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Spatial-temporal gait parameters based on a wearable inertial sensor of healthy Brazilian subjects

Parâmetros de referência espaço-temporais de um sensor inercial para sujeitos brasileiros sadios

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ABSTRACT

Gait analysis in a laboratory may be expensive, time-consuming, and restricted to a controlled environment. Validated wearable technology may be an alternative to such analysis. However, wearable technologies should demonstrate reference values of a healthy population. **Objective:** To establish spatio-temporal gait reference values of an accelerometer (G-Walk) in a healthy Brazilian population. **Methods:** This is a cross-sectional study with 124 healthy subjects evaluated with G-Walk in the 6-minute and 10-meter walk tests (6MWT and 10MWT). Gait parameters of Velocity, Cadence, Distance, and gait symmetry variables were retrieved for analysis. Clinical and demographical characteristics were also collected and tested with simple linear regression as covariables of the gait characteristics. The bootstrapped 5th percentile of the gait parameter established the reference values. If a covariable influence was found, the reference values were established by subgroup analysis according to the covariable. **Results:** The study analyzed 114 subjects, mostly women (67.74%), aged 39.36 (SD 12.18). Height was a covariable of cadence for the 10MWT and cadence and stride length for the 6MWT. Age and sex combined were covariables of 6MWT velocity, and sex alone was a covariable of 6MWT. All reference values for symmetry were above 89%, velocity at the 10MWT was above 1.0m/s, and distance at the 6MWT was 354m and 359.5 for females and males, respectively. **Conclusions:** Our study generated reference values for spatio-temporal gait analysis with G-Walk of a population of a major urban area, considering the covariables of age, height, and sex.

Keywords: Gait Analysis, Reference Values, Wearable Electronic Devices

RESUMO

Análises da marcha em laboratório tem custo elevado, demandando tempo e ambiente controlado. *Wearables* são equipamentos portáteis que podem ser alternativas aos laboratórios. Valores de referência podem determinar parâmetros para análises de marcha de pessoas com patologias. **Objetivo:** Estabelecer valores de referência espaço-temporais de um acelerômetro (G-Walk) em uma população saudável. **Métodos:** Trata-se de um estudo transversal com indivíduos saudáveis avaliados com G-Walk nos testes de caminhada de 6 minutos e de 10 metros (TC6 e TC10). Velocidade, cadência, distância e de simetria da marcha foram analisados. Características clínicas e demográficas também foram testadas com regressão linear simples como covariáveis das características da marcha. Os valores de referência foram estabelecidos pelo quinto percentil dos parâmetros por bootstrap e na presença de covariáveis demográficas, os valores foram estabelecidos por análise de subgrupos, de acordo com a covariável. **Resultados:** O estudo analisou 114 sujeitos, em sua maioria mulheres (67,74%), com idade de 39,36 (DP 12,18). A altura foi uma covariável da cadência do TC10 e da cadência e comprimento da passada do TC6. Idade e sexo combinados foram covariáveis da velocidade do TC6, e o sexo foi uma covariável do TC6. Todos os valores de referência para simetria foram superiores a 89%, a velocidade no TC10 foi superior a 1,0m/s e a distância no TC6 foi de 354m e 359,5m para mulheres e homens, respectivamente. **Conclusões:** Nosso estudo gerou valores de referência para análise espaço-temporal da marcha com o equipamento G-Walk em uma população de uma grande área urbana, considerando as covariáveis idade, altura e sexo.

