D-$MSWT_{peak}$.

Measures of heart rate (HR) and blood lactate concentration ([BLac])

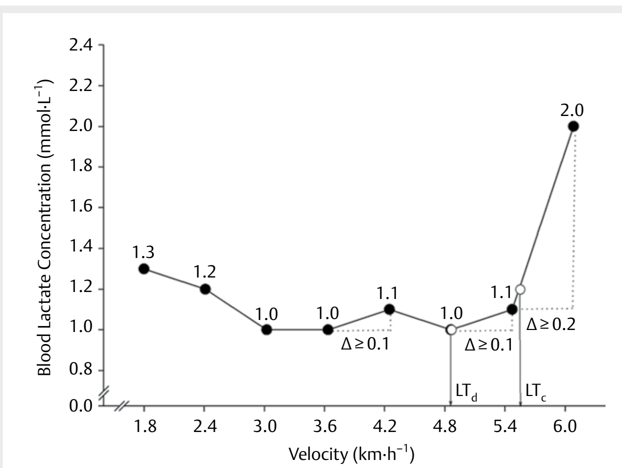
Throughout all the exercise tests HR was monitored (Polar Electro Oy, RS800CX, Finland), and capillary blood samples (0.5 µL) from the earlobe for [BLac] assessment were obtained at rest, at the completion of the test, and at the 1st and 3rd min of recovery. In the D-MSWT, capillary blood samples were also obtained immediately after each exercise stage. [BLac] was determined via amperometric measurement using a portable analyzer (Arkray KDK Corporation, Lactate Pro LT-1710, Shiga, Japan) calibrated before every test. Manufacturers report coefficients of variation (CVs) of 3.2 % and 2.6 % for lactate standards of 2 and 11 mmol · L^{-1}, respectively.

Determination of the lactate thresholds (LT)

Two LTs were determined by plotting the individual velocity vs. [BLac] curves [8, 19]. 1) To overcome the error associated with the analyzer [30], LT was defined as the highest stage velocity above which [BLac] increased by ≥ 0.1 mmol · L^{-1} in the following stage and ≥ 0.2 mmol · L^{-1} in the subsequent stage. Thus, LT was determined on the discrete values of the velocity-rate stages. A continuous rather than a discrete LT was also determined. 2) To the [BLac] associated with the discrete values of the velocity-rate stages previously determined, a 0.2 mmol · L⁻¹ was added in the individual velocity vs. [BLac] curves, and the continuous LT was calculated via linear interpolation. ▶ **Fig. 1** illustrates the determination of LTs. Velocities at the LTs frequently show test-retest intraclass correlation coefficients > 0.94, and CVs ≤ 3 % [30]. Absolute HR (b · min^{-1}) values at the LT (HR-LT) were computed from the individual HR vs. velocity linear regression equations (r > 0.98; P < 0.001). These HR-LT values were used to calculate the relative HR-LT values as percentage of the HR_{max} obtained in the CPX test.

Statistical analysis

Standard statistical methods were used for the calculation of means, standard deviations (SD), standard errors of the estimates (SEE), and confidence intervals (CI). Data were analyzed using parametric statistics following confirmation of normality, homoscedasticity, and, when appropriate, sphericity. Differences in [BLac] and HR within each FWT were identified by repeated measures ANOVA with Bonferroni correction. Linear regression analyses with *Pearson*'s product-moment correlation coefficients (*r*) were used to determine the magnitude of the relationships between the variables of interest. Evaluation of Cook's distance revealed a minimal influence of the individual data points on the correlation magnitudes. The accuracy of each linear regression was evaluated using the SEEs and the 90 % CIs of the slope. $\dot{V}O_{2max}$ was also predicted from the performance on the 6MWT using reference equations for older adults [31–33]. For clinical applicability purposes, the HR corresponding to the boundary between the *moderate*- and the *heavy*-intensity domain was determined using 1) the HR_{max} obtained in the CPX ($HR\text{-}CPX_{m\text{-}h}$) [26] and 2) the HR at the LT (HR-LT) [7]. These



▶ **Fig. 1** Illustration of blood lactate threshold (LT) determination in a representative participant. The test finalized when blood lactate concentration ([BLac]) increased over two consecutive exercise stages as follows: an increase in [BLac] change (Δ) of ≥ 0.1 mmol · L⁻¹ followed by a Δ of ≥ 0.2 mmol · L⁻¹ in the subsequent stage. Discrete LT (LT_d): The highest stage velocity above which [BLac] increased by ≥ 0.1 mmol · L⁻¹ in the following stage and ≥ 0.2 mmol · L⁻¹ in the subsequent stage. Continuous LT (LT_c): The velocity associated with the LT_d plus 0.2 mmol · L⁻¹ determined via linear interpolation in the [BLac] vs. velocity individual curve. In this participant, LT_d = 4.9 km · h^{-1} and LT_c 5.5 km · h^{-1}.

