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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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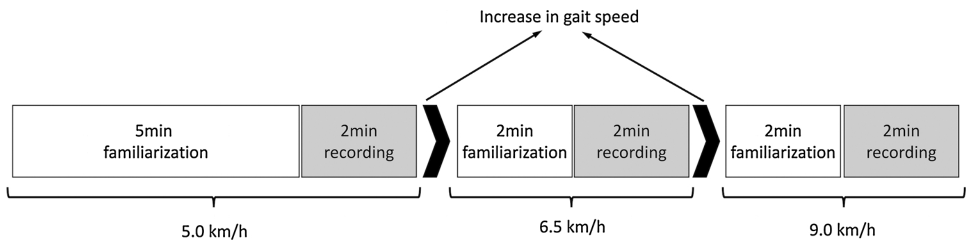

Fig. 1. Overview of a measurement session with familiarization and recording periods at each gait speed.

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

Table 1
Mean (1 standard deviation) spatiotemporal and force and pressure parameters of within-day sessions (session 2 and 3) and between-day sessions (session 1 and 2) for three different speeds (5 km/h, 6.5 km/h, and 9.0 km/h).

	Within-day					
	5.0 km/h		6.5 km/h		9.0 km/h	
	Session 2	Session 3	Session 2	Session 3	Session 2	Session 3
Foot rotation (°)	8.2 (3.6)	8.2 (4.0)	7.7 (3.2)	7.6 (3.4)	7.5 (4.2)	7.9 (4.5)
Step width (cm)	9.4 (2.4)	9.1 (2.5)	9.1 (2.3)	9.0 (2.3)	6.3 (2.5)	6.0 (2.6)
Step length (cm)	70.5 (3.3)	70.6 (3.4)	81.8 (3.6)	81.9 (3.6)	92.1 (5.1)	92.2 (5.3)
Stride length (cm)	140.5 (6.6)	140.6 (6.4)	162.7 (7.5)	162.8 (7.3)	183.8 (9.8)	183.7 (9.9)
Step time (s)	0.501 (0.024)	0.501 (0.024)	0.445 (0.020)	0.445 (0.020)	0.362 (0.019)	0.362 (0.019)
Stride time (s)	1.003 (0.047)	1.004 (0.047)	0.891 (0.041)	0.892 (0.040)	0.725 (0.039)	0.724 (0.039)
Stance phase (%)	61.7 (0.9)	61.7 (0.9)	59.8 (0.8)	59.8 (0.7)	41.1 (3.6)	40.9 (3.3)
Swing phase (%)	38.3 (0.9)	38.3 (0.9)	40.2 (0.8)	40.2 (0.7)	58.9 (3.6)	59.1 (3.3)
Double support phase (%)	23.4 (1.6)	23.4 (1.7)	19.4 (1.5)	19.5 (1.4)	–	–
Cadence (steps/min)	119.9 (5.6)	119.8 (5.5)	135.0 (6.2)	134.9 (6.1)	166.0 (8.9)	166.2 (9.0)
Peak force forefoot (N)	592.4 (87.0)	590.7 (88.0)	574.8 (87.7)	576.2 (89.5)	786.2 (113.0)	800.6 (115.3)
Peak force midfoot (N)	141.5 (50.8)	139.9 (55.0)	143.4 (56.9)	146.2 (60.1)	229.6 (97.4)	234.0 (96.1)
Peak force heel (N)	408.8 (75.9)	406.0 (72.0)	497.3 (79.7)	495.6 (83.3)	378.5 (184.9)	377.6 (187.0)
Peak pressure forefoot (N/cm^2)	35.3 (6.9)	34.3 (6.8)	35.5 (6.1)	**34.4 (6.0)**[b]	34.9 (5.4)	34.7 (5.4)
Peak pressure midfoot (N/cm^2)	14.7 (3.8)	14.2 (3.3)	15.6 (4.2)	15.4 (4.1)	15.1 (4.5)	15.2 (4.0)
Peak pressure heel (N/cm^2)	29.6 (5.1)	**28.7 (4.8)**[b]	38.0 (6.1)	**37.0 (5.5)**[a]	23.5 (10.7)	22.9 (10.2)

