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Repeatability of spatiotemporal, plantar pressure and force parameters during treadmill walking and running

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ABSTRACT

Background: Instrumented treadmills with integrated pressure mats measure spatiotemporal, pressure and force parameters and are often used to investigate changes in gait patterns due to injury or rehabilitation.
Research question: What is the within- and between-day repeatability of such an instrumented treadmill for spatiotemporal parameters, peak pressures and forces during walking and running?
Methods: Treadmill gait and running analysis were performed at 5.0, 6.5, and 9.0 km/h in 33 healthy adults (age: 31.6 ± 7.4 years; body mass index: 23.8 ± 3.2 kg/m^2) once on day 1 and twice on day 7. For all three speeds, intraclass correlation coefficents (ICC) and smallest detectable differences (SDC) corresponding to 95% limits of agreement were calculated for spatiotemporal parameters and peak pressures and forces in the heel, midfoot, and forefoot regions.
Results: All spatiotemporal parameters and peak forces in the heel, midfoot, and forefoot regions showed a good within- and between-day repeatability (ICCs > 0.878) for all gait speeds with within-day repeatability being generally higher. For peak pressures, only the heel and forefoot regions but not the midfoot region, showed good repeatability (ICC > 0.9) at all gait speeds. SDCs ranged from 1.5 to 2.5° for foot rotation, 4.4 to 6.6 cm for stride length, 0.7 to 2.5% for length of stance phases, and 2.8 to 9.2 N/cm^2 for peak pressures in all foot regions. For walking, SDCs of peak forces in the heel, midfoot and forefoot regions were below 60 N, and for running below 135 N.
Significance: Except for peak pressures in the midfoot, spatiotemporal and kinetic gait parameters during walking and running showed a good within- and between-day repeatability. Hence, the investigated treadmill is suitable to analyze gait patterns and changes in gait patterns due to interventions.

1. Introduction

Instrumented treadmills with built-in force plate or plantar pressure plate are often used in clinical and research settings to investigate changes in gait or running patterns due to injury or during rehabilitation. Treadmills with integrated plantar pressure plates allow measuring spatiotemporal parameters (e.g. step length, step width and step time), and pressure and force related parameters (e.g. center of pressure path, peak forces and peak pressures in different regions of the foot). These systems have been used to quantify gait impairments in several diseases including multiple sclerosis [1–3], Parkinson's disease [4,5] or after Achilles tendon rupture [6]. The advantage of instrumented treadmills is that pressure and force data at the interface with the ground is measured allowing to draw conclusions, for instance, about the trajectory of the center of pressure [3] and information on step width and foot rotation angle [7], which is not possible with pressure insoles. Moreover, compared to in-floor pressure plates, data for many consecutive steps can be collected continuously allowing to assess step-to-step variability and potential fatigue effects during prolonged walking.

Previous studies reported good within- and between-day repeatability of spatiotemporal parameters measured with instrumented

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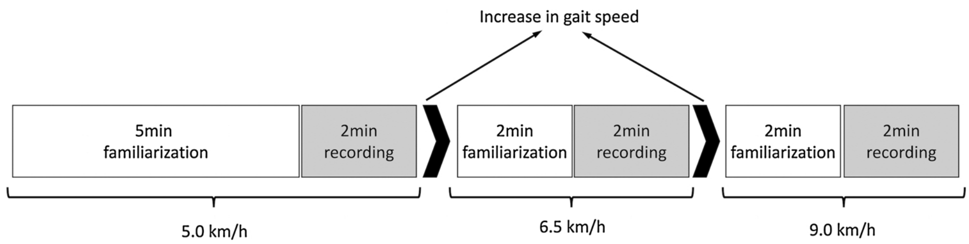

Fig. 1. Overview of a measurement session with familiarization and recording periods at each gait speed.

treadmills in healthy elderly people [8]. However, walking speed has been shown to influence the repeatability of gait parameters during treadmill walking. One study reported significant differences in spatiotemporal parameters and peak vertical ground reaction forces between test-retest measurements in healthy young people when treadmill walking speed was self-selected, and thus different, in each session [9]. Another study on young healthy participants showed that walking speed (between 2.0 and 5.0 km/h) influenced the test-retest repeatability of spatiotemporal and force parameters with lower agreement for slow walking speeds [10]. These results imply the importance of assessing the reliability of gait parameters during treadmill walking at different constant gait speeds, but also at more than one gait speed.

