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Reproducibility of gait parameters at different surface inclinations and speeds using an instrumented treadmill system

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ABSTRACT

Instrumented treadmill systems allow the practical assessment of gait parameters under several walking conditions. Aim of this study was to evaluate the reproducibility of gait parameters at different surface inclinations and walking speeds using an instrumented treadmill system in healthy individuals. A total of 20 subjects (10 women) with a mean age of 31 years were evaluated with an instrumented treadmill system (FDM-T, Zebris Medical GmbH) during two identical test sessions. Spatial (step length, step width, foot rotation), temporal (cadence, single-limb support, step time) and ground reaction force (heel force, toe force, time to heel force, time to toe force) gait parameters were assessed at three treadmill inclinations (level, uphill, downhill) and five speeds (2, 3, 4, 5, 6 km/h). Between-day reproducibility was evaluated with smallest detectable changes for agreement and intraclass correlation coefficients for reliability. Low agreement and reliability were observed for (i) step length, cadence and step time during slow (2 and 3 km/h) and uphill walking and (ii) time to heel force and time to toe force under the majority of walking conditions. The instrumented treadmill system used in this study provided reproducible measurements for the majority of the evaluated spatial, temporal and ground reaction force gait parameters in healthy individuals. The assessment of time to heel/toe force should be however avoided, and particular care should be taken for some spatial (step length) and temporal (cadence and step time) parameters while walking uphill and/or at slow speeds.

1. Introduction

Quantitative gait analysis has been widely used for the evaluation of various gait parameters in studies with both discriminative purposes (to examine differences between subjects allocated to different groups) [1–4] and evaluative purposes (to monitor changes over time) [5–9]. In the clinical setting, gait analysis should (a) be practical for patients and experimenters, (b) provide reproducible gait parameters, and (c) reflect the functional conditions that patients experience during daily activities [10,11]. Gait characteristics are usually investigated during level walking at predetermined or self-selected “normal” speeds [12,13]. Nevertheless, some patients may not be able to complete standard walking trials because of pain [1] or, in contrast, they may not demonstrate gait impairments because of compensating strategies [3]. Therefore, gait parameters should also be assessed in less demanding (i.e., slow speeds) or more demanding conditions (i.e., uphill/downhill walking and/or fast speeds) [1]. It has indeed been demonstrated that lower limb muscle activation is greater during uphill and downhill walking compared to level walking, and is also greater at fast compared to normal walking speeds [11].

Besides overground walkway systems equipped with force sensors, pressure sensors or photoelectric cells, and video analysis systems, instrumented treadmills (i.e., treadmills with an integrated measuring sensor matrix consisting of capacitive force sensors) are increasingly used for quantitative gait analysis [12,13]. They allow practical and fast recording of spatial, temporal and ground reaction force gait parameters in clinical settings without the need of much space (e.g., long overground measuring systems) and time (e.g., video analysis systems). In addition, gait parameters can be easily and quickly evaluated at different treadmill inclinations and speeds. These instrumented treadmills have demonstrated acceptable reproducibility for the assessment of spatial, temporal and ground reaction force parameters during level walking at a self-selected speed in active healthy elderly [12]

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as well as in healthy young adults [13]. Nevertheless, the reproducibility of these instrumented treadmill systems for the assessment of gait variables at different inclinations and speeds has not been investigated so far. It is expected that spatial, temporal and ground reaction force gait parameters would vary significantly under different walking conditions, and this variability would affect their reproducibility.

Therefore, the primary aim of this study was to evaluate the between-day reproducibility of spatial, temporal and ground reaction force gait parameters obtained at different inclinations and speeds by means of an instrumented treadmill system in healthy subjects. A secondary aim was to examine the effect of instrumented treadmill inclination and speed on the different gait parameters.

2. Methods

2.1. Subjects

A total of 20 healthy subjects (10 women) were recruited from our institution and volunteered to participate in the study. They had no prior surgery to the lower limbs, and no symptoms or signs referable to overt cardiorespiratory, orthopedic, neurological or general diseases, which could have negatively affected walking function. Their age, weight, and height were 31 ± 6 years (mean $\pm$ SD), 69 ± 11 kg, and 174 ± 9 cm, respectively. All subjects were active and participated in a range of sports and recreational physical activities. This study was conducted according to the principles expressed in the declaration of Helsinki, and the protocol was approved by the local ethics committee. All the subjects signed a written informed consent before participating in the study.