	Between-day					
	5.0 km/h		6.5 km/h		9.0 km/h	
	Session 1	Session 2	Session 1	Session 2	Session 1	Session 2
Foot rotation (°)	8.1 (3.7)	8.2 (3.6)	7.8 (3.3)	7.7 (3.2)	7.4 (4.0)	7.5 (4.2)
Step width (cm)	9.4 (2.4)	9.4 (2.4)	9.1 (2.1)	9.1 (2.3)	6.3 (2.5)	6.3 (2.5)
Step length (cm)	70.3 (3.2)	70.5 (3.3)	81.8 (3.6)	81.8 (3.6)	92.3 (5.0)	92.1 (5.1)
Stride length (cm)	140.3 (6.3)	140.5 (6.6)	162.8 (7.3)	162.7 (7.5)	184.3 (9.7)	183.8 (9.8)
Step time (s)	0.500 (0.023)	0.501 (0.024)	0.445 (0.020)	0.445 (0.020)	0.363 (0.019)	0.362 (0.019)
Stride time (s)	1.003 (0.045)	1.003 (0.047)	0.892 (0.041)	0.891 (0.041)	0.727 (0.038)	0.725 (0.039)
Stance phase (%)	61.7 (0.9)	61.7 (0.9)	59.8 (0.8)	59.8 (0.8)	41.1 (3.8)	41.1 (3.6)
Swing phase (%)	38.3 (0.9)	38.3 (0.9)	40.2 (0.8)	40.2 (0.8)	58.9 (3.8)	58.9 (3.6)
Double support phase (%)	23.4 (1.7)	23.4 (1.6)	19.5 (1.5)	19.4 (1.5)	–	–
Cadence (steps/min)	119.9 (5.2)	119.9 (5.6)	134.9 (6.0)	135.0 (6.2)	165.6 (8.7)	166.0 (8.9)
Peak force forefoot (N)	588.5 (87.3)	592.4 (87.0)	574.1 (89.4)	574.8 (87.7)	797.7 (105.8)	786.2 (113.0)
Peak force midfoot (N)	140.9 (55.4)	141.5 (50.8)	145.8 (65.0)	143.4 (56.9)	224.7 (103.4)	229.6 (97.4)
Peak force heel (N)	412.0 (76.6)	408.8 (75.9)	505.1 (86.1)	497.3 (79.7)	377.2 (187.1)	378.5 (184.9)
Peak pressure forefoot (N/cm^2)	36.0 (7.1)	35.3 (6.9)	35.7 (6.3)	35.5 (6.1)	35.3 (5.5)	34.9 (5.4)
Peak pressure midfoot (N/cm^2)	14.2 (3.7)	14.7 (3.8)	15.7 (4.0)	15.6 (4.2)	14.9 (3.7)	15.1 (4.5)
Peak pressure heel (N/cm^2)	30.2 (5.1)	29.6 (5.1)	38.9 (6.3)	38.0 (6.1)	23.7 (11.1)	23.5 (10.7)

[a] P value paired t-test < 0.01.
[b] P value paired t-test < 0.001.

measurements (Table 1).

Except of peak pressure in the midfoot during walking at 5.0 and 6.5 km/h, all parameters had good within-day repeatability with ICCs > 0.9 (Table 2). SDCs of the spatiotemporal parameters were approximately 2° for foot rotation, between 1.4 and 5.1 cm for step width, step length and stride length, between 10 and 26 ms for step and stride time, and below 2% for stance and swing phase. For peak pressures, SDCs were below 10 N/cm^2 and for peak forces below 60 N with the largest values (> 20% of mean) occurring in the midfoot for all gait speeds (Table 2).

