**Analyzing Gait Using a Force-Measuring Walkway: Intrasection Repeatability
in Healthy Children and Adolescents**

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Running title: Repeatability of Gait Analysis

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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) in healthy children.

Methods: Nineteen healthy children and adolescents (age range: 7 to 17 years) walked at a self-selected speed on an 11 m long walkway. Vertical ground reaction forces were measured in the central 6 m of the walkway. Each participant performed three blocks of three trials while walking barefoot and three blocks of three trials while wearing shoes.

Results: There were no differences between trials within each condition. All force and spatiotemporal parameters had intraclass correlation coefficients above 0.87 and coefficients of variation in the order of 1% to 6%.

Conclusions: In this group of healthy children and adolescents, gait analysis with a force plate system produced repeatable intra-day results.

Key words: gait– ground reaction force– healthy children – healthy adolescent – variability - repeatability

1. Introduction

Assessment of gait is performed in numerous clinical settings to make diagnoses, recommend interventions, and monitor the effect of interventions. In many situations, the clinician’s methodological armamentarium is limited to visual observation of a patient’s gait pattern, which however has questionable validity and reliability (Krebs et al. 1985). Quantitative gait analysis including kinematic and kinetic measurements is widely used in research settings but such analysis imposed the use of expensive device and is also time consuming. Thereby quantitative gait analysis is often not feasible in a clinical context.

The clinical need for simpler over-ground gait analysis instruments has driven the development of a number of new analytical tools, such as mats with pressure sensors (Webster et al. 2005) or accelerometer-based devices (Senden et al. 2009). However, most of these systems measure only temporal and spatial gait parameters and provide little or no information on the kinetic aspects of gait.

In the present study, we assessed a gait analysis device that determines spatiotemporal parameters based on the measurement of the vertical component of the forces produced during walking. The system consists of a series of force plate modules. It has been devised for clinicians and is provided with its own software analysis package. Raw force data are automatically analyzed following each data acquisition trial and spatiotemporal and force gait parameters are quickly presented to the clinician within a user friendly interface. The reliability of the system has already been demonstrated in healthy adults indicating that only nine 10m trials are necessary to obtain repeatable measurements (Veilleux et al. 2011). Although gait patterns generally stabilize around the age of 7 years (Sutherland 1997), specific gait parameters, such as stride-to-stride variability, may reach maturity later in development (Hausdorff et al. 1999). Such variations can

greatly impact device accuracy. The goal of the present study was to establish repeatability of gait parameter as measured by a force measuring walkway in healthy children and adolescents.

2. Methods

2.1 Participant

Nineteen healthy children and adolescents (15 males) aged between 7 and 17 years (Table 1) took part in this study. Participants were excluded if they reported a neurological or orthopedic condition affecting gait. Participants with 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 (Montreal, Canada). All participants provided written informed consent prior testing.

2.2 Equipment

Gait parameters were measured using a Leonardo Mechanograph® Gangway system (Novotec Medical GmbH, Pforzheim, Germany). The set-up was described in detail in a previous study (Veilleux et al. 2011). Six force plate modules were placed on the floor to form a 9 m long walkway on which ground reaction forces were measured. A 2 m long custom-build wooden platform was added at the end of the walkway in order to obtain at least a 10 m long walkway, the length classically used in clinical gait analysis (Coutts 1999). The first two meters of the walkway allowed participants to accelerate and reach steady state walking velocity whereas they decelerated on the last two meters of the walkway. This allowed us to assess gait during steady state walking (Macfarlane and Looney 2008).

In the present study the data acquisition 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.b05.64b). On the start of each experimental day, the four force sensors of each force plate were calibrated with the calibration tool included in the software package.

2.3 Procedures

For each participant, the experimenter provided a description of the procedure and a demonstration of the task. The force platform was zeroed before a participant stepped onto it. Prior to the beginning of testing the participant received the following instructions: “Start walking at a speed that is normal or comfortable for you. The test ends when you step off the walkway”. As requested by the system, body mass was recorded while the participant stood still for 2 seconds after which a single-tone pitch instructed the participant to initiate their walk.

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 everyday life wearing shoes is probably more common than walking barefoot and therefore the shod condition was evaluated as well. For the shod condition, participants used their own flat heeled shoes.

