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Original Article

Gait analysis using a force-measuring gangway: Intrasession repeatability in healthy adults

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Abstract

Objectives: The goal of the present study was to determine the repeatability of gait parameters measured by a force plate gait analysis system (Leonardo Mechanograph® GW). **Methods:** Fifteen healthy adult participants walked at a self-selected speed on a 10 m long walkway. Vertical ground reaction forces were measured in the central 6 m of the walkway. Each participant performed three trials while walking barefoot and three trials while wearing shoes, each trial consisting of three 10 m walks. **Results:** There were minimal differences between trials at each condition. All primary force, time, distance and velocity parameters had intraclass correlation coefficients above 0.90 and coefficients of variation in the order of 2% to 4%. Compared to walking barefoot, walking in shoes resulted in 14% lower maximal vertical ground reaction force, 5% longer step length and 2% higher average velocity and caused less lateral translation of the center of force. **Conclusions:** In this group of healthy adults, gait analysis with a force plate system produced repeatable intra-day results. The observation that barefoot and shod walking yield different results indicates that it is important to standardize test conditions.

Keywords: Ground Reaction Force, Mobility, Muscle Function, Velocity

Introduction

Assessment of gait is performed in many clinical settings to make diagnoses, recommend interventions, and monitor the effect of interventions. In most circumstances, the clinician's methodological armamentarium is limited to visual observation of a patient's gait. However, observational gait analysis has questionable validity and reliability[1]. Quantitative gait analyses with complex motion capture systems and floor-mounted force platforms are widely used in research settings but are expensive and time consuming and therefore are often not feasible in a clinical context.

The clinical need for simpler gait analysis instruments has driven the development of a number of new analytical tools, such as mats with pressure sensors[2] or accelerometer-based devices[3]. However, most of these systems measure only temporal and spatial gait parameters and provide little or no information on the kinetic aspects of gait. Force-measuring treadmills do not have this disadvantage but require some training before they can be used comfortably, and may not exactly mimic regular walking[4].

In the present study we assessed a gait analysis device that determines both temporo-spatial parameters and the forces that are produced by walking. The system consists of a series of force plate modules and derives gait parameters from the measurement of the vertical component of ground reaction forces. As a first step to evaluate the validity of this system, we analyzed the intra-session repeatability of the measurements in a group of healthy adults.

Subjects and Methods

Study population

Fifteen healthy adult participants (9 men, 6 women) aged between 21 and 45 years (Table 1) took part in this study. Participants were hospital and research staff as well as students. Participants were excluded if they reported a neurological or orthopedic condition that affected gait. Participants with

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The authors have no conflict of interest.

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	n	Age (years)	Mass (kg)	Height (m)
All	15	28.7 (8.5)	67.3 (10.6)	1.72 (0.08)
Male	6	30.6 (8.5)	73.3 (9.4)	1.77 (0.07)
Female	9	25.8 (8.3)	58.3 (3.3)	1.65 (0.04)

Results are given as mean (SD)

Table 1. Characteristics of the study population.

known cardiac or respiratory disease or uncorrected visual impairment were also excluded. This study was approved by the Ethics Committee of Sainte-Justine Hospital Research Center. All participants provided informed consent.

Equipment

Gait parameters were measured using a Leonardo Mechanograph® Gangway system (Novotec Medical GmbH, Pforzheim, Germany) with four force plate modules (Figure 1). Each module consists of a rectangular aluminum frame that contains a force sensor (strain gauge) in each of the four corners of the frame, and a rigid platform that is placed on these sensors. Horizontal movements of the plate are prevented by the aluminum frame. Each module is 150 cm long and 78 cm wide. The four force plate modules are placed on the floor to form a 6 m long walkway. The modules rest on height-adjustable legs, which allow precise horizontal positioning of the walkway. Depending on the position of the adjustable legs, the walkway is about 7 cm above the floor. In order to prolong the walking distance to 10 m, the length often used in clinical gait analysis[5], we added a 2 m long custom-build wooden platform at each end of the 6 m Leonardo Mechanograph® GW, thus resulting in a 10 m long gangway (Figure 1). This provided space for the acceleration and deceleration phases of the walk[6].