Palavras-chaves: Análise da Marcha, Valores de Referência, Dispositivos Eletrônicos Vestíveis

INTRODUCTION

Walking is an essential requirement for many daily activities.[1] Gait characteristics constitute a clinical marker of well-being and level of activity, and when it is impaired, it is a precursor to falls and disability.[2] Assessment methods of gait and mobility are necessary to identify structural, biomechanical, and functional capacities,[1,3] and functional motor aspects such as activity level[1,4] and participation, as well as the quality of life, are emphasized in The World Health Organization in the ICF – International Classification of Functioning Disability and Health. This document emphasizes the importance of monitoring the quantity and quality of motor activities in rehabilitation to define therapeutic intervention settings and outcome evaluations.[5]

In research settings, quantitatively, advanced gold standard motion analysis systems are applied to analyze and evaluate the spatio-temporal, kinematic, and kinetic data. Such approaches have been successfully developed and applied in gait laboratories.[1,4,6]

However, these systems are limited to laboratory use, a context in which the equipment does not necessarily reflect the subject's usual environment,[4] generating changes in gait parameters, such as shorter gait length than in everyday life, creating unusual walking conditions and limiting the determination of gait variability and symmetry, essential variables for the evaluation of pathological gait.[1]

The wireless and wearable technology of accelerometers and gyroscopes has emerged as a potential alternative to clinical/laboratory testing, overcoming the above-mentioned limitations. Different wearable sensors have yielded significant results over the past few years, promising approaches to solving various problems in human health.[7] A wearable inertial sensor, also known as a wearable inertial measurement unit (IMU), is small, lightweight, inexpensive, does not require the complex set-up times of traditional motion capture systems, and does not have to be confined to a clinic/laboratory. Therefore, a wearable inertial sensor can provide continuous real-time spatial-temporal gait parameters during activities of daily living, as opposed to artificial movements of traditional assessment tests.[8]

A single sensor is often attached at the waist level to minimize the alteration of the natural gait of the subject and increase wearer compliance, accurately detecting gait movements.[9] As Lijima H et al.[9] emphasize in recent research, to verify the state of the field of the waist-mounted sensor algorithm for gait events, "much work is required before it can be recommended as a valid strategy for clinical practice".[9] Previous studies reported gait data for groups of healthy subjects and provided reference gait data for normal subjects.[4,5] However, we observed that healthy populations in these previous studies had different anthropometric data than the Brazilian population.

Developing a new country-specific instrument is costly and time-consuming and may jeopardize the comparison data between populations from different countries or cultures.[10] Nonetheless, the lack of such reference values, especially regarding the Brazilian population, can contribute to the underuse of gait analysis provided by the wearable inertial sensor.

OBJECTIVE

Therefore, this study aims to obtain spatio-temporal gait reference parameters based on a cohort of healthy subjects of all ages and to establish associations between gait parameters and demographical characteristics.

METHOD

This study is a cross-sectional analysis for establishing reference values for Gait Analysis with G-Walk®. Participants were recruited, screened, and enrolled at the Physical Medicine and Rehabilitation Institute of the University of Sao Paulo (Instituto de Reabilitação da Faculdade de Medicina da Universidade de São Paulo – IMREA-FMUSP). All volunteers were adequately instructed about the study procedures, agreed to participate, and signed the Informed Consent Form. This study is an ancillary publication of a major project, which was approved by the Independent Ethics Committee Comissão de Ética para Análise de Projetos de Pesquisa – CAPPESQ (reg. number 86832518.7.0000.0068).[11]

Volunteers above 18 years of age, of both sexes and with clinical stability verifiable by a medical doctor were eligible for the study. Also, the participants were considered healthy and included if they did not report pain or functional limitations. Volunteers with chronic or acute pain, uncontrolled diseases verified by a medical doctor, psychological instability verified by screening assessments, and pregnant women were excluded.

After the screening process, the objectives of the study, risk of participation, and procedures were explained, and the Informed Consent Form (ICF) was given to the volunteers. Those who signed the ICF were included. The volunteers were a convenient sample of the ancillary previously mentioned project.

After inclusion, demographical data on age, body mass index (BMI), height, sex, knee extension/flexion strength, and clinical data regarding morbidities and medication were collected from each participant. Knee extension/flexion strength was measured by peak concentric isokinetic force at 60° per second.