Participants performed a total of three blocks of three trials in each of the two conditions. Each block of three trials in a condition was followed by three trials in the other condition. The order of presentation of the two conditions was counterbalanced across participants: half of the

participants initiated their trials with the barefoot condition while the other half started with the shoes condition.

2.4 Gait parameters and data analysis

The system measures force at a frequency of 800 Hz and from these data derives spatiotemporal (step length, step time, average velocity and cadence) and kinetic (peak vertical ground reaction force and peak vertical ground reaction force normalized to body weight) gait parameters, as described previously (Veilleux et al. 2011). In addition, the system measures the ratio of the displacement of the center of force (i.e. path length) over the walking distance. This ratio increases with increasing lateral translation of the center of force (COF) curve during locomotion (Veilleux et al. 2011). Gait parameters were recorded for each trial across the platform using the Leonardo Mechanograph® RES software. All trials were considered for data analysis. The software was set to automatically discard the first two steps and the last step of each trial recorded by the platform. This data processing was done to ensure assessment of steady state walking. The results of three consecutive trials in the same condition were averaged after normalization for the number of steps. This average result for three trials was called a 'block'. A minimum of four steps and a maximum of eight steps per trial were recorded for each participant, depending on step length. Therefore, a minimum of 12 and a maximum of 24 steps were included in a given block.

2.5 Statistical analyses

To assess for the presence of adaptation repeated measures ANOVAs contrasting the change in the mean between the three blocks of a specific condition was performed for each parameter. 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 (Atkinson and Nevill 1998). For each parameter in each of the two conditions (barefoot, shoes), the CV was calculated as suggested by Gluer et al. (1995).

Regarding ICC, a two-way mixed effect model with a consistency definition was used following the algorithm proposed by McGraw and Wong (McGraw and Wong 1996). 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 trials performed in each condition using paired t-tests. Calculations were performed using PASW 20® (SPSS Inc., Chicago, IL, USA).

3. Results

The analysis did not reveal any adaptation as no systematic differences between trials were found (Tables 2 and 3).

The body weight measurements obtained before each trial (N = 9 measurements for each participant at each condition) had a CV of 0.49% in the barefoot condition and 0.41% with shoes. During walking, all primary force, time, distance and velocity parameters had ICCs above 0.87 and CVs in the order of 1% to 6% (Table 4).

Compared to walking barefoot, walking in shoes resulted in 14% lower maximal vertical ground reaction force, 7% longer step length and 2% higher average velocity (Table 5).

4. Discussion

This study shows that in healthy children and adolescent, the Leonardo Gangway force plate system measured gait parameters with high repeatability, as indicated by low CVs and high ICCs between three intrasession trials. As in our previous adult study (Veilleux et al. 2011), walking with shoes is associated with higher velocity, longer step length and lower Fmax than walking barefoot.

No adaptation was reported despite the fact that the walkway is slightly elevated and that it offers a narrower walking surface (0.77 m) than over-ground walking. This absence of adaptation is important because force measuring treadmills, which could have similar clinical applications, require a familiarization period (Dierick et al. 2004).

The repeatability (ICCs and CVs) of temporal and spatial parameters observed in this study was comparable to that reported for other gait analysis systems (Kadaba et al. 1989; Bilney

et al. 2003; Menz et al. 2004). 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 (Steinwender et al. 2000).

Whatever the condition the coefficients of variation reported for each parameter ranged between 1 and 6%. In comparison with our previous study, CVs were generally higher in children than in adults. Interestingly, CVs reported for the path length/distance ratio parameter was also 5% higher in children than in adult. These results support previous study results which highlighted children gait variability (Bollens et al. 2012). Nevertheless, the variability reported in the present study is lower than that reported for healthy children (aged 6 to 11 years) with another device (White et al. 1999). In that study, the CV for maximum vertical ground reaction force measurements was 8.5% for the left foot and 9.7% for the right foot. Variability may have been lower in our study because our study population was older (Stansfield et al. 2001; Diop et al. 2005).

As previously observed in adults, significant differences between shoe and barefoot walking was observed. Such modification could result from the lengthening of lower extremities due to the shoe soles. Indeed, as supported by the inverted pendulum theory, longer lower extremities can result in longer step (Cavagna et al. 1963). This indicates that it is important to standardize conditions, especially when serial assessments of the same participant are planned. In most clinical settings it is probably easier to standardize for the barefoot condition than to ensure that patients are wearing the same shoes during each test session. Therefore, barefoot testing may be preferable in many settings.