HRs were stratified by exercise intensity domains according to the current established guidelines for exercise testing and prescription [26]. The exercise stratification is as follows: "*very light*" (below 57 %HR_{max}), "*light*" (57–64 %HR_{max}), "*moderate*" (64–76 %HR_{max}), "*vigorous*" (76–96 %HR_{max}), "*near maximal to maximal*" (96–100 %HR_{max}). Student's paired t-tests were used to evaluate differences among the variables of interest. The magnitudes of the differences were assessed using 90 % CIs and Hedges' *g* effect sizes (ES). The agreement was assessed by mean bias and limits of agreement (LOAs) [34]. Relative estimation errors and agreements were calculated as the percentage of the SEE / LOAs divided by the mean. Relative SEE and LOAs < 10 % were considered acceptable [35]. The magnitudes of correlation coefficients (*r*) and the differences (i. e. ESs) were interpreted as described elsewhere [36]. Analyses were performed using IMB SPSS Statistics 22 (IBM Corporation, NY, USA). Significance was set at P < 0.05 for the analyses that did not require post-hoc adjustment.

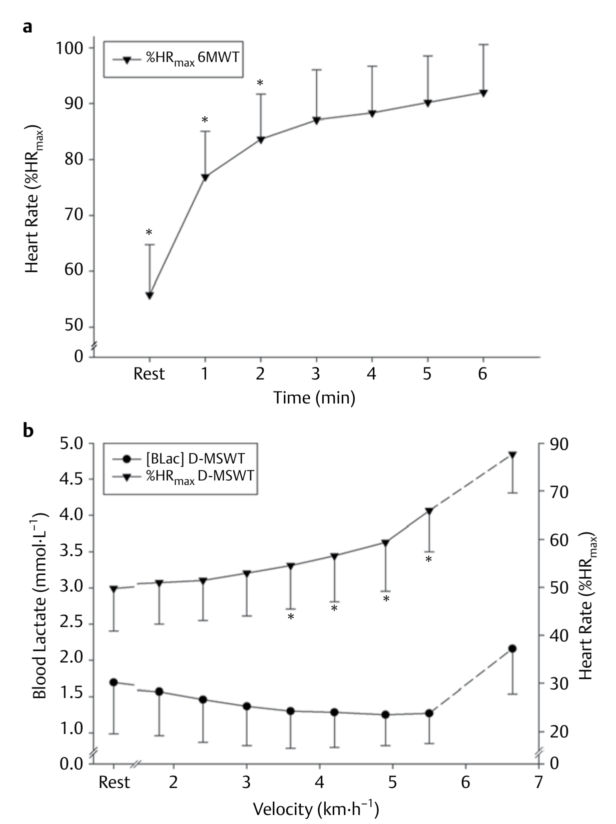
Results

Estimated MET_{max} during the CPX was 8.6 ± 1.9 (range: 5.1 to 12.3), that is, estimated $\dot{V}O_{2max}$ of 29.9 ± 6.6 mL · kg^{-1} · min^{-1} (range: 17.7 to 43.0). Measured $\dot{V}O_{2max}$ and HR_{max} were 29.6 ± 7.1 mL · kg^{-1} · min^{-1} (range: 19.2 to 44.4) and 144 ± 26 b · min^{-1} (range: 102 to 176), respectively. RER_{max}, peak [BLac] ([$BLac_{peak}$]), percentage of age-predicted HR_{max}, and $\dot{V}O_2$ increment among the last two final workloads were 1.15 ± 0.06 (range: 1.07 to 1.23), 6.6 ± 1.7 mmol · L^{-1} (range: 3.9 to 9.0), 90 ± 15 % (range: 64 to 108) and 0.78 ± 1.79 mL · kg^{-1} · min^{-1} (range: -2.80 to 2.72), respectively.

▶ **Fig. 2a** depicts the mean HR pattern response to the 6MWT, and ▶ **Fig. 2b** the mean HR and [BLac] responses to the D-MSWT. HR_{peak} and [$BLac_{peak}$] in the 6MWT were 92 ± 9 %HR_{max} (range: 71 to 100) and 4.3 ± 1.3 mmol · L^{-1} (range: 2.8 to 6.7), respectively. During the D-MSWT, HR_{peak} and [$BLac_{peak}$] were 76 ± 8 %HR_{max} (range: 65 to 87), and 2.2 ± 0.6 mmol · L^{-1} (range: 1.3 to 3.4), respectively. These HR_{peak} and [$BLac_{peak}$] values were smaller (P < 0.01; ES: 1.3 to 2.1) in the D-MSWT compared to the 6MWT. Distance walked during the 6MWT was 680 ± 67 m (range: 581 to 771). LT determined on discrete values during the D-MSWT occurred at 5.5 ± 0.8 km · h^{-1} (range: 4.2 to 6.7) and 64 ± 9 % HR_{max} (range: 50 to 78). LT determined on continuous values during the D-MSWT occurred at 5.9 ± 0.7 km · h^{-1} (range: 4.9 to 6.9) and 68 ± 8 % HR_{max} (range: 55 to 79).