The gait was evaluated with Gait Analysis (GA) by G-walk®, a wearable sensor for assessing functional capacity and mobility, dynamic balance, and walking. The GA is used to analyze the time to walk a route of 7 meters or more in a straight line at a self-selected speed. These conditions are recommended for GA with G-Walk®, and, in our study, we standardized the 10-meter Gait Analysis based on a 10-minute walk test and 6-minute walk tests (10MWT and 6MWT, respectively). The 6MWT was performed in a 14-meter straight leveled path, and the 10MWT was performed in a 30-meter straight leveled path.

The tests mentioned above were performed with a portable, wireless G-WALK® sensor (G-sensor, BTS Bioengineering S.p.A., Italy), which provides linear accelerations along three orthogonal axes: anteroposterior, mid-lateral, and vertical. The single portable G-sensor is a wireless system of inertial sensors for analyzing human movement. The sensors are made of 4 inertial platforms (MEMS) composed of a triaxial accelerometer, a magnetic sensor, a triaxial gyroscope, and a temperature sensor combined with advanced algorithms provided by the Sensor Fusion technology and a GPS. These systems of analog interface with microsystems are controlled by a data recording unit (up to 16 elements) using ZigBee-type radio communication. Each sensor is 62mm × 36mm x 16mm in size, weighing 60g, and consists of a three-axis accelerometer (maximum scale of ± 6g), a 3-axis gyroscope (full-scale ± 300 °/s), and a three axes magnetometer (full scale ± 6 Gauss).[12] This device is calibrated with gravity acceleration immediately after manufacture. The data from the inertial sensor is transmitted via Bluetooth to a computer and processed using its dedicated software (BTS G-STUDIO, version: 3.3.22.0), which automatically provides the parameters during the 10MWT Step length (meters, m), stride length (meters, m); gait speed (meters per second, m/s), cadence (steps per minute, steps/min), and duration of the support, single support, double support and swing as percentages of the complete gait cycle duration (%). The 6MWT recorded distance (meters, m), anteroposterior symmetry, mean cadence (steps per minute, step/minute), mean velocity (meters per second, m/s), and stride length (meters, m).

The analyzed values were the cadence, velocity (gait speed), right/left symmetry of stance and swing duration, single and double support, and stride and step length.

For data acquisition, the single sensor was positioned on the volunteers' waist with a semi-elastic belt, covering the intervertebral space between S1 intervertebral space so that acceleration is collected on the three orthogonal anatomical axes, i.e., the anterior-posterior, mediolateral and vertical axes. The coordinate reference frame had the z-axis oriented to the front, the x-axis oriented vertically upward, and the y-axis orthogonal to both the z and x-axis towards the right side. This motion analysis was performed with the accelerometer sensitivity of 3G and a sampling frequency of 50 Hz4.

Descriptive statistics of demographical data were provided with means and standard deviations for continuous variables and frequencies for categorical variables. The normality of the continuous data was tested with the Shapiro-Wilk test and histogram analysis. After the data characterization, the demographic, clinical, and strength variables were tested by simple linear regression to detect possible covariables of the main results of G-walk®. These variables were considered covariables if $p<0.10$, $r^2 > 0.05$, and the β coefficient was relevant. Whenever a variable had two or more covariables, they were tested with multiple linear regression followed by a likelihood ratio test (LRT), allowing for selecting the most significant covariable or the best fitting model.[12] Finally, the covariables were tested for heteroscedasticity with the Breusch-Pagan / Cook-Weisberg test.[13,14]

If a gait parameter had homoscedastic covariables, its reference values were established according to subgroups of the covariable. If a gait parameter had a heteroscedastic covariable, the analysis would be conducted within fractional polynomial regression, considering the different data distribution along the axis of the regression plot.[15,16] Gait parameters with homoscedastic dichotomic covariables, such as sex, were divided into two groups and analyzed as described below.