Contrary to spatiotemporal and vertical ground reaction force parameters during treadmill walking, little is known about the repeatability of plantar pressure parameters such as peak pressures in different foot regions during treadmill walking or running. For overground walking, peak pressure parameters showed a good repeatability (coefficient of repeatability $< 10\%$) but were also found to be dependent of the investigated foot region [11,12]. To our knowledge, it is not known whether the repeatability of peak pressure parameters measured during barefoot treadmill walking is comparable to overground walking. For treadmill running, plantar pressure distribution is often measured with pressure insoles which allows the participants to wear their own shoes. Compared to overground walking, reported ICCs were generally higher for treadmill running at 2.24 m/s and at 3.13 m/s (ICCs > 0.88) [13]. While these results indicate a good test-retest repeatability for insole peak pressure parameters that depends on walking and/or running speed and measurement methods, comparable data for pressure mats is lacking. The aim of our study was to quantify the test-retest repeatability (within-day and between-day) of spatiotemporal and pressure parameters at different gait speeds measured on an instrumented treadmill system (Zebris FDM-THM-S).

2. Methods

2.1. Participants

Thirty-three healthy adults (17 female, 16 male; age: 31.6 (standard deviation (SD): 7.4) years; height: 1.72 (SD: 0.07) m, body mass: 71.0 (SD: 12.0) kg; body mass index 23.8 (SD: 3.2) kg/m^2) participated in this study. Exclusion criteria were injuries or surgeries on the lower extremity in the 6 months prior to testing, pregnancy, and neurological disorders affecting gait. The study was approved by the regional ethics committee and conducted in accordance with the Declaration of Helsinki. All participants signed informed consent before participation.

2.2. Procedures

The study was performed using an instrumented treadmill system (h/p/cosmos mercury, h/p/cosmos sports & medical GmbH, Nussdorf, Germany) with an integrated capacitive pressure platform (Zebris FDM-THM-S, Zebris Medical GmbH, Isny, Germany; size, 150 × 50 cm; number of sensors, 7168; sampling frequency, 120 Hz). All participants were tested three times, once on the first day and twice 7 days later with a 30-min rest period between measurements. For each of the three measurements the same protocol was used: i) after an initial warm-up and familiarization period of 5 min a 2-min measurement of walking at 5.0 km/h was recorded, ii) after a 2-min familiarization period with increased walking speed, a 2-min measurement for walking at 6.5 km/h was recorded, and iii) after increasing the treadmill speed to 9.0 km/h and a 2-min familiarization period, a 2-min measurement for running at 9.0 km/h was recorded (Fig. 1). These speeds correspond to normal to fast walking for 5.0 km/h [14], to very fast walking for 6.5 km/h (transition speed to running) [15], and running for 9.0 km/h [16]. The pressure platform was calibrated (set to zero) before the familiarization period at each speed.

2.3. Data processing and statistical analysis

The following spatiotemporal parameters calculated by the Zebris software were analyzed for repeatability: cadence, foot rotation (angle between the longitudinal axis of the foot and the walking/running direction), step width, step length and step time, stride length and stride time, percentage of duration of stance phase, swing phase and double stance phase. The software divides the foot into three regions of equal length (heel, midfoot, and forefoot) and calculates peak pressure and peak force in these regions. The repeatability of the peak force and peak pressure in these regions was analyzed. All statistical analyses were performed using Matlab (Mathworks Inc., Natick MA, USA) and SPSS (Version 22, IBM Corporation, Armonk, NY).

For each 2-min recording, the mean and standard deviation of the selected parameters for both the left and right side were exported from the Zebris software. Overall, data for around 120 steps each for walking at 5.0 km/h, 135 steps at 6.5 km/h and 165 steps at 9.0 km/h were used for further analysis. To reduce the amount of data and complexity of the statistical analysis, only data from the right side were further analyzed. Differences in parameters within days (sessions 2 and 3) and between days (sessions 1 and 2) were analyzed separately using paired *t*-tests. The significance level was adjusted to multiple comparisons (three speeds, two comparisons) and set a priori to 0.01. ICCs with a two-way random model for consistency and 95% confidence intervals of the difference between two measurements were calculated to assess the within-day and between-day repeatability. Additionally, smallest detectable changes (SDC) corresponding to 95% limits of agreement were calculated as 1.96 * standard deviation of the difference between measurements [17]. For the between-day comparison of peak forces and peak pressures, systematic bias (mean difference between measurements) and 95% limits of agreement were calculated and depicted as Bland-Altman plots.

3. Results

3.1. Within-day repeatability

For walking, peak pressure decreased significantly in the forefoot (6.5 km/h, $P < 0.001$) and in the heel regions (5.0 km/h, $P < 0.001$; 6.5 km/h, $P = 0.001$) from session 2 to session 3 (Table 1) and 95% CI of the difference between these two sessions were below 2.0 N/cm^2 (Table 2). All other spatiotemporal, peak pressure and peak force parameters showed no significant differences for within-day