▶ **Fig. 3** shows the correlations among some key variables of interest. There was an *extremely large* correlation with acceptable relative SEE (7 %) between measured $\dot{V}O_{2max}$ and estimated $\dot{V}O_{2max}$ using the ACSM's metabolic equation (▶ **Fig. 3a**). ▶ **Fig. 3b** shows a *large* correlation with a high relative SEE (19 %) between the performance on the 6MWT and the measured $\dot{V}O_{2max}$. Correlations between the LTs and the measured $\dot{V}O_{2max}$ were *extremely large* with acceptable relative SEE values (10–11 %) (▶ **Fig. 3c, d**). Estimation of the individual $\dot{V}O_{2max}$ values in these participants using previously published 6MWT reference equations is shown in ▶ **Fig. 4**. ▶ **Table 2** reports the accuracy of the agreement between predicted and measured $\dot{V}O_{2max}$ of these equations.

▶ **Fig. 5** illustrates, in absolute (*upper panel*) and relative (*lower panel*) values, the comparison of the HRs at the finalization of each



▶ **Fig. 2** Mean (SD) heart rate (HR) [relative to maximal heart rate (%HR$_{max}$)] response to the *Six-Minute Walk Test* (6MWT) (**a**), and mean HR (%HR$_{max}$) and blood lactate concentration ([BLac]) responses to the *Discontinuous Modified Shuttle Walk Test* (D-MSWT) (**b**). In the D-MSWT (B) all participants terminated the 5.5 km · h^{-1} exercise stage. Mean (SD) values at completion of the test of participants achieving ≥ 5.5 km · h^{-1} are indicated by dashed lines. *Significantly different from the rest of the time-points within the same field walking test (P < 0.01).

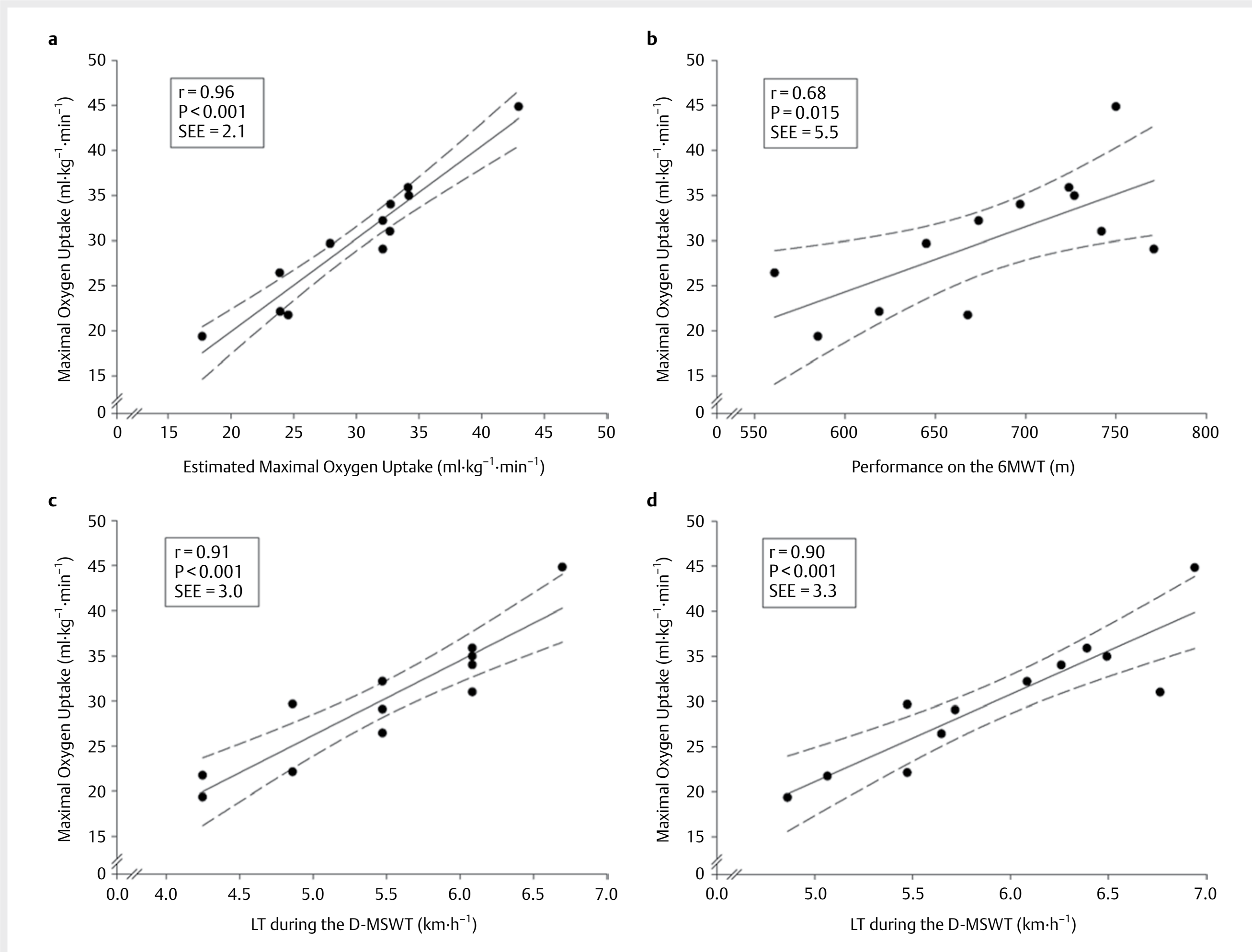
test, and the comparison of the HRs corresponding to the boundary from the *moderate*- to the *heavy*-intensity domain determined by the CPX (HR-CPX$_{m-h}$) and the D-MSWT (HR-LT). HR$_{max}$ reached on the CPX was 10 % higher than HR-6MWT$_{peak}$ (P = 0.006; 90 %CI: 6.58 to 21.1, ES: 0.6). Mean bias was 14 ± 14 b · min^{-1} and LOAs ± 35 b · min^{-1}. HR-6MWT$_{peak}$ was 16 % higher than HR-D-MSWT$_{peak}$ (P < 0.001; 90 %CI: 15.1 to 27.1, ES: 1.1, mean bias: 21 ± 12 b · min^{-1}, LOAs: ± 21 b · min^{-1}). HR-CPX$_{m-h}$ was 20 % higher than HR-LT (P = 0.001; 90 %CI: 10.9 to 25.1, ES: 1.0). Mean bias and LOAs were 18 ± 14 and ± 16 b · min^{-1}, respectively. Eight percent of the participants finished the 6MWT in the *moderate*, 58 % in the *vigorous*, and 33 % in the *near maximal to maximal* intensity domain. No participant finished the D-MSWT in the *near maximal to maximal* intensity zone. Two-thirds (67 %) of the participants finished the D-MSWT in the *moderate* zone and one-third (33 %) in the *vigorous* zone. The stratification of the HR-LT by exercise intensity domains according to the established guidelines indicates that participants fall into the *very light* (25 %), *light* (33 %), *moderate* (33 %), and *vigorous* (8 %) zones.