The reference values of each G-walk® output without a known covariable or with dichotomic covariables, such as sex, considered the performance classification as normal or outside the normal range. The values for these classifications were established by bootstrapping the 5th percentile of the gait parameter with 5000 repetitions, such that the lower bond of the 95% Confidence Interval (95%CI) of the bootstrapped value was the cutoff for classifying a parameter as normal or outside the normal range.[17,18]

This calculation was consistent with measurements of gait assessment from previous seminal studies with physiological gait range.[5]

The 95%CI upper bond was also calculated to establish the normal range for all gait parameters, i.e., the range from the 5th to the 95th percentile. Nonetheless, values exceeding the 95th percentile should not necessarily be considered non-normal or unhealthy.

RESULTS

The study included 124 volunteers, mostly women (n= 84; 67.74%), with a mean age of 39.36 (SD 12.18) and BMI of 27.23 (SD 5.02) (Table 1) from April 2020 to January 2022. After inclusion, ten volunteers dropped out. Therefore, 114 subjects were analyzed.

Table 1. Demographic baseline characteristics

Characteristic	Females (n= 84; 67.74%)	Males (n= 40; 32.26%)
Age (years) ǂ	38.92 (12.61)	40.30 (11.30)
Height (m) ǂ	1.61 (0.06)	1.75 (0.08)
BMI (kg•m-1) ǂ	27.05 (5.17)	27.57 (4.75)
Knee strength (N.m)	86.22 (16.68)	136.69 (24.65)
Cardiovascular diseases	9 (10.84%)	6 (15%)
Endocrine diseases	10 (13.25%)	0 (0%)
Lung diseases	5 (6.02%)	1 (2.5%)
Rheumatic diseases	1 (1.2%)	1 (2.5%)
Musculoskeletal diseases	8 (9.5%)	3 (7.5%)

ǂ mean (standard deviation); kg, kilogram; m, meters; N, Newton; BMI, body mass index; Knee strength described as an average of extension and flexion of both knees

The diseases listed in Table 1 were under treatment and non-symptomatic. Concerning cardiovascular diseases, 12 patients had systemic arterial hypertension, one had chronic venous insufficiency, and two had supraventricular arrhythmia. As for the endocrine diseases, seven patients had hypothyroidism, and three had Type II Diabetes Mellitus. The lung disease found was asthma, and two patients had a diagnosis of celiac disease. Musculoskeletal diseases were found in four patients with osteopenia, two with chondromalacia patellae, two with a mild discal protrusion, one with hip dysplasia, one with patellofemoral hypertension, and one with gout. All these diseases were considered stable and controlled during medical screening, and the participants reported no acute or chronic pain.

The normality analysis for the measurements of the 10MWT showed that cadence was the only parametric variable. Regarding the 6MWT, distance, velocity, and stride length were considered parametric, whereas cadence was non-parametric.

The analysis of covariables of 10MWT evidenced that height is a covariable for cadence. As for the 6MWT, the distance was initially influenced by the female sex and height, cadence was influenced by height, velocity was influenced by age, female sex, and height, and the female sex and height influenced stride length. Knee strength was not considered a covariable regardless of the gait variable tested.

The Likelihood Ratio Test of sex and height as explicatory variables for distance collected during the 6MWT showed that height did not contribute to the model ($p_{chi^2} = 0.775$) and was not considered a covariable. Likewise, for velocity, the LRT evidenced that height was not a significant predictor ($p_{chi^2} = 0.993$) and was removed from the covariables. Concerning the stride length analysis of covariables, the LRT results showed that sex should not be considered a covariable ($p_{chi^2} = 0.260$). The covariables were all homoscedastic, and Table 2 presents the final covariables, their β-coefficients, p-values, and r^2.