The 16 force sensors of the four modules continuously measure forces in a vertical direction and transmit the reading at a rate that can be adjusted by the user (software default: 400 Hz). In the present study the rate was set at 800 Hz (the maximal value allowed by the software) for maximal temporal resolution. The signal was analyzed using Leonardo Mechanography GW RES® software (Version 4.2.b05.50c). The center of force (COF) is defined as the point where the resultant vector of all vertical forces applied to the platform hits the surface of the platform. At each time point, this is derived from the simultaneous input of the four force sensor of each force-plate module. The spatial variation of the COF during the walk and the temporal variation in the total force applied to the walkway are recorded (Figure 2).

On the start of each experimental day, a calibration routine was used to verify that each of the four force sensors of each force plate provided a signal within acceptable limits. Adjustments were made by lowering or increasing the height of the legs of the platform, as necessary. The calibration routine included in the software package was used for this purpose (Figure 3).

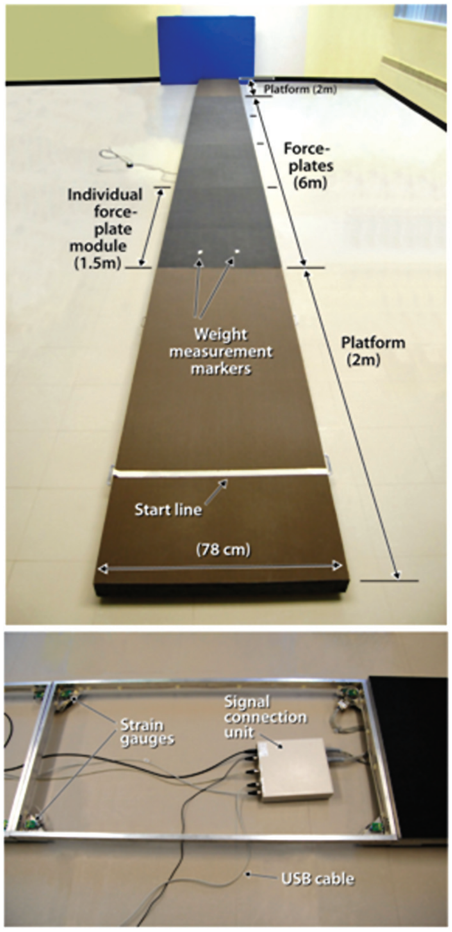

Figure 1. Experimental setup. The upper picture shows the four 1.5 m force plate modules (black surface) of the system and the two 2 m custom-build modules (brown surface) at each end. The lower panel depicts the different components of a force plate module.

Gait parameters

The various elements of the gait analysis are detected from the force-time and spatial COF data (Table 2, Figure 2). Steps are detected based on the maxima and minima of the spatial COF curve. To eliminate noise, the software uses a moving average filter that calculates the mean result of eight consecutive data points. The force-based definition of steps used by this system is different from most other gait analysis methodologies which determine steps based on the location of the footfalls (e.g., paper and pencil method[7], insole pressure systems[8] and pressure sensitive instrumented walkways[2]). The user can manually determine the series of consecutive steps that are to be included in the analysis. By the software's default settings, the first and the last step are ignored. The parameters shown in Table 3 are then calculated by the software.