3.2. Between-day repeatability

There were no statistically significant differences in all spatiotemporal, peak force, and peak pressure parameters for between-day comparisons (Table 1). The 95% CI of the differences in peak pressures between two sessions were below 2.0 N/cm^2 for walking at 5.0 km/h, below 2.5 N/cm^2 for walking at 6.5 km/h, and below 3.3 N/cm^2 for running at 9.0 km/h (Table 2).

For spatiotemporal parameters, ICCs were greater than 0.890 at all gait speeds where the highest value of 0.979 was observed for foot rotation at 5.0 km/h and the lowest value of 0.890 for stance and swing phase at 6.5 km/h. The corresponding SDCs were generally higher during running than during walking with values below 2.5° for foot rotation, between 2 and 4 cm for step length and between 0.5 and 2.5% for gait phases (Table 2). ICCs for peak forces ranged from 0.878 (midfoot at 6.5 km/h) to 0.970 (forefoot at 5.0 km/h). Limits of agreement of peak forces were greater for running at 9.0 km/h than for walking at 5.0 and 6.5 km/h with one participant exhibiting a difference in heel force of around 300 N at 9.0 km/h (Fig. 2) and SDCs ranged from 38 to 134 N (Table 2). For peak pressures, limits of agreements for the three foot-regions were similar for all gait speeds (Fig. 3). The foot print of the two measurements of the participant with the large difference in heel force revealed a change in foot strike pattern from midfoot to rearfoot runner (Fig. 4).

4. Discussion

The aim of this study was to quantify the within-day and between-day repeatability of spatiotemporal parameters and peak forces and pressures in three foot regions measured with an instrumented treadmill at three different gait speeds. For all gait speeds, we found good within- and between-day repeatability for the spatiotemporal parameters with high ICCs (> 0.89) and no statistically significant differences between measurements. Differences in peak pressure and peak forces in the heel, midfoot and forefoot regions between measurements were greater than differences in spatiotemporal parameters as indicated by lower ICCs especially for peak pressure in the midfoot (between 0.69 and 0.93) for both within- and between-day repeatability.

4.1. Within-day repeatability

The within-day repeatability of the spatiotemporal parameters (ICCs > 0.9) observed in our study was comparable to that reported for level walking at around 5.0 km/h in healthy elderly adults [8]. In contrast to our results, Reed et al. [9] observed significant differences in most of the spatiotemporal parameters. These discrepancies can be explained by a significantly higher walking speed in the third session compared to the first (one week earlier) and second session (same day) in their study [9], as it is for example known that stride length increases and double support phase decreases with increasing walking speed [10,18].

To the best of our knowledge, the results presented here represent the first data on within-day repeatability of peak forces and peak pressures in the heel, midfoot and forefoot regions during treadmill walking. Except of peak pressure in the midfoot for walking at 5.0 km/h

Table 2
Within-day and between-day repeatability of spatiotemporal and force and pressure measurements assessed at three different seeds (5.0 km/h, 6.5 km/h, and 9.0 km/h). Within-day repeatability was assessed in two sessions with a 30-min break. Between-day repeatability was assessed in two sessions 1 week apart.