The reference values of Cadence measured by G-Walk during the 10MWT and Cadence and Stride Length, given the covariable demonstrated in Table 2, were dichotomized according to the Brazilian official data of the average height of the Brazilian population as 164.37cm.[19]

Table 2. Covariables of GA analysis by G-Walk (n= 114)

		β-coefficient	95%CI		p-value	r^2
10MWT	**Cadence**					
	Height (h)	-0.244	-0.411	-0.077	0.005	0.070
6MWT	**Distance**					
	Sex (female)	-43.30	-71.25	-15.34	0.003	0.078
	Cadence					
	Height (h)	-0.37	-0.56	-0.17	<0.001	0.110
	Velocity					
	Age (h)	-0.004	-0.007	≅ 0.00	0.047	0.035
	Sex (female)	-0.151	-0.241	-0.060	0.001	0.09
	Stride length					
	Height (h)	0.008	0.005	0.011	<0.001	0.202

CI, confidence interval; 10MWT, 10-meter walk test; 6MWT, 6-meter walk test; (h), homoscedastic

The reference values of Cadence measured by G-Walk® during the 10MWT and Cadence and Stride Length, given the covariable demonstrated in Table 2, were dichotomized according to the Brazilian official data of the average height of the Brazilian population as 164.37cm.[19] Therefore, the reference values were established for those under and above 164.37cm. Regarding Distance measured during the 6MWT, two reference values were established, one for females and another for males. At last, Velocity measured during the 6MWT generated four reference values for sex (males or females) and age (below and above 45 years). Table 3 shows all reference values for all G-Walk® Gait Analysis variables collected during the 10MWT and 6MWT.

Table 3. Reference values for GA variables without known covariables (n= 114)

	Reference values
GA – 10MWT variables	
Cadence (height ≤ 164.37cm), steps/min	101 – 132
Cadence (height > 164.37cm), steps/min	99 – 137
Velocity, (m/s)	1.00 – 1.76
Stance duration symmetry, (%)	> 89.69
Swing duration symmetry, (%)	> 90.24
Double support duration symmetry, (%)	> 90.43
Single support duration symmetry, (%)	> 90.45
Stride length symmetry, (%)	> 96.62
Step length symmetry, (%)	> 90.16
GA – 6MWT variables	
Distance, female population, (m)	353 – 547
Distance, male population, (m)	359 – 626
Cadence (height ≤ 164.37cm), steps/min	98 – 135
Cadence (height > 164.37cm), steps/min	97 – 131
Velocity, females under 45 y.o, (m/s)	1.17 – 1.85
Velocity, females above 45 y.o, (m/s)	0.95 – 1.86
Velocity, male under 45 y.o, (m/s)	1.12 – 2.04
Velocity, male above 45 y.o, (m/s)	0.96 – 2.17
Stride length, height ≤ 164.37cm, (m)	1.23 – 1.83
Stride length, height > 164.37cm, (m)	1.32 – 1.91
Anterior-posterior symmetry, (%)	> 95.08

GA, gait analysis; 10MWT, 10-meter walk test; 6MWT, 6-meter walk test; y.o. years old

All analyses were conducted a second time without the participants with musculoskeletal diseases, as post-hoc. Even though these diseases were controlled, and the participants did not report pain or function limitation, their influence could not be discarded without a proper analysis. The post-hoc analysis showed that the results were not altered without the presence of such participants.

DISCUSSION

This study aimed to present reference values concerning the Brazilian population to contribute to using the gait analysis provided by the portable inertial sensor and to establish associations between gait parameters and demographic characteristics. The present study has described and examined the demographic characteristics, analysis, and differentiation in the performance of spatio-temporal variables using the inertial sensor G-walk® during the GA of 10MWT and 6MWT tests in healthy subjects of all ages.

Research using the Portable Inertial Sensor allows this technology to become an accurate, valid alternative to classic laboratory-based and clinical assessments.[4-6,20,21] The results of the confounding analysis between the demographic data and the readings of the inertial sensor (Tables 1 and 2) showed that weight, BMI, and gender within age groups are not enough to influence the results of the inertial sensor spatio-temporal gait parameters analysis, due to the wide variation within each age group as shown in a previous study by Schwesig et al.[4]. However, our study showed that the anthropometric variable of height influenced the cadence of the short and long distances (10MWT and 6MWT, respectively).