Discussion

The main findings of this study were as follows: (a) the heterogeneous internal response among individuals during the 6MWT (71 to 100 % HR$_{max}$) brings serious doubts about its submaximal nature and on the applicability of the HR obtained in such a test for training guidance purposes; (b) application of the 6MWT reference equations for older adults overestimated actual average $\dot{V}O_{2max}$ values; (c) the velocity associated with the LTs measured during a submaximal test better estimated the $\dot{V}O_{2max}$ compared to the 6MWT; (d) HR corresponding to the boundary from the *moderate*- to the *heavy*-intensity domain determined by the CPX differed from that obtained by the LT; (e) the wide range of %HR$_{max}$ at which LT occurs suggests that physical activity programs using exercise intensity prescriptions based on percentages of $\dot{V}O_{2max}$ or HR$_{max}$ would lack uniformity in the metabolic stress responses among individuals.

Although $\dot{V}O_{2max}$ is considered the best physiological parameter to assess aerobic fitness, the assessment of $\dot{V}O_{2max}$ is not always possible in advanced age [6]. One of the alternatives is to indirectly determine $\dot{V}O_{2max}$ using the final grade and speed obtained in the CPX [26]. In the present study, correlation magnitude indicated an *extremely large* relationship (r: 0.96) between estimated and actual $\dot{V}O_{2max}$ with a small SEE (2.1 mL · min^{-1} · kg^{-1}, i. e. 7.1 % of the mean) (▶ **Fig. 3a**). The mean difference between the estimated and measured values was < 1 %, and LOAs < 10 % (▶ **Table 2**), indicating that the maximum individual error in $\dot{V}O_{2max}$ estimation is relatively small (≈ 2.8 mL · min^{-1} · kg^{-1}). However, this procedure still requires maximum effort, which is often unfeasible due to motivational reasons or reluctance to perform maximal testing due to possible adverse cardiovascular events [6]. Then, the non-maximal 6MWT is one of the most commonly used tools to assess aerobic performance in healthy and diseased older adults [37]. In the present study, the estimation of $\dot{V}O_{2max}$ from the 6MWT was not significantly different compared to direct evaluation of $\dot{V}O_{2max}$ (▶ **Table 2**), and a *large* (r: 0.68) correlation, explaining 44 % of the variance, was observed (▶ **Fig. 3b**). However, the low individual agreement of the data (LOAs: 35 %) and the high SEE (19 %) make the predicted values unacceptable. For example, these LOAs indicate that, for a 69 year-old individual with a $\dot{V}O_{2max}$ of 29.6 ml · min^{-1} · kg^{-1}, the estimation of $\dot{V}O_{2max}$ would vary between 19 and 40 ml · min^{-1} · kg^{-1}. These results are in line with studies analyzing the relationship of the distance obtained during the 6MWT vs. $\dot{V}O_{2max}$ in older adults, where they found *moderate* (*r*: 0.5 to 0.6) associations between the two variables [10, 11]. Furthermore, the application of the previously developed 6MWT reference equations for the estimation of $\dot{V}O_{2max}$ in older individuals [31–33] showed significant differences between actual and estimated values (▶ **Fig. 4**), with SEE values of 15 to 20 %, mean differences of 10 to 23 %, and LOAs of 28 to 38 % (▶ **Table 2**). Collectively all these results suggest that the error in $\dot{V}O_{2max}$ estimation by the 6MWT in older males is unacceptable to be utilized in clinical practice.