Procedures

For each participant, the experimenter provided a description of the procedure and a demonstration of the task. The

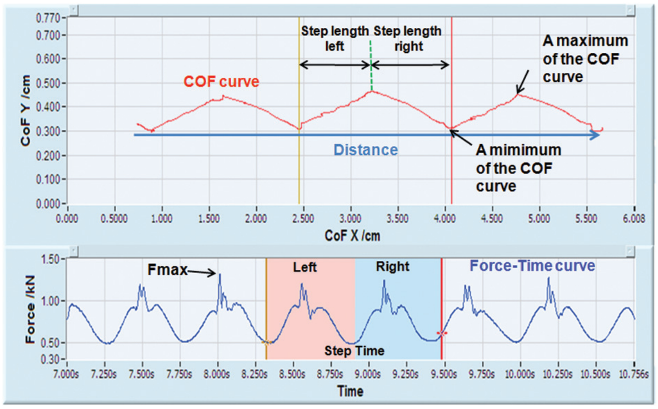

Figure 2. Software output of the COF curve (red line) and the force-time curve (blue line). Step length is derived from the COF curve. A step of the left leg starts at a minimum value of the COF curve and ends at a maximum value. A step of the right leg starts at a maximum value of the COF curve and ends at a minimum value. Path length is the length of the COF curve, from the start of the first step to the end of the last step that is included in the analysis. Distance is the length (in the direction of the x-axis) of all steps that are included in the analysis.

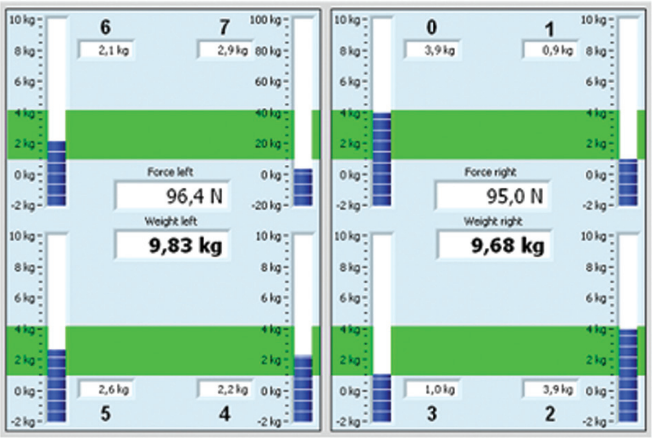

Figure 3. Calibration tool. The blue bars represent the reading of each sensor of two force plate modules. The green area represents the acceptable range for the sensor output. The right panel represents the first force plate module, the left panel represents the second force plate module. In the present figure, all sensors except for sensor #7 are adjusted properly (i.e., the blue bar is in the green area).

	Definition
Left Step	Starts at a minimum value of the COF and ends at the following maximum value of the COF
Right Step	Starts at a maximum value of the COF and ends at the following minimum value of the COF
Step length	Distance between a minimum of the COF curve to the next maximum (left step length) or distance between a maximum of the COF curve to the next minimum (right step length). Step length measurements reflect the longitudinal displacement in the direction of the x-axis. The displacement in the direction of the y-axis is not taken into consideration.
Step time	Time elapsed per step as defined above
Distance	Total length of all steps (in the direction of the x-axis) that are included in the analysis
Path length	Length of the COF curve
Ratio path length/distance	Indicates to what extent the COF curve deviates from a straight line. A perfectly straight COF curve would result in a relative path length of 1. The relative path length increases with increasing lateral translation of the COF curve during locomotion.

Table 2. Basic definitions used in this study.

force platform was zeroed before a participant stepped onto it. The participant did not perform a familiarization trial, as in the intended clinical use of this system familiarization procedures will typically not be possible due to time constraints. The participant stood on the device in an upright position, with each foot on a position marker (Figure 1). Body mass was recorded while the participant stood still for 8 seconds. Following a single-tone pitch, the participant was instructed to “go to the start line and start walking at a speed that is normal or comfortable for you. The test ends when you step off the gangway.”

Participants performed the walking trials in two different conditions: wearing shoes and barefoot. This was done in order to assess whether these conditions influenced results and thus required standardization in clinical use. Barefoot walking was tested because it eliminates variability due to different types of shoes. However, in Western civilizations wearing shoes is probably more common than walking barefoot and therefore the shod condition was evaluated as well. In the absence of differences between the barefoot and the shod conditions, testing while wearing shoes would be easier in most clinical settings. For the shoes condition, participants used their own flat heeled shoes.