	Within-day									Between-day								
	5.0 km/h			6.5 km/h			9.0 km/h			5.0 km/h			6.5 km/h			9.0 km/h		
	95% CI Difference	SDC	ICC	95% CI Difference	SDC	ICC	95% CI Difference	SDC	ICC	95% CI Difference	SDC	ICC	95% CI Difference	SDC	ICC	95% CI Difference	SDC	ICC
Foot rotation (°)	[−0.3 0.4]	2.1	0.959	[−0.2 0.2]	1.0	0.988	[0.1 0.7]	1.7	0.980	[−0.2 0.3]	1.5	0.979	[−0.4 0.2]	1.7	0.966	[−0.4 0.5]	2.4	0.954
Step width (cm)	[−0.6 0.1]	2.0	0.909	[−0.3 0.2]	1.4	0.952	[−0.5 −0.0]	1.4	0.962	[−0.4 0.3]	1.7	0.934	[−0.3 0.2]	1.6	0.933	[−0.3 0.3]	1.6	0.950
Step length (cm)	[−0.1 0.4]	1.5	0.974	[−0.4 0.6]	2.5	0.936	[−0.4 0.6]	2.8	0.963	[−0.2 0.6]	2.2	0.939	[−0.4 0.5]	2.4	0.944	[−0.9 0.4]	3.6	0.935
Stride length (cm)	[−0.4 0.7]	3.1	0.970	[−0.7 0.9]	4.6	0.950	[−1.1 0.8]	5.1	0.964	[−0.5 1.0]	4.2	0.946	[−0.9 0.7]	4.4	0.954	[−1.7 0.7]	6.6	0.940
Step time (s)	[−0.002 0.003]	0.011	0.970	[−0.002 0.003]	0.012	0.953	[−0.002 0.002]	0.012	0.952	[−0.002 0.003]	0.016	0.938	[−0.002 0.002]	0.011	0.961	[−0.003 0.002]	0.013	0.934
Stride time (s)	[−0.003 0.005]	0.022	0.972	[−0.004 0.006]	0.026	0.947	[−0.004 0.003]	0.021	0.963	[−0.005 0.006]	0.030	0.946	[−0.005 0.003]	0.024	0.955	[−0.007 0.003]	0.026	0.939
Stance phase (%)	[−0.1 0.2]	0.7	0.924	[−0.1 0.1]	0.5	0.930	[−0.5 0.1]	1.8	0.966	[−0.1 0.1]	0.6	0.940	[−0.2 0.1]	0.7	0.890	[−0.4 0.5]	2.5	0.941
Swing phase (%)	[−0.2 0.1]	0.7	0.924	[−0.1 0.1]	0.5	0.930	[−0.1 0.5]	1.8	0.966	[−0.1 0.1]	0.6	0.940	[−0.1 0.2]	0.7	0.890	[−0.5 0.4]	2.5	0.941
Double support phase (%)	[−0.2 0.2]	1.1	0.943	[−0.1 0.3]	1.1	0.926	–	–	–	[−0.3 0.1]	1.0	0.951	[−0.3 0.2]	1.4	0.896	–	–	–
Cadence (steps/min)	[−0.6 0.3]	2.6	0.971	[−0.9 0.6]	4.0	0.945	[−0.7 1.0]	4.5	0.966	[−0.7 0.6]	3.7	0.938	[−0.5 0.8]	3.6	0.954	[−0.6 1.5]	5.9	0.942
Peak force forefoot (N)	[−8.0 4.7]	35.0	0.979	[−6.1 9.0]	41.8	0.971	[−2.1 30.8]	91.0	0.917	[−3.6 11.5]	41.7	0.970	[−7.3 8.7]	44.1	0.968	[−29.4 6.5]	99.4	0.893
Peak force midfoot (N)	[−8.4 5.1]	37.3	0.935	[−4.7 10.2]	41.0	0.936	[−4.7 13.4]	49.9	0.965	[−6.3 7.6]	38.4	0.932	[−13.1 8.3]	59.1	0.878	[−10.0 19.8]	82.2	0.913
Peak force heel (N)	[−7.7 2.1]	27.3	0.982	[−8.2 4.7]	35.6	0.975	[−11.4 9.5]	57.8	0.987	[−10.5 4.1]	40.6	0.963	[−17.4 1.8]	52.9	0.947	[−23.0 25.5]	134.1	0.932
Peak pressure forefoot (N/cm^2)	[−1.8 −0.2]	4.2	0.950	[−1.5 −0.6]	2.5	0.977	[−0.8 0.3]	3.1	0.958	[−1.2 −0.1]	3.1	0.974	[−0.9 0.4]	3.4	0.961	[−0.9 0.2]	3.0	0.961
Peak pressure midfoot (N/cm^2)	[−1.3 0.3]	4.6	0.783	[−1.1 0.7]	4.9	0.819	[−0.5 0.6]	3.2	0.926	[−0.5 1.5]	5.3	0.733	[−1.2 1.1]	6.3	0.693	[−0.8 1.3]	5.8	0.746
Peak pressure heel (N/cm^2)	[−1.3 −0.5]	2.1	0.977	[−1.6 −0.5]	3.1	0.962	[−1.3 0.1]	4.0	0.981	[−1.1 −0.1]	2.8	0.962	[−1.5 −0.2]	3.6	0.956	[−1.9 1.4]	9.2	0.907