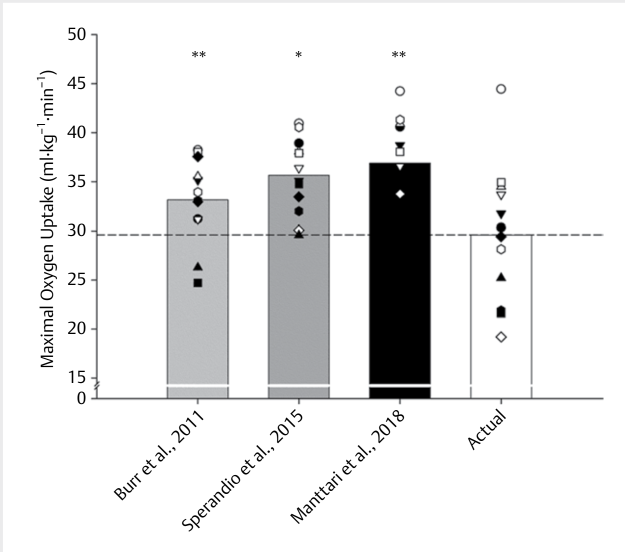
One reason why the 6MWT is one of the most widely used aerobic assessments in older men is its submaximal nature [9, 37]. In this study, however, the 6MWT did not always meet the submaximal criterion of < 85 % HR$_{max}$ established by current exercise testing guidelines [26]. The mean HR$_{peak}$ was 92 % of that reached on the CPX, with a wide heterogeneity of response (range: 71 to 100). Moreover, only 16 % of the participants (2 out of 12) reached a HR



▶ **Fig. 3** Individual data points and linear relationships between measured maximal oxygen uptake ($\dot{V}O_{2max}$) and the following: **a**) estimated $\dot{V}O_{2max}$ using ACSM's metabolic equation; **b**) distance covered on the *Six-Minute Walk Test* (6MWT); **c**) LT determined on discrete values of the velocity-rate stages during the *Discontinuous Modified Shuttle Walk Test* (D-MSWT); and **d**) LT determined on continuous values during the D-MSWT. Solid lines: linear regressions. Dashed lines: 90 % confidence intervals.

lower than 85 %HR_{max} at the completion of the test. This is in line with previous studies in older adults of similar age (range: 60–75) reporting mean values of ≈ 86–89 %HR_{max} [10, 29] at completion of the 6MWT. On average, this mean relative intensity is very similar to that found in this study (92 %HR_{max}) and corresponds to the upper edge of the *vigorous* exercise intensity domain according to the established guidelines [26]. These results confirm that the 6MWT requires, on average, a high level of effort. The range in the relative intensity is however wide (71–100 %HR_{max}), corresponding to the *moderate*, *vigorous,* and *near maximal or maximal* intensity domains (▶ **Fig. 5**, *lower panel*) [26]. This variability in the internal response to the 6MWT indicates that the relative effort during such a test was very wide among participants, thereby further explaining the observed low accuracy of the 6MWT to predict $\dot{V}O_{2max}$. The disparity in the HR response to the 6MWT may be due to the lack of standardization of the protocol [11], although our study and most studies follow established test instructions [28]. A plausible explanation, in addition to the ceiling effect previously mentioned, is the intrinsic nature of the test where subjective factors such as motivation and course strategy play an important role [6]. These results cast serious doubts on the submaximal nature of the test, and on its precision to assess, design, and monitor the aerobic exercise training in older men.

To the best of our knowledge, no previous study has examined the association between the LT and $\dot{V}O_{2max}$ in older adults. A key finding of this study was that the different determinations of the LT were good predictors of $\dot{V}O_{2max}$ based on the *extremely large* correlation magnitudes found that explained 81–83 % of the variance in $\dot{V}O_{2max}$ estimation, with acceptable (≈ 10 %) SEE values (▶ **Fig. 3c, d**). The estimation of $\dot{V}O_{2max}$ from LT was much better than that observed from the 6MWT. This might be partially due to the fact that LT performance, unlike 6MWT performance, does not depend on subjective factors such as motivation or self-paced strategies during the test. The estimation of $\dot{V}O_{2max}$ from LT is also better than those observed from the *estimated LT* [4], also named the *first ventilatory threshold* (VT_1), the *gas exchange threshold* (GET), or the *Anaerobic Threshold* (AT), determined



▶ **Fig. 4** Comparison of mean (columns) and individual (symbols) values between measured maximal oxygen uptake ($\dot{V}O_{2max}$) ("Actual", white column) and estimated $\dot{V}O_{2max}$ using the reference equations for older adults of 1) [31], 2) [32] and 3) [33]. The horizontal dashed line indicated mean actual $\dot{V}O_{2max}$ values. *Significantly different from actual $\dot{V}O_{2max}$ at $P<0.05$. ** Significantly different from actual $\dot{V}O_{2max}$ at $P<0.01$.