Participants performed a total of three trials in each of the two conditions. The following trial sequence was maintained for each participant: Shoes – barefoot – shoes – barefoot – shoes – barefoot. Each trial consisted of three consecutive walks. The participants thus performed a total of nine walks in each condition.

Parameter[a]	Unit	Definition
Fmax	kN	Maximum force measured during a trial
Fmax left	kN	Maximum force during a left step
Fmax right	kN	Maximum force during a right step
Fmax/BW	No Unit	Fmax as a multiple of body weight
Fmax/BW left	No Unit	Fmax left as a multiple of body weight
Fmax/BW right	No Unit	Fmax right as a multiple of body weight
Average velocity	m/s	Distance between the start of the first and the end of the last step divided by time
Maximum velocity	m/s	Speed of the fastest step during the walk
Cadence	steps/min	Number of steps per minute
Average step length	cm	Average step length, both sides combined
Average step length left	cm	Average step length for the left side
Average step length right	cm	Average step length for the right side
Ratio path length/distance	No Unit	Path length divided by distance in the direction of the x-axis
Average time per step	s	Average time per step, both sides combined
Time per step left	s	Time per step for the left side
Time per step right	s	Time per step for the right side

[a] *All force-based measurements take only into account the vertical component of force.*

Table 3. Gait parameters used in this study.

Data analysis

Basic gait parameters were recorded for each walk across the platform using the Leonardo Mechanograph® RES software. The results of three consecutive walks in the same condition were averaged after normalization for the number of steps. This average result for three walks was called a 'trial'. A minimum of four steps per walk and a maximum of eight steps per walk were recorded for each participant depending on step length. Therefore, because a trial is an average of three walks, we ensured that a minimum of 12 and a maximum of 24 steps were included in a given trial.

Statistical analyses

To assess for the presence of a learning effects we computed for each parameter a repeated measures ANOVA contrasting the change in the mean between the three trials of a specific condition. When the sphericity assumption was violated, the Greenhouse-Geisser correction was applied and the corresponding adjusted P-value is reported. All significant effects revealed by the post-hoc analysis are reported at $P<0.05$ adjusted for the number of comparisons with the Bonferroni technique.

Repeatability was assessed by calculating the coefficient of variation (CV) and the intraclass correlation coefficient (ICC) which all are widely used repeatability parameters in the literature on human performance measures[9]. For each parameter in each of the two conditions (barefoot, shoes), the CV was calculated as indicated by Gluer et al.[10]. First, we computed the standard deviation of each participant:

$$(1)\ SD_j = \sqrt{\sum_{i=1}^{n_j} \frac{(x_{ij} - \bar{x}_j)^2}{n_j - 1}}$$

where n_j is the number of measurements performed, x_{ij} is the result of the *ith* measurement for subject *j*, and $\bar{x}_j$ is the mean of all x_{ij} for this subject. Then, we computed the common within-subject standard deviation[10,11]:

$$(2)\ SD = \sqrt{\sum_{j=1}^{m} \frac{SD_j^{\ 2}}{m}}$$

where SD_j is the standard deviation of one subject and *m* the number of subjects. Finally, to represent the standard deviation as a percentage, we used the coefficient of variation (*CV*):

$$(3)\ CV = \left(\frac{SD}{\sum_{j=1}^{m} \left(\frac{\bar{x}_j}{m} \right)} \right) X100$$

Regarding ICC, a two-way mixed effect model with a consistency definition was used following the algorithm proposed by McGraw and Wong[12]. In the mixed model the participant is treated as a random effect, whereas measurement error is considered as a fixed effect. Thus, ICC(C,k) and their 95% confidence intervals (95% CIs) were computed. The average measure ICC is reported.