The differences in speed and step length between barefoot and shod walking were similar in this study as in previous studies (Lythgo et al. 2009; Veilleux et al. 2011). Our observation that Fmax was lower in shod walking is consistent with our previous study on adults but in contrast

with a study by Keenan et al, who found that maximal vertical ground reaction forces were slightly higher when wearing shoes (Keenan et al. 2011). The characterization of differences between barefoot and shod walking warrants further study.

5. Conclusions

In conclusion, gait analysis in healthy children and adolescent using a force-plate based system yielded measures with low variability on intrasession test-retest assessment. Based on these results, it is now justified to further evaluate the reliability of the system in different patient populations.

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1 Table 1. Characteristics of the study population

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	n	Age	Weight (kg)	Height (m)
	19	11.5 (2.2)	43.8 (11.7)	1.54 (0.13)
Male	15	11.6 (2.4)	43.2 (12.9)	1.54 (0.14)
Female	4	11.0 (1.4)	46.3 (5.1)	1.52 (0.09)

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4 Results are given as mean (SD)

Table 2. Results for the three trials in the Barefoot condition

Gait parameter	Trial 1	Trial 2	Trial 3	P
Fmax (kN)	0.83 (0.20)	0.87 (0.22)	0.84 (0.21)	0.03 ^a
Fmax Left (kN)	0.81 (0.20)	0.83 (0.22)	0.82 (0.21)	0.23
Fmax Right (kN)	0.79 (0.20)	0.81 (0.20)	0.79 (0.19)	0.09
Fmax/BW	1.95 (0.20)	2.02 (0.20)	1.97 (0.20)	0.06
Fmax/BW Left	1.90 (0.20)	1.94 (0.22)	1.93 (0.22)	0.42
Fmax/BW Right	1.84 (0.18)	1.90 (0.15)	1.86 (0.14)	0.06
Average horizontal velocity (m/s)	122 (17)	125 (20)	125 (20)	0.10
Cadence (steps/min)	124 (7)	125 (8)	125 (8)	0.27
Average step length (cm)	59.3 (7.1)	60.0 (8.1)	60.0 (7.8)	0.35
Average step length left (cm)	58.2 (7.1)	60.3 (8.4)	59.6 (8.8)	0.06
Average step length right (cm)	60.2 (7.9)	59.7 (8.1)	60.2 (7.5)	0.77
Ratio path length/distance	1.46 (0.2)	1.49 (0.20)	1.51 (0.23)	0.03 ^a
Average time per step (s)	0.49 (0.03)	0.48 (0.03)	0.48 (0.03)	0.27
Time per step left side (s)	0.48 (0.05)	0.48 (0.05)	0.47 (0.04)	0.62
Time per step right side (s)	0.50 (0.05)	0.48 (0.05)	0.49 (0.05)	0.14

Results are given as mean (SD). ^a ANOVA revealed significant main effect of trials but post-hoc testing between individual trials did not show any significant differences following Bonferroni correction

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1 Table 3. Results for the three trials in the Shoes condition

Gait parameter	Trial 1	Trial 2	Trial 3	P
Fmax (kN)	0.72 (0.20)	0.73 (0.20)	0.73 (0.20)	0.23
Fmax Left (kN)	0.70 (0.19)	0.69 (0.19)	0.70 (0.20)	0.63
Fmax Right (kN)	0.70 (0.21)	0.71 (0.20)	0.71 (0.19)	0.34
Fmax/BW	1.65 (0.23)	1.67 (0.24)	1.68 (0.24)	0.22
Fmax/BW Left	1.61 (0.24)	1.60 (0.23)	1.61 (0.23)	0.75
Fmax/BW Right	1.61 (0.22)	1.64 (0.23)	1.64 (0.21)	0.48
Average horizontal velocity (m/s)	126 (20)	127 (19)	128 (20)	0.53
Cadence (steps/min)	119 (9)	119 (9)	119 (8)	0.92
Average step length (cm)	63.5 (7.7)	63.7 (7.5)	64.3 (7.9)	0.15
Average step length left (cm)	63.2 (8.0)	63.3 (8.3)	63.4 (8.7)	0.96
Average step length right (cm)	63.7 (8.2)	64.1 (7.3)	65.0 (7.5)	0.33
Ratio path length/distance	1.32 (0.2)	1.28 (0.13)	1.31 (0.17)	0.36
Average time per step (s)	0.51 (0.04)	0.51 (0.04)	0.51 (0.04)	0.90
Time per step left side (s)	0.50 (0.05)	0.50 (0.05)	0.50 (0.05)	0.88
Time per step right side (s)	0.52 (0.07)	0.52 (0.06)	0.51 (0.06)	0.61