CI—confidence interval; SDC—smallest detectable change; ICC—intraclass correlation coefficient.

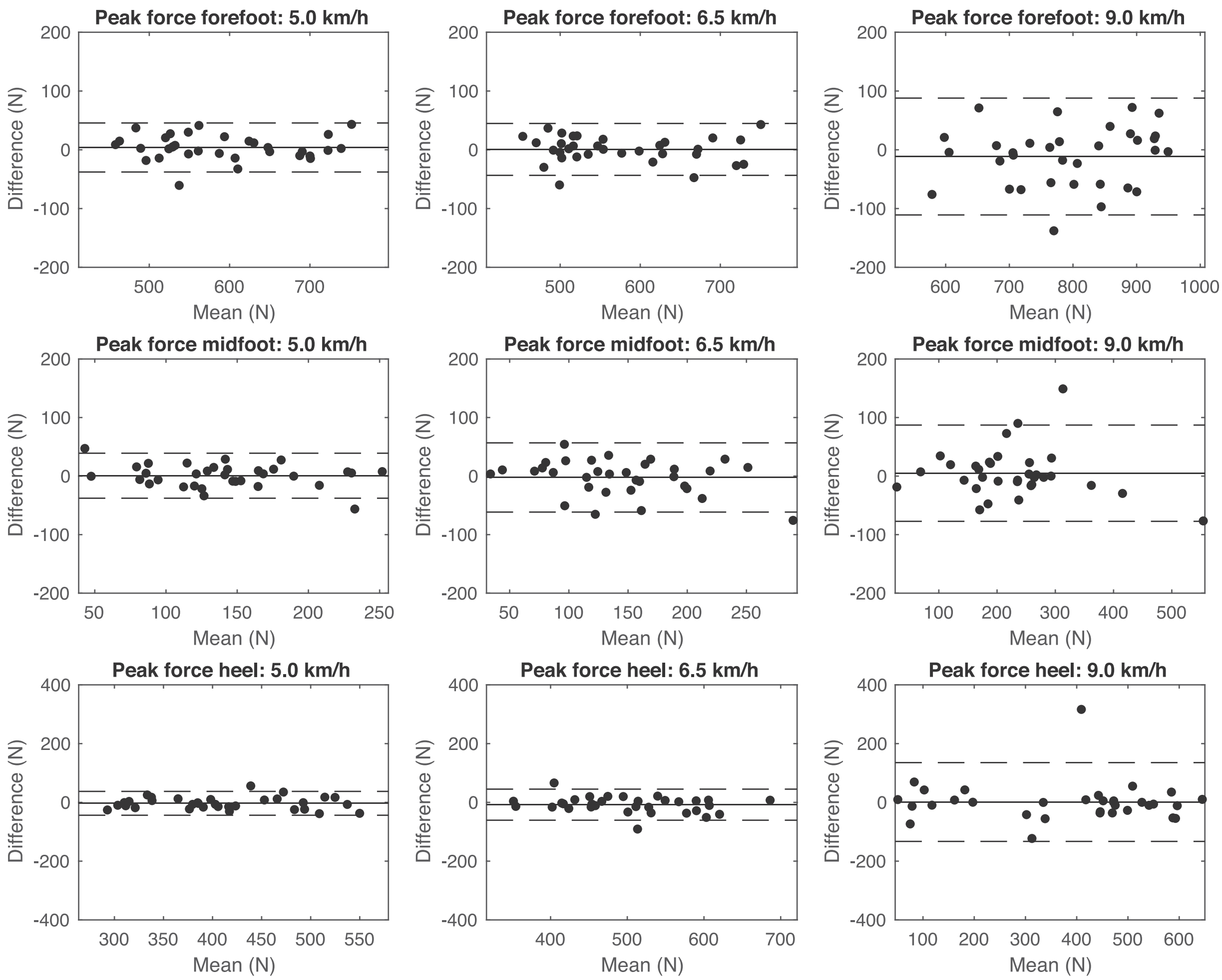

Fig. 2. Bland-Altmann plots for the peak forces in the forefoot (top row), midfoot (middle row), heel (bottom row) at the three different speeds for the comparison of between-day measurements. Each graph presents the mean difference (solid line) and 1.96-fold standard deviation of the difference (dashed lines) between the measurements of different days.

and 6.5 km/h, the within-day repeatability of peak forces and pressures was comparable to that of spatiotemporal parameters. The small differences between mean values, high ICCs and small SDCs indicated good repeatability suggesting that these data are reliable.

4.2. Between-day repeatability

Generally, between-day repeatability was lower than within-day repeatability as shown by lower ICCs confirming reported results by Faude et al. [8]. As in our study, previous results on spatiotemporal parameters showed a good between-day repeatability with high ICCs ($>$ 0.87) for level walking at a speed of around 5.0 km/h in both young and elderly healthy adults [8,10]. Item-Glatthorn et al. [10] defined thresholds for acceptable SDCs in their study (i.e. 5 cm for step length, or 100 N for peak forces). The SDCs for all spatiotemporal parameters at all three gait speeds in our study were below these thresholds indicating acceptable repeatability for both within- and between-day measurements. Mann et al. [19] reported an SDC of 24.5 ms for stride time in running using capacitive insoles which is comparable to the 26 ms of the instrumented treadmill in our study. The SDCs for spatiotemporal parameters during walking in our study were smaller than those in healthy elderly [8], which may be related to less variable gait in young healthy people [20,21].

