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Feasibility of whole-body gait kinematics to assess the validity of the six-minute walk test over a 10-m walkway in the elderly

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ABSTRACT

Background: The six-minute walk test (6MWT) assesses the functional exercise capacity and its impairments due to chronic cardiorespiratory and/or musculoskeletal conditions, particularly in the elderly. The clinimetric properties and clinical utility of the 6MWT are well-described, but little is known about the gait kinematics during this test. This study evaluated the feasibility of a study protocol based on whole-body gait kinematics to assess the validity of the 6MWT over a 10-m walkway in the elderly.
Methods: Eight elderly healthy participants (7 women, aged 61–77 years) underwent the 6MWT over a 10-m rectilinear walkway. The data were collected using infrared cameras and a spherical marker covered with retroreflective tape firmly attached to a helmet worn by the participant during the 6MWT.
Results: The total distance measured by the assessor was significantly smaller than both its kinematics ($P = 0.012$) and model-predicted ($P = 0.017$) counterparts. The total distance measured by the kinematics was also smaller than the predicted one ($P = 0.025$). A large bias toward underestimating the 6MWD, as measured by the assessor (mean = −32, SD = 6.3 m), was observed along with a high determination coefficient ($R^2 = 99.2\%$). Most of the participants presented a negative trend for the average speed as a function of half-turns.
Discussion: Analysis of whole-body gait kinematics is feasible using motion capture systems and can be used to assess the validity of the 6MWT over a 10-m walkway in the elderly. The 6MWD, as measured by the assessor, underestimates the actual covered distance in the 6MWT but not the functional exercise capacity.

1. Introduction

Since the 1960s, functional exercise capacity has been assessed using field tests [1]. Currently, routine assessment in the cardiorespiratory rehabilitation setting utilizes the six-minute walk test (6MWT), a reliable, cost-effective, time-limited field test [2]. The 6MWT task requires a subject to walk as fast as possible along a given walkway and to turn around two delimiting traffic cones; therefore, the total distance walked during the test is a surrogate measure of the functional exercise capacity, which is also directly proportional to the number of turns [3]. The test's score, namely, the six-minute walked distance (6MWD), is the total distance a subject covers in absolute or predicted percent values obtained by population-specific reference equations [4,5]. The assessment of functional capacity is of particular interest in the elderly (≥60 years old) due to the high cardiovascular morbidity and physical disability in this population [6,7]. Indeed, the 6MWT has been widely applied in the clinical setting to assess functional exercise capacity in the elderly population using both measured and predicted walked distances [5].

The clinimetric properties and clinical utility of the 6MWT, as well as the methodological sources of variability of the 6MWD, are both well described [2]; nonetheless, the kinematic aspects of the 6MWT remains largely unknown. Whenever either the recommended walkway length or its layout—a 30-m rectilinear walkway—are not available, assessors interpret the variability in the 6MWD with assumptions or claims regarding the gait kine-

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matics during the test [3]. For instance, clinical settings usually provide shorter walkways (e.g., 10 m long [8,9]) that lead to a larger number of turns and smaller 6MWD with speculative explanations about the body's acceleration [10]. Non-rectilinear—e.g., circular or elliptical—walkway layouts increase the 6MWD, again without evidence about the underlying kinematic factors [11–13]. The assumption that the participants' trajectory is perfectly rectilinear between cones—a 'pinball trajectory'—comprises another source of variability for the calculation of the 6MWD. Such variability is thus certainly toward an underestimation of the actual 6MWD, but the underlying model describing the relationship between the 6MWD measured by the assessor and by kinematic analysis—including, if any, bias and/or slopes—remains unknown.

Motion capture systems are valuable tools for recording and describing human movements using kinematic analysis [14]. Gait kinematic analysis has been performed by assessing several body landmarks to represent the center of body mass [15,16] or a single body landmark as a surrogate of the center of body mass, with both approaches aiming at characterizing the whole-body dynamics [17]. However, studies on gait kinematic analysis focus on joint kinematics [18,19], body segment movements [20], whole-body gait kinematics in treadmills [16], partial walkway (3-m long) gait kinematics of the 6MWT [21], and short-distance whole-body gait kinematics that are not related to assessing functional capacity [15,22]. No study has used a motion capture system to assess whole-body gait kinematic analysis in such a large distance as required for the 6MWT. It is also unknown how accurate and precise the assessor's measurement of 6MWD is compared with a measurement made considering the actual participant's trajectory. We argue that kinematic analysis during the 6MWT may help explain this test's assumptions and methodological sources of variability of 6MWD, as well as the validity of the assessors' in measuring this test's score. Therefore, the aim of this study was to evaluate the feasibility of a study protocol based on whole-body gait kinematics to assess the validity of the 6MWT over a 10-m walkway in the elderly.