We also found that shorter individuals have a higher cadence when compared to those with higher statures due to the high number of steps taken per minute. This finding can be explained by the shorter stature that may lead to a smaller size of the lower limbs, demanding more steps to cover the same distance compared to taller individuals (above 1.64m). For the long-distance analysis (6MWT), the stride length presented a positive association with height and a negative association with cadence, i.e., taller subjects have wider stride length and shorter cadence.

In this context, the data generated by the G-Walk device demonstrated robust readings, once during the 6MWT, velocity was not influenced by height, given the opposed associations of cadence and stride length with height, which may have equalized the gait speed. Conversely, Bohannon[22] found that height and strength were associated with gait speed and other variables. His finding is valuable for shedding light on the need to control for covariables of gait analysis. However, comparing both samples may be jeopardized, given the different age groups and assessments reported in his publication. The gait analysis we proposed is significantly longer as our patients undertook 10-meter and 6-minute walk tests, whereas Bohannon assessed the subjects with 8^{ft} and 20^{ft} long gait tests (approximately 2.44m and 6.10m, respectively). Another significant difference is that our study population ranges from 20 to 69, and the data generated in our study was performed by algorithms built within an electronic device. In contrast, Bohannon included subjects above 50 years,[22] and their data collection was based on a hand-held stopwatch. These differences show that our publications had different objectives.

Regarding the general spatio-temporal gait variables, sex and age influenced the parameters collected, showing agreement with previous studies.[1,4,23] The average self-selected walking speed was differently presented between the 10MWT and 6MWT, showing that at a long distance, age and sex influence gait speed, agreeing with the specialized literature.[24,25] According to Kirtley et al.[26] a self-selected walking speed of less than 1m/s indicates a disability or pathology, agreeing with our results regardless of the length of the assessments. In our classifications of reference speed, however, the values found for the male population during the 6MWT were slightly above 1m/s, mildly different from the female sub-sample. Even though it seems to be a disparity, this issue is consonant with the literature that reports that speed reduction is usually associated with the female population.[22] Moreover, our results for speed were above 1.0m/s, not characterizing possible disabilities or pathologies in the population.

To date, few studies have reported parameters for the phases of the gait in percentages of the complete gait cycle correlating with age group and other demographic data.[5,27] Also, the establishment of reference values itself is usually associated with biochemical quantifications,[18,28] hospital-based data,[29,30] and animal studies.[28] The specialized literature discusses that critical aspects for establishing a reference value are the proper selection of the sample and the specific definition of “healthy subject” because of the possibility of misclassifying such variables.[28-30]

Our sample allowed individuals with minor pathologies as long as these diseases were controlled according to extensive medical screening once they did not report pain or functional limitations. Participants who underwent pharmacological treatments with psychoactive drugs or medication with possible iatrogenic effects over musculoskeletal diseases or with disabling pain were not included in our study to reduce bias and generate a sample of subjects as close to healthy as possible.

As discussed by other publications, reference values should be established with large sample sizes, usually above 120 subjects,[28] which was one limitation of our study. Nonetheless, several studies discuss the possibility of addressing this issue and the non-parametric distribution of data or covariable dependent reference values with alternative ways of studying and establishing reference values.[17,31-34] Such alternatives include bootstrapping strategies for analyzing reference values[33] and linear regression analysis for determining reference limits.[17,31] Another limitation is that, although the eligibility criteria did not restrict sample selection and the data collection included healthy subjects from a major urban area, there was small population variability as the study was single-center.

CONCLUSION

The results of this study established spatio-temporal reference values for gait analysis of a wearable inertial sensor G-Walk® in a group of healthy Brazilian subjects. The established reference values considered the covariable influences of age, height, and sex.

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