from ventilatory [10], gas exchange [38], or a combination of ventilatory and gas exchange alterations [10]. These studies, evaluating individuals with an average age of 62 [38] or 70 yrs [10] reported relatively low correlation magnitudes of ≈ 0.40 between the *estimated LT* and $\dot{V}O_{2max}$. It is uncertain why our LTs vs. $\dot{V}O_{2max}$ correlation magnitudes were considerably higher than the correlations between the *estimated LT* and $\dot{V}O_{2max}$. Those relatively low correlation magnitudes might be partially related to the moderate test-retest reliability coefficients ($r=0.72–0.77$) [39] and measurement errors (5–10 %) [40] observed in the *estimated LT* determination when correction of gas-exchange computations are not performed [3, 27]. For clinical application purposes, some additional advantages of the LT determination by means of the D-MSWT might include the following:

a) Its submaximal nature. The finalization of the D-MSWT, that is, the required intensity to measure the LT, occurred at a mean intensity of ≈ 76 %HR_{max} (range: 65 to 87). All participants but one fulfilled the submaximal testing criterion established by current exercise testing guidelines [26]. This HR range corresponds to the *moderate* and *vigorous* HR-related intensity zones [26] and is lower than the one found in the 6MWT (71–100 % HR_{max}) (▶ **Fig. 5**). The objective and submaximal nature of the D-MSWT makes this test independent of individual motivational factors, and it is better tolerated than tests where participants are brought to exhaustion [5].
b) Since the 1970s, it is considered that exercise intensity designed relative to LT or *estimated LT* brings more uniform stress and metabolic responses compared to exercise intensities designed relative to maximal anchors such as $\dot{V}O_{2max}$ or HR_{max} [7, 39, 41, 42]. The wide range of %HR_{max} at which LT occurs (50–78 % HR_{max}; ▶ **Fig. 5**) confirms that training programs using exercise prescriptions based on percentages of $\dot{V}O_{2max}$ or HR_{max}, without consideration of the individual LT, lack uniformity in the metabolic and ventilatory responses among individuals. This may create multiple training stimuli among the individuals, which in turn results in a wide range of "*improvements*" (or even the lack thereof) in cardiovascular and metabolic functions [7, 41]. A better and safer approach to design exercise intensities is to assess the LT and use the individual HRs corresponding to the LT as a point of reference to deduce and design their individual exercise training stimulus [15, 42]. This should attenuate the interindividual variation in the training responses compared to exercising relative to %HR_{max} or % $\dot{V}O_{2max}$ [43].

Limitations and methodological considerations

First, we studied a relatively small sample of older male adults. However, $\dot{V}O_{2max}$ [26] and 6MWT [9, 37] results indicate that our sample is a representative sample of physically active well-conditioned older male adults. Their $\dot{V}O_{2max}$, indeed, is on average 5 to 20 % higher than their gender-and age-related groups of USA [39], Canada [44] and Norway [45]. Second, the developed regression models are only applicable to older males with $\dot{V}O_{2max}$ values ranging from 19.2 to 44.4 ml · min^{-1} · kg^{-1}. Whether the relationships between LTs and $\dot{V}O_{2max}$ are maintained in individuals with lower or higher aerobic conditioning, or in female older adults, is a question that remains unclear. Third, verification of the determination of the boundary from the *moderate*- to the *heavy*-intensity domain by constant velocity trials was not performed. Nonetheless, we utilized the direct LT determination procedure, which is the standard LT determination procedure against which indirect methods should be evaluated [4, 7, 14]. Four, the D-MSWT duration was 26 ± 4 min (range: 20–32). This test duration might hinder the applicability of the D-MSWT in clinical settings. However, it might be worthwhile to invest this time in the assessment of the LT at the beginning of any physical activity program in order to design more precise individual exercise intensities and consequently economize the required exercise training for improving the cardiorespiratory fitness. Furthermore, in this study, the initial workload and subsequent workload increments were low to allow a preliminary [BLac]-baseline phase on the [BLac] kinetics and allow a precise LT assessment [46]. Three to four exercise stages could have been omitted, allowing for two [BLac]-baseline measurements in every participant and reducing the test duration to 15–18 min (range: 9 to 24). Further cross-validation and longitudinal studies with a larger number of participants are required to 1) validate our proposed LT vs. $\dot{V}O_{2max}$ equations, and 2) corroborate whether the relationships are maintained in a dose-response manner along longitudinal physical activity programs aiming to improve the cardiorespiratory capacity and functionality of older men.