2. Materials and methods

2.1. Ethics

This research protocol comprises two sequential phases, the feasibility study and clinical study, in elderly persons with chronic obstructive pulmonary disease (COPD). Herein are presented the results of phase 1. The Institutional Ethics Committee approved this study protocol before its execution (protocol No. 53542816.7.0000.5235). The participants provided written informed consent after being verbally instructed about the study aims and procedures.

2.2. Participants

The sample size was calculated based on the validity of the assessor for measuring the 6MWD as the main outcome. A sample of eight participants was required to observe an expected mean of difference equal to 0 m, an expected standard deviation of differences equal to 5 m, and the maximum allowed difference equal to 25 m—at least half the minimal clinically important difference [3]—at $\alpha = 5\%$ and $\beta = 80\%$.

Eight elderly healthy participants (7 women; aged 61–77 years; body mass: 48–94 kg; body height: 1.48–1.64 m) were consecutively enrolled. A single assessor screened all the participants to exclude cardiopulmonary or neurological conditions, musculoskeletal pain, or injuries that could affect their performance during the test.

2.3. Field test: 6MWT

The 6MWT was performed according to all the reference instructions [3], but the walkway length was set up equal to 10 m (center-to-center cone distance = 9 m) as a minimal walkway length [4,8] for a feasibility study. The participants performed the test twice (30-min rest between tests), and the test with the largest distance was used for further analysis. No instruction was provided to the participants regarding their trajectory during the test, although standard verbal encouragement was provided every 1 min [3]. The assessor measured the 6MWD considering the number of complete half-turns—defined as the crossing of the two delimiting cones—and the residual walked distance. The predicted values were obtained from the corresponding 'basic' reference equation and considering sex, age, and body mass index (BMI) as independent variables [8]: $6MWD_{men} = 1266–(7.80*age)–(5.92*BMI)$ or $6MWD_{women} = 1064–(5.28*age)–(6.55*BMI)$.

2.4. Instrumentation and system calibration

Four infrared cameras (ProReflex MCU 240; Qualisys, Gothenburg, Sweden) were semi-circularly aligned to allow different view angles when capturing images and were positioned 2 m away from the nearest cone as suggested in the manufacturer's manual (Fig. 1). The distal cone was positioned 9 m away from the closest cone as manually measured using a 30-m metric tape. The participant was initially positioned to the right side of the proximal cone while waiting for the start command. All the participants were instructed to walk toward the distal cone, turn around the distal cone, return walking towards the proximal cone, turn around again and repeat until the they heard the command to stop. The acquisition system was calibrated before each clinical session using the manufacturer's equipment (wand length = 749.4 mm), procedure, and software (Qualisys Track Motion 2.4, Qualisys, Gothenburg, Sweden). Calibrations were repeated, if necessary, until the measurement errors were all <1.0 mm [14].

A hollow-body, plastic spherical marker (diameter = 0.58 m) covered with retroreflective tape (model TS-02; IFM Eletrônica Ltda., SP, Brazil) was firmly attached to a helmet (total mass: ~0.5 kg), which was worn by the participant during the 6MWT (Fig. 2).

2.5. Data acquisition and signal processing

Data acquisition started after a 5-s delay and lasted 360 s at a sampling frequency of 100 Hz. The starting command for the participant and acquisition were concurrent, and the participant was required to stop immediately after the timeout. The spatial coordinates of the helmet's marker were exported for off-line analysis in *R* version 3.3.3 [23].

Existing gaps in the data were programmatically located and filled by a two-point linear interpolation algorithm [24] implemented using the function *approx* in the 'stats' package [23]. The interpolated signal was smoothed with a symmetric, 95-sample moving average filter (~2 Hz low-pass filtering) [25]. To minimize the loss of the measured 6MWD, the signal was (1) rescaled by minimizing the root mean square error between raw and filtered signals and (2) inputted with samples at the start and end of the signal by a two-point linear extrapolation algorithm implemented using the function *approxExtrap* in the 'Hmisc' package [26]. Time series of the marker's displacement were visually inspected at each processing stage to ensure no artifacts (e.g., signal discontinuities) were generated due to signal processing.

Half-turns were programmatically determined using a sample-by-sample, direct search of extreme values ('peaks' and 'valleys') of displacement in the walkway' longitudinal axis based on the