2 Results are given as mean (SD).

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Table 4. Test-retest repeatability for each of the gait parameters in the Barefoot and Shoes conditions

Gait paramter	Barefoot		Shoes	
	ICC(C,k)	CV (%)	ICC(C,k)	CV (%)
Fmax (kN)	0.99 (0.99 - 1.00)	4.78	1.00 (0.99 - 1.00)	3.04
Fmax Left (kN)	0.99 (0.99 - 1.00)	4.66	1.00 (0.99 - 1.00)	3.11
Fmax Right (kN)	0.99 (0.98 - 1.00)	4.53	1.00 (0.99 - 1.00)	3.14
Fmax/BW	0.94 (0.88 - 0.97)	4.60	0.97 (0.94 - 0.99)	3.43
Fmax/BW Left	0.93 (0.86 - 0.97)	4.66	0.96 (0.92 - 0.98)	3.72
Fmax/BW Right	0.93 (0.86 - 0.97)	4.45	0.96 (0.92 - 0.98)	3.25
Average horizontal velocity (cm/s)	0.98 (0.96 - 0.99)	4.00	0.98 (0.96 - 0.99)	3.59
Cadence (steps/min)	0.97 (0.93 - 0.98)	2.44	0.97 (0.94 - 0.98)	2.65
Average step length (cm)	0.99 (0.98 - 1.00)	2.94	1.00 (0.99 - 1.00)	1.94
Average step length left (cm)	0.99 (0.98 - 1.00)	4.75	0.99 (0.98 - 1.00)	3.34
Average step length right (cm)	0.98 (0.95 - 0.99)	4.72	0.98 (0.96 - 0.99)	4.01
Ratio path length/distance	0.98 (0.96 - 0.99)	3.85	0.97 (0.95 - 0.99)	6.41
Average time per step (s)	0.97 (0.94 - 0.99)	2.35	0.97 (0.94 - 0.99)	2.44
Time per step left side (s)	0.87 (0.74 - 0.94)	5.75	0.91 (0.82 - 0.96)	5.76
Time per step right side (s)	0.95 (0.90 - 0.98)	4.39	0.97 (0.94 - 0.99)	4.39

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Table 5. Comparison of the Barefoot and Shoes conditions

Gait parameter	Conditions		
	Barefoot	Shoes	P
Fmax (kN)	0.85 (0.21)	0.73 (0.02)	<0.001
Fmax Left (kN)	0.82 (0.04)	0.70 (0.02)	<0.001
Fmax Right (kN)	0.80 (0.03)	0.71 (0.02)	<0.001
Fmax/BW	1.98 (0.09)	1.67 (0.05)	<0.001
Fmax/BW Left	1.92 (0.09)	1.60 (0.05)	<0.001
Fmax/BW Right	1.87 (0.08)	1.63 (0.05)	<0.001
Average horizontal velocity (m/s)	124 (5)	127 (4)	0.02
Cadence (steps/min)	125 (3)	119 (3)	<0.001
Average step length (cm)	59.8 (1.7)	63.8 (1.2)	<0.001
Average step length left (cm)	59.4 (2.6)	63.3 (2.1)	<0.001
Average step length right (cm)	60.0 (2.4)	64.3 (2.5)	0.004
Ratio path length/distance	1.49 (0.06)	1.30 (0.08)	<0.001
Average time per step (s)	0.48 (0.01)	0.51 (0.01)	<0.001
Time per step left side (s)	0.48 (0.03)	0.50 (0.03)	0.003
Time per step right side (s)	0.49 (0.02)	0.52 (0.02)	0.004

Results are given as mean (SD)