2.2. Instrumentation

We used an instrumented treadmill (FDM-T system, Zebris Medical GmbH, Isny, Germany) with an integrated measuring sensor matrix consisting of capacitive force sensors. The base of the treadmill has a recording surface of 108×47 cm with 7,168 sensors, which record vertical ground reaction force (i.e., the force vector component perpendicular to the walking surface) at a sampling frequency of 120 Hz. The speed of the treadmill was manipulated from 2 to 6 km/h using 1 km/h intervals. The inclination of the treadmill was manipulated between -10% (downhill walking), 0% (level walking) and 10% (uphill walking) [11,14]. The backside of the treadmill was positioned on two metal sockets (height: 20 cm) for downhill and level walking, while it was on the ground for uphill walking. Spatial, temporal, and ground reaction force gait parameters were collected using a dedicated proprietary software (WinFDM-T, Zebris Medical GmbH, Isny, Germany) and analyzed using MATLAB 7.0 (The MathWorks Inc., Natick, MA, USA).

2.3. Experimental protocol

The experimental protocol consisted of two identical test sessions separated by 1–8 days. Subjects were first asked to walk 1 min at each of the five experimental speeds (2, 3, 4, 5, and 6 km/h) with no inclination for familiarization purposes. Testing consisted of several walking trials at three different inclinations (level, uphill and downhill) and five different speeds (2, 3, 4, 5, and 6 km/h). The testing order was first randomized for inclination, and then for walking speed within each inclination (unrestricted randomization, card shuffling). The two test sessions were separately randomized. For each inclination and speed, gait parameters were collected during 20 s following an additional familiarization period of 30 s. We evaluated three spatial, three temporal and four ground reaction force gait parameters, as provided by the proprietary software. Based on the information provided by the manufacturer, a rectangle including all force sensors activated by each single footprint is generated in the sensor matrix for data analysis. This rectangle is divided into three sections of equal area: the toe, midfoot and heel area. The threshold for sensor activation is 1 N/cm^2. Accordingly, the evaluated gait parameters are defined as follows:

- *step length*: the distance (in cm) parallel to walking direction between the posterior border of the heel area of one side and the following posterior border of the heel area of the contralateral side;
- *step width*: the distance (in cm) perpendicular to walking direction between the geometric center of mass of the heel area of one side and the following geometric center of mass of the heel area of the contralateral side;
- *foot rotation*: the angle (in°) between the line passing through the geometric center of mass of the heel area and the geometric center of mass of the toe area plus 4.58°, and the reference line corresponding to the walking direction;
- *cadence*: the number of steps per minute;
- *single-limb support (SLS)*: the time between when the toe area of the contralateral side is deactivated and the heel area of the same side is activated, as a percentage of the gait cycle;
- *step time*: the time (in s) between when the heel area of one side is activated and the heel area of the contralateral heel area is activated;
- *heel force (HF)/toe force (TF)*: the maximal vertical ground reaction force (in Newtons) measured in the heel/toe area;
- *time to heel force (THF)/time to toe force (TTF)*: the time between when the heel area is activated and the maximal vertical ground reaction force is reached in the heel/toe area, as a percentage of the gait cycle.

2.4. Statistical analysis

Gait parameters were averaged for test session and side. Normality of data distribution was assessed with Shapiro–Wilk tests. Changes in the mean between the two test sessions were analyzed with two-tailed paired t tests to assess the presence of systematic bias. The between-day reproducibility of gait parameters at the different inclinations and speeds was assessed as agreement and reliability. Agreement was evaluated using the smallest detectable change (SDC = $1.96 \times \sqrt{2} \times$ standard error of measurement (SEM), where SEM = standard deviation of the difference between test sessions/$\sqrt{2}$) [15]. Thresholds for acceptable SDC were a priori arbitrarily defined for each single gait parameter based on respective changes reported in patient populations following an intervention [16]: step length < 5.0 cm, step width < 2.5 cm, foot rotation $< 2.5°$, cadence < 8 steps/min, SLS $< 2\%$, step time < 0.06 s, HF and TF < 100 N, THF and TTF $< 2\%$ [5–9,17–19]. Reliability was evaluated using intraclass correlation coefficient $(ICC)_{2,1}$. An $ICC_{2,1} > 0.70$ with the lower limit of the confidence interval (CI) > 0.60 was considered acceptable [20]. The effect of inclination (level, uphill, downhill) and speed (2, 3, 4, 5, 6 km/h) on the different gait parameters was evaluated using 2-way repeated measures ANOVA. Tukey's HSD tests were used for post hoc pairwise comparisons of the means. The level of significance was set at $p < 0.05$. Since between-day reproducibility was tested for 10 different gait parameters at each walking condition, a Bonferroni correction was consistently applied for the evaluation of systematic bias ($p < 0.005$). Statistical analyses were performed with Statistica 7.0 (StatSoft Inc., Tulsa, OK, USA) and PASW Statistics 18.0 (SPSS Inc., Chicago, IL, USA).