Peak forces during walking showed good repeatability indicated by high ICCs ($>$ 0.87), SDCs below 60 N without significant differences between measurements. These results are comparable to the results for the heel and forefoot regions reported by Item-Glatthorn et al. [10]. The between-day repeatability of peak forces during running was lower than the within-day repeatability especially for the heel region. Fig. 2 shows an outlier with a difference in heel force of around 300 N. Visual inspection of the foot print of the two measurements of this individual revealed a change in foot strike pattern from midfoot to rearfoot runner (Fig. 4) possibly explaining why peak forces in the heel region were much higher in the second measurement a week later. For peak pressures, previous studies investigated the plantar pressure distribution during overground walking where the foot was divided into more detailed regions (heel, midfoot, individual metatarsal heads, toes) [11,12,22]. Therefore, a direct comparison of our results to the literature is not possible. Nevertheless, Putti et al. [11] and Maetzler et al. [22] showed for instance that the coefficient of repeatability which corresponds to the SDCs relative to the mean was below 15% of the mean for all peak pressures in the analyzed foot regions. In comparison, we observed higher SDCs relative to the mean value for the midfoot region (30–40%). It is possible that the variability of midfoot peak pressure is higher for walking on the instrumented treadmill because the midfoot is less loaded than the heel and forefoot region [12]. However, together with the lower ICCs, our results suggest that the repeatability of peak pressures in the midfoot region is limited and that differences between measurements (i.e. during rehabilitation) have to be interpreted with caution especially if differences are small.