Differences in gait parameters between walking with shoes and walking barefoot were assessed by comparing the mean of the nine walks performed in each condition using paired t-tests. Calculations were performed using PASW 18® (SPSS Inc., Chicago, IL, USA).

Results

In order to test for the presence of a learning effect, systematic differences between trials were evaluated by comparing

Gait parameter	Trial 1	Trial 2	Trial 3	P
Fmax total (kN)	1.17 (0.22)	1.17 (0.23)[a]	1.19 (0.24)	0.02
Fmax left (kN)	1.14 (0.22)	1.14 (0.23)	1.16 (0.24)	0.30
Fmax right (kN)	1.12 (0.20)	1.14 (0.19)	1.15 (0.21)	0.03[b]
Fmax/BW	1.74 (0.14)	1.75 (0.15)[a]	1.78 (0.16)	0.03
Fmax/BW left	1.73 (0.16)	1.73 (0.16)	1.76 (0.17)	0.28
Fmax/BW right	1.70 (0.15)	1.74 (0.14)	1.75 (0.16)	0.03[b]
Average velocity (m/s)	128 (10)	128 (10)	127 (11)	0.86
Maximum velocity (m/s)	1.41 (0.14)	140 (0.15)	140 (0.15)	0.88
Cadence (steps/min)	112 (6)	111 (6)	111 (6)	0.45
Average step length (cm)	68.5 (5.4)	69.1 (5.7)	69.1 (5.8)	0.17
Average step length left (cm)	69.2 (6.0)	69.8 (5.5)	69.1 (6.1)	0.38
Average step length right (cm)	67.9 (5.7)	68.5 (6.9)	68.9 (7.2)	0.23
Ratio path length/distance	1.39 (0.18)	1.42 (0.15)	1.44 (0.18)	0.15
Average time per step (s)	0.54 (0.03)	0.54 (0.03)	0.54 (0.03)	0.43
Time per step left (s)	0.54 (0.06)	0.54 (0.07)	0.54 (0.07)	0.82
Time per step right (s)	0.53 (0.05)	0.54 (0.06)	0.54 (0.07)	0.19

[a] *Trial 2 significantly differs from Trial 3, p<0.05*

[b] *The ANOVA revealed significant main effect of trials but post-hoc test did not reveal any significant differences when corrected for the number of comparisons (Bonferroni).*

Table 4. Mean (SD) values for the three trials of barefoot walking.

Gait parameter	Trial 1	Trial 2	Trial 3	P
Fmax total (kN)	1.04 (0.17)	1.04 (0.18)	1.04 (0.17)	0.82
Fmax left (kN)	1.02 (0.18)	1.02 (0.18)	1.03 (0.18)	0.81
Fmax right (kN)	1.02 (0.16)	1.02 (0.18)	1.01 (0.16)	0.59
Fmax/BW	1.54 (0.13)	1.54 (0.12)	1.53 (0.12)	1.00
Fmax/BW left	1.53 (0.12)	1.54 (0.13)	1.54 (0.12)	0.73
Fmax/BW right	1.54 (0.12)	1.54 (0.12)	1.53 (0.12)	0.76
Average velocity (m/s)	1.29 (0.10)	1.31 (0.09)	1.32 (0.10)	0.21
Maximum velocity (m/s)	1.44 (0.16)	1.42 (0.16)	1.41 (0.16)	0.88
Cadence (steps/min)	107 (5)	109 (6)	109 (5)	0.04[a]
Average step length (cm)	72.6 (5.7)	72.6 (6.1)	72.4 (5.7)	0.89
Average step length left (cm)	73.9 (6.3)	73.6 (7.1)	73.2 (6.3)	0.55
Average step length right (cm)	71.5 (6.5)	71.6 (6.5)	71.5 (6.5)	1.00
Ratio path length/distance	1.10 (0.04)	1.09 (0.04)	1.09 (0.04)	0.36
Average time per step (s)	0.56 (0.03)	0.55 (0.03)	0.55 (0.03)	0.04[a]
Time per step left side (s)	0.56 (0.06)	0.56 (0.07)	0.55 (0.06)	0.18
Time per step right side (s)	0.56 (0.06)	0.54 (0.06)	0.55 (0.06)	0.24