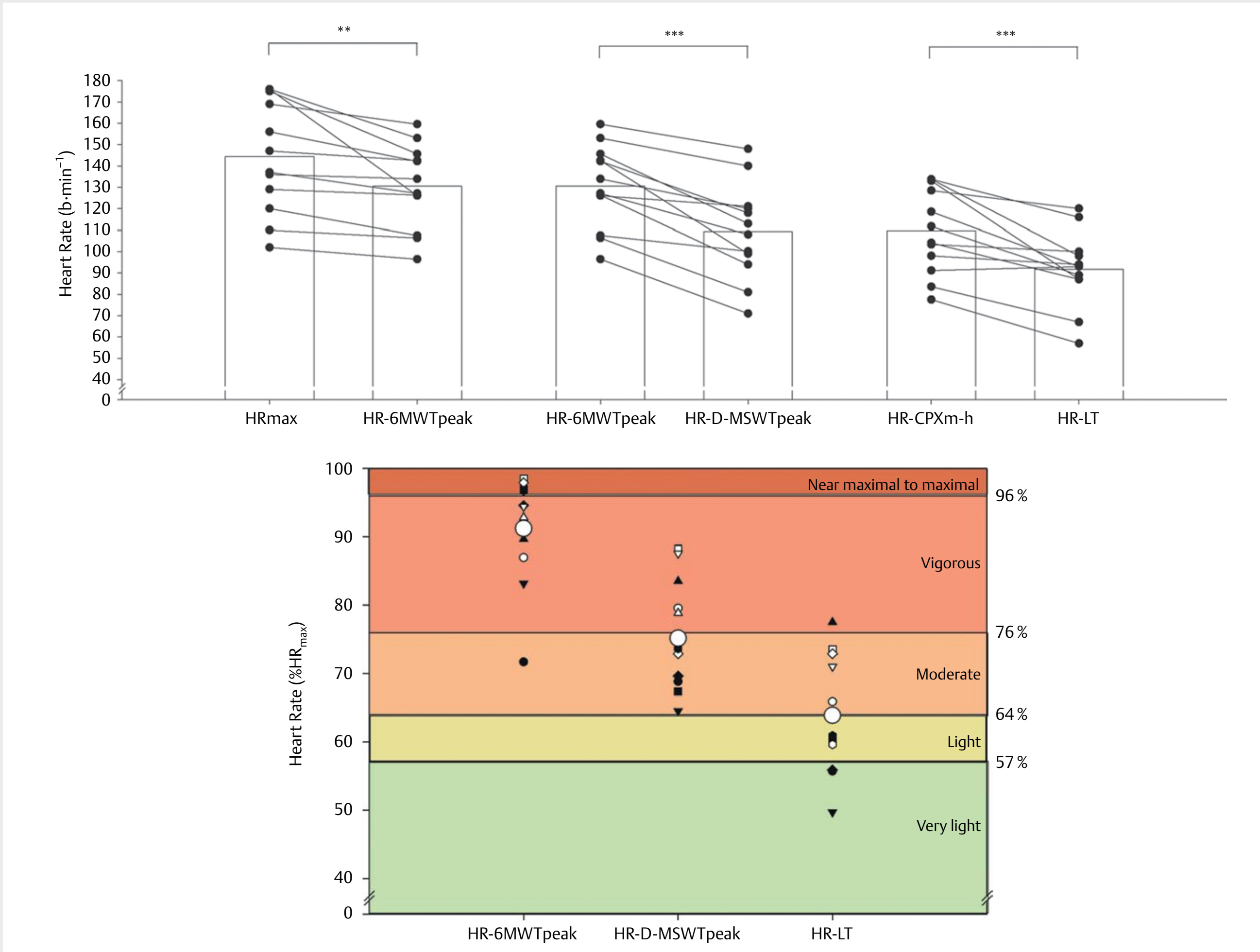
Practical applications

The interindividual heterogeneous response and the high mean effort required to complete the 6MWT highlights the limitations of this evaluation as a practical test for training guidance purposes in older adults. In addition, it was shown that the indirect determination of $\dot{V}O_{2max}$ by the 6MWT is imprecise. We demonstrated that LT testing resulted in more submaximal responses than the 6MWT,

▶ **Table 2** Application (agreement and relationship between estimated and measured values) of the linear regressions models to estimate $\dot{V}O_{2max}$ ($n = 12$)