4.3. Limitations

All measurements were performed for barefoot walking or running

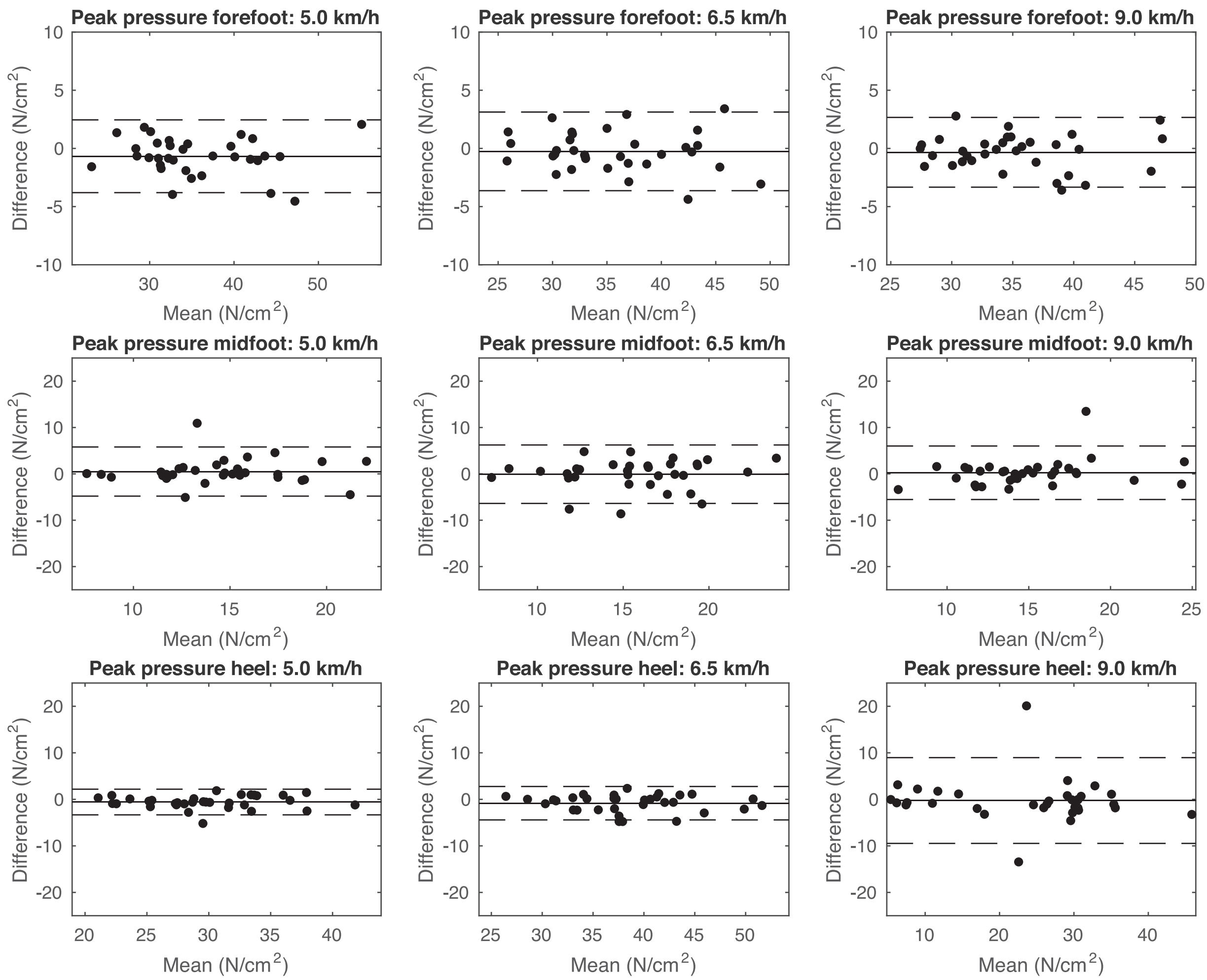

Fig. 3. Bland-Altmann plots for the peak pressure in the forefoot (top row), midfoot (middle row), heel (bottom row) at the three different speeds for the comparison of between-day measurements. Each graph presents the mean difference (solid line) and 1.96-fold standard deviation of the difference (dashed lines) between the measurements of different days.