[a] *The ANOVA revealed significant main effect of trials but post-hoc test did not reveal any significant differences when corrected for the number of comparisons (Bonferroni).*

Table 5. Mean (SD) values for the three trials of walking in shoes.

the three trials at each condition (Table 4 and 5). This revealed that maximal force increased significantly (by 1.7%) between trials when walking barefoot, but not when walking in shoes. No other systematic differences between trials were found. That only one parameter differed significantly from one trial to another suggests that participants did not need to get accustomed to walk on an elevated platform.

As to test-retest variability, the body weight measurements obtained before each walk (N=9 measurements for each participant at each condition) had a CV of 0.17% in the barefoot condition and 0.22% with shoes. During walking, all primary force, time, distance and velocity parameters had ICCs above 0.90 and CVs in the order of 2% to 4% (Table 6).

Compared to walking barefoot, walking in shoes resulted in 14% lower maximal vertical ground reaction force, 5% longer step length and 2% higher average velocity (Table 7). Walking in shoes also caused less lateral translation of the COF than walking barefoot, as indicated by the lower path length to distance ratio.

	Barefoot		Shoes	
Gait parameter	**ICC(C,k)**	**CV (%)**	**ICC(C,k)**	**CV (%)**
Fmax total	1.00 (0.99 to 1.00)	2.1	0.99 (0.99 to 1.00)	1.9
Fmax left	0.99 (0.98 to 1.00)	2.7	1.00 (0.99 to 1.00)	1.8
Fmax right	0.99 (0.99 to 1.00)	2.3	0.99 (0.98 to 1.00)	1.8
Fmax/BW	0.98 (0.95 to 0.99)	2.2	0.97 (0.93 to 0.99)	2.0
Fmax/BW left	0.97 (0.92 to 0.99)	2.7	0.98 (0.94 to 0.99)	1.9
Fmax/BW right	0.97 (0.92 to 0.99)	2.6	0.97 (0.92 to 0.99)	1.9
Average velocity	0.97 (0.94 to 0.99)	1.9	0.96 (0.90 to 0.99)	2.2
Maximum velocity	0.97 (0.92 to 0.99)	2.7	0.90 (0.77 to 0.97)	4.1
Cadence	0.91 (0.78 to 0.97)	2.3	0.94 (0.86 to 0.98)	1.9
Average step length	0.99 (0.98 to 1.00)	1.3	0.98 (0.96 to 0.99)	1.6
Average step length left	0.98 (0.96 to 0.99)	1.8	0.97 (0.94 to .099)	2.0
Average step length right	0.98 (0.96 to 0.99)	2.0	0.97 (0.94 to 0.99)	2.2
Ratio path length/distance	0.94 (0.85 to 0.98)	4.4	0.94 (0.85 to 0.98)	2.5
Average time per step	0.92 (0.80 to 0.97)	2.4	0.94 (0.86 to 0.98)	2.0
Time per step left side	0.95 (0.88 to 0.98)	4.2	0.95 (0.87 to 0.98)	3.9
Time per step right side	0.94 (0.86 to 0.98)	4.1	0.91 (0.79 to 0.97)	4.4

Table 6. Test-retest repeatability for each of the gait parameters in the barefoot and shoes conditions.