	Estimated values	Measured values	*Agreement*					*Relationship*			
$\dot{V}O_{2max}$ Prediction Models			**Mean bias**	**LOAs**	**P**	**90 %CI**	**ES**	***r* [90 %CI]**	**p**	**SEE**	**90 %CI**
ACSM metabolic equation											
$\dot{V}O_{2max} = 0.1 \cdot (S) + 1.8 \cdot (S) \cdot (G) + 3.5$	29.9 ± 6.6	29.6 ± 7.1	0.2 ± 2.0	2.8	0.587	−1.4 to 0.7	0.043	0.96 [± 0.05]	< 0.001	2.1	1.0 to 1.2
Performance on the 6MWT											
$\dot{V}O_{2max} = 0.0722 \cdot (6MWT) - 18.9719$	30.1 ± 4.9	29.6 ± 7.1	0.0 ± 5.2	10.2	0.566	−3.3 to 1.7	0.002	0.74 [± 0.26]	0.006	5.0	0.4 to 1.7
LTd during the D-MSWT											
$\dot{V}O_{2max} = 8.3125 \cdot (LTd) - 15.3775$	30.1 ± 6.5	29.6 ± 7.1	0.0 ± 2.9	4.4	0.575	−2.1 to 1.1	0.002	0.90 [± 0.12]	< 0.001	3.2	0.6 to 1.3
LTc during the D-MSWT											
$\dot{V}O_{2max} = 9.6551 \cdot (LT_c) - 27.1474$	30.1 ± 6.4	29.6 ± 7.1	0.0 ± 3.2	6.1	0.587	−2.2 to 1.1	0.001	0.89 [± 0.13]	< 0.001	3.4	0.6 to 1.3
6MWT reference equation (Burr* et al.*, 2011)											
$\dot{V}O_{2max} = 70.161 + 0.023 \cdot (6MWT) - 0.276 \cdot (weight) - 6.79 \cdot (sex) - 0.193 \cdot (resting\ HR) - 0.193 \cdot (age)$	33.1 ± 4.3	29.6 ± 7.1	−3.0 ± 5.7	11.1	0.001	−8.6 to −3.5	0.534	0.74 [± 0.26]	0.006	5.0	0.5 to 2.2
6MWT reference equation (Sperandio* et al.*, 2015)											
$\dot{V}O_{2max} = -2.863 + 0.0563 \cdot 6MWT$	35.6 ± 3.8	29.6 ± 7.1	−5.5 ± 5.0	9.8	0.049	−6.4 to 0.7	1.009	0.62 [± 0.34]	0.033	5.8	0.1 to 1.9
6MWT reference equation (Mänttäri* et al.*, 2018)											
$\dot{V}O_{2max} = 110.546 + 0.063 \cdot (6MWT) - 0.250 \cdot (age) - 0.486 \cdot (BMI) - 0.420 \cdot (height) - 0.109 \cdot (HR\ end\ of\ the\ test)$	36.9 ± 4.6	29.6 ± 7.1	−6.8 ± 4.3	8.4	< 0.001	−9.5 to −5.1	1.187	0.82 [± 0.2]	0.001	4.3	0.6 to 1.9

$\dot{V}O_{2max}$, maximal oxygen uptake; LOAs, limits of agreement; CI, coefficient interval; ES, effect size; SEE, standard error of the estimate; ACSM, American College of Sports Medicine; S, speed; G, grade; 6MWT, Six-minute walk test; BMI, body mass index; HR, heart rate; LT_1, the highest stage-velocity above which blood lactate concentration increased by ≥ 0.1 mmol · L^{-1} in the following stage and ≥ 0.2 mmol · L^{-1} in the subsequent stage; $LT_{0.2mM}$, velocity associated with LT_1 plus 0.2 mmol · L^{-1} in the individual velocity vs. blood lactate concentrations curves; HR, heart rate. $\dot{V}O_{2max}$ in ml/kg/min; 6MWT in meters; weight in kilograms; height in centimeters; HR in beats per minute; age in years; speed in m · min^{-1} in the ACSM equation; grade in percent grade in decimal form, speed in km · min^{-1} in the LT equations.



▶ **Fig. 5** Upper panel: Individual (symbols) and mean (columns) heart rate (HR) absolute (b · min-1) values corresponding to 1) the finalization of the incremental exercise test (CPX) to exhaustion (HR_{max}), 2) the finalization of the Six-Minute Walk Test (HR-$6MWT_{peak}$), 3) the finalization of the Discontinuous Modified Shuttle Walk Test (HR-D-$MSWT_{peak}$), 4) the boundary between the *moderate*- to the *heavy*-intensity domain determined by the HR_{max} (HR-$CPX_{m\text{-}h}$), and 5) the boundary between the *moderate*- to the *heavy*-intensity domain determined by the HR at the lactate threshold (HR-LT). Lower panel: Individual (symbols) and mean (open bigger circles) values of HR-$6MWT_{peak}$, HR-D-$MSWT_{peak}$ and HR-LT relative to HR-CPX_{max} and stratified by exercise intensity domains according to the established guidelines [26]. **Significant difference at $P<0.01$. ***Significant difference at $P<0.001$.

and that the LT test might be a valuable on-field test to precisely estimate the $\dot{V}O_{2max}$ in older male adults. LT testing is a relatively easy procedure to be implemented in physical activity programs in old age and might help improving the quality of the professional assistance in the assessment and prescription of the aerobic capacity, particularly in the *moderate*- to the *heavy*-intensity domain. The monitoring of HR is very easy, and thus, assessment of HR at the LT can help in the monitoring of the training stimuli during aerobic exercise. The submaximal nature and the direct HR applicability make LT testing an attractive objective alternative to CPX ($\dot{V}O_{2max}$) and 6MWT. Other special populations, for instance, patients with chronic respiratory or cardiovascular diseases and with similar aerobic conditioning might also benefit from the results of this study.

Conclusions

First, LT testing elicited more submaximal responses than the 6MWT, and it estimated $\dot{V}O_{2max}$ better in older male adults. Second, the HR corresponding to the boundary from the *moderate*- to the *heavy*-intensity domain determined by the CPX was ≈ 20 % higher than obtained by the LT. The wide range of $\%HR_{max}$ at which LT occurs suggests that physical activity programs using exercise intensity prescriptions based on percentages of maximal anchors ($\dot{V}O_{2max}$ or HR_{max}) would lack uniformity in the metabolic stress responses among individuals. In this sense, LT and its associated HR (HR-LT) might improve the design of aerobic exercise training, particularly in the upper *moderate*- to *heavy*-intensity domain.

Data availability

Data are available on reasonable request from the corresponding author.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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