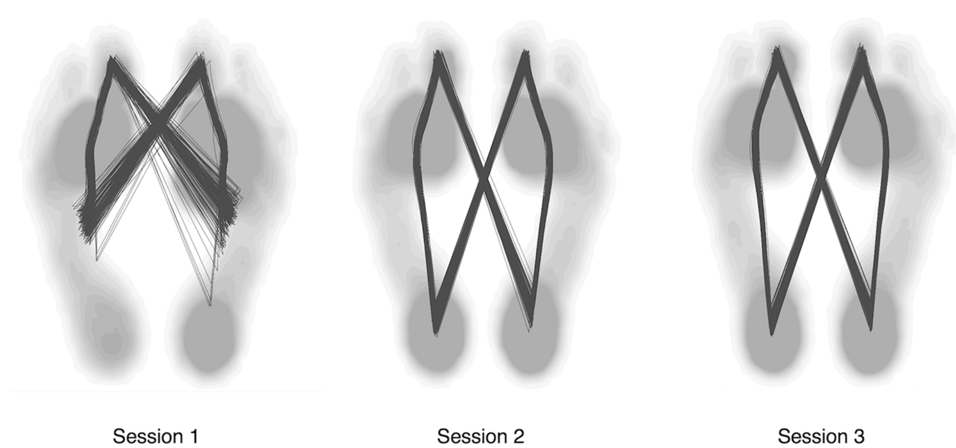

Fig. 4. Center of pressure path and footprint of one subject during the three measurements for running at 9.0 km/h. Session 1 was on day 1, while session 2 and session 3 were on day 2.

because this allows measuring the plantar pressure distribution. Especially for running, being barefoot may be unfamiliar for some participants and hence increase the variability. However, measuring barefoot treadmill walking is often necessary to analyze detailed foot kinematics with optoelectronic systems. Moreover, there is a natural variability in a person's gait patterns that will influence the test-retest repeatability, but this variability is also present when assessing a person's gait before and after an intervention (i.e. training, orthotics, surgery). Hence, the results of this study represent the within- and between-day repeatability of the instrumented treadmill combined with the participants' gait variability. The participants in our study were healthy young adults. Therefore, our results on ICCs and SDCs apply to this population, and it remains unknown whether the same repeatability of spatiotemporal parameters and peak forces/pressures can be expected in other populations such as elderly people or orthopaedic patients.

In gait and running studies, assessing joint loads is often of interest. The investigated instrumented treadmill comprises an integrated capacitive pressure mat and thus, as in overground measurements with pressure plates, it is only possible to calculate vertical ground reaction forces. Therefore, to estimate three-dimensional joint loads (i.e. mediolateral knee joint moments), it would require an instrumented treadmill with a force plate for treadmill running or a three-dimensional force plate for overground walking and running.

4.4. Conclusion

In conclusion, our study showed a good within- and between-day repeatability of both spatiotemporal parameters and peak forces during barefoot treadmill walking. Peak pressures in the midfoot region were less repeatable and differences between measurements have to be interpreted with caution. For running, spatiotemporal parameters showed a good repeatability, while peak forces and pressures, except of peak pressure in the midfoot showed acceptable repeatability. However, it is important to note that the foot strike pattern (i.e. rearfoot runner or forefoot runner) can influence the results and that this has to be consistent between measurements to obtain meaningful data. Nevertheless, measuring spatiotemporal parameters, peak forces, and peak pressures with an instrumented treadmill during barefoot walking and running is reliable and is suitable to analyze gait patterns and changes in gait patterns due to interventions.

Conflict of interest

There is no conflict of interest.

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