	Barefoot	**Shoes**	**P**
Fmax (kN)	1.18 (0.23)	1.04 (0.17)	<0.001
Fmax Left (kN)	1.15 (0.23)	1.02 (0.17)	<0.001
Fmax Right (kN)	1.14 (0.20)	1.02 (0.16)	<0.001
Fmax/BW	1.75 (0.15)	1.54 (0.12)	<0.001
Fmax/BW left	1.74 (0.16)	1.54 (0.12)	0.001
Fmax/BW right	1.73 (0.14)	1.54 (0.12)	<0.001
Average velocity (m/s)	1.28 (0.10)	1.31 (0.09)	0.004
Maximum velocity (m/s)	1.40 (0.14)	1.42 (0.14)	0.15
Cadence (steps/min)	111 (6)	108 (5)	0.001
Average step length (cm)	68.9 (5.5)	72.5 (5.8)	<0.001
Average step length left (cm)	69.3 (5.7)	73.6 (6.3)	<0.001
Average step length right (cm)	68.5 (6.5)	71.5 (6.4)	<0.001
Ratio path length/distance	1.41 (0.16)	1.09 (0.04)	<0.001
Average time per step (s)	0.54 (0.03)	0.56 (0.03)	<0.001
Time per step left side (s)	0.54 (0.06)	0.56 (0.06)	0.03
Time per step right side (s)	0.54 (0.06)	0.55 (0.05)	0.04

Table 7. Comparison between barefoot and shod walking.

Discussion

This study shows that in young adults, the new force plate system measured gait parameters with high repeatability, as indicated by low CVs and high ICCs between three intrasession trials. We also found that walking with shoes is associated with higher velocity, longer step length, less lateral translation of the COF and lower Fmax than walking barefoot.

With regard to test-retest analyses, minimal systematic changes were found between trials. Even though one of these differences were statistically significant (Fmax when walking barefoot) due to the low variability of these measures, the differences are so small that they probably can be neglected in most clinical settings.

The repeatability (ICCs and CVs) of temporal and spatial parameters observed in this study was comparable to that reported for other gait analysis systems[8,13,14]. Presumably, the overall variability of test results depends more on the variability of a test person's gait than on the technical variability of the measurement device. This is suggested by our observation that the dynamic measurement of maximal vertical force was about 10 times more variable than the static measurement of body weight at the beginning of each test (2% vs 0.2%).

In contrast to most other gait analysis systems, the device used in this study provides continuous force measurements over several step cycles. Force-measuring treadmill systems also determine forces during many step cycles, but we are not aware of repeatability data with such devices. Typical gait laboratory testing includes force measurements during only one or two steps in the course of a 10 m walk. The repeatability of kinetic parameters obtained with such methods has been studied in some detail, but is typically not presented in the same manner as in the present study, which makes comparisons with our study difficult[13]. However, one study on healthy children (6 to 11 years) reported that the CV for maximum vertical ground reaction force measurements was 8.5% for the left foot and 9.7% for the right foot[15]. Possible explanations for the lower variability of force measurements in our study include the fact that our measurement device determined forces over many gait cycles. It is also possible that adults have a lower variability in such measures than children, as it is the case for temporal and spatial parameters[16].

The path length to distance ratio is an indicator of lateral translation of the COF during gait. This measure does not seem to have been determined in previous gait analysis studies but can be derived with the present device. Low variability was found for this parameter, which makes this an interesting measure of dynamic balance during human gait.

The comparison between shoe and barefoot walking was undertaken to address an obvious question in the practical use of the present gait analysis system: Barefoot or shoes - does it matter? The answer is yes. We observed significant differences between these conditions. This indicates that it is important to standardize conditions, especially when serial assessments of the same subject are planned. In most clinical settings it is probably easier to standardize for the barefoot condition than to ensure that subjects are wearing the same shoes during each test session. Therefore, barefoot testing may be preferable in many settings.

We note that the differences in speed and step length between barefoot and shod walking were similar in this study as in a previous study on young adults[17]. However, our observation that Fmax was lower in shod walking is in contrast to a study by Keenan et al, who found that maximal vertical ground reaction forces were slightly higher when wearing shoes[18]. This discrepancy between studies may be due to differences in testing setup (overground walking vs. treadmill walking). The characterization of differences between barefoot and shod walking warrants further study.

In conclusion, gait analysis in healthy adults using a force-plate based system yielded measures with low variability on intrasession test-retest assessment.

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