Analysing gait using a force-measuring walkway: intrasession repeatability in healthy children and adolescents

Louis-Nicolas Veilleuxa,b*, Laurent Ballazb,c, Maxime Robertb,c, Martin Lemayb,c and Frank Raucha,b

aShriners Hospital for Children and Department of Pediatrics, McGill University, Montréal, Québec, Canada; bCentre de Réadaptation Marie-Enfant, Research Center, Sainte-Justine University Hospital, Montréal, Québec, Canada; cDépartement de Kinanthropologie, Université du Québec à Montréal, Montréal, Québec, Canada

(Received 21 June 2012; final version received 19 November 2012)

The goal of this study was to determine the repeatability of gait parameters measured by a force plate gait analysis system (Leonardo Mechanograph® GW) in healthy children. Nineteen healthy children and adolescents (age range: 7–17 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. 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 1–6%. In this group of healthy children and adolescents, gait analysis with a force plate system produced repeatable intra-day results.

Keywords: 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 overground 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 this 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 analysed 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 10-m trials are necessary to obtain repeatable measurements (Veilleux et al. 2011). Although gait patterns generally stabilise 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 this study was to establish the 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 orthopaedic 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 to 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-in-long walkway, the length classically used in clinical gait analysis (Coutts 1999). The first two meters of the walkway allowed the participants to accelerate and reach steady-state walking velocity whereas they decelerated on the last 2 m of the walkway. This allowed us to assess gait during steady-state walking (Macfarlane and Looney 2008).

In this study, the data acquisition rate was set at 800 Hz (the maximal value allowed by the software) for maximal temporal resolution. The signal was analysed 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 s after which a single-tone pitch instructed the participant to initiate his/her 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 standardisation in clinical use. Barefoot walking was tested because it eliminates the 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 shod 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 normalised to body weight) gait parameters, as described previously (Veilleux et al. 2011). In addition, the system measures the ratio of the displacement of the centre of force (COF; i.e. path length) over the walking distance. This ratio increases with increasing lateral translation of the 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 normalisation 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 ANOVA 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 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 and 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 (1996). In the mixed model, the participant is treated as a random effect, whereas
the 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, primary force, time, distance and velocity parameters had ICCs above 0.87 and CIs in the order of 1–6% (Table 4).

Compared with 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 adolescents, the Leonardo Gangway force plate system measured gait parameters with high repeatability, as indicated by low CIs 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 \( F_{\text{max}} \) 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 overground walking. This absence of adaptation is important because force-measuring treadmills, which could have similar clinical applications, require a familiarisation 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 that highlighted children gait variability (Bollens et al. 2012). Nevertheless, the variability reported in this study is lower than that reported for healthy children (aged 6–11 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 might 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 were observed. Such modifications could result from the lengthening of lower extremities due to the shoe soles. Indeed, as supported by the inverted pendulum theory, longer lower

Table 4. Test–retest repeatability for each of the gait parameters in the barefoot and shod conditions.

| Gait parameter          | Barefoot ICC(C,k) | CV (%) | Shod ICC(C,k) | CV (%) |
|-------------------------|-------------------|--------|---------------|--------|
| $F_{\text{max}}$ (kN)   | 0.99 (0.99–1.00)  | 4.78   | 1.00 (0.99–1.00) | 3.04   |
| $F_{\text{max}}$ left (kN) | 0.99 (0.99–1.00) | 4.66   | 1.00 (0.99–1.00) | 3.11   |
| $F_{\text{max}}$ right (kN) | 0.99 (0.98–1.00) | 4.53   | 1.00 (0.99–1.00) | 3.14   |
| $F_{\text{max}}$/BW   | 0.94 (0.88–0.97)  | 4.60   | 0.97 (0.94–0.99) | 3.43   |
| $F_{\text{max}}$/BW left | 0.93 (0.86–0.97) | 4.66   | 0.96 (0.92–0.98) | 3.72   |
| $F_{\text{max}}$/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   |

Table 5. Comparison of the barefoot and shod conditions.

| Gait parameter          | Barefoot | Shod | $P$   |
|-------------------------|----------|------|-------|
| $F_{\text{max}}$ (kN)   | 0.85 (0.21) | 0.73 (0.02) | <0.001 |
| $F_{\text{max}}$ left (kN) | 0.82 (0.04) | 0.70 (0.02) | <0.001 |
| $F_{\text{max}}$ right (kN) | 0.80 (0.03) | 0.71 (0.02) | <0.001 |
| $F_{\text{max}}$/BW   | 1.98 (0.09) | 1.67 (0.05) | <0.001 |
| $F_{\text{max}}$/BW left | 1.92 (0.09) | 1.60 (0.05) | <0.001 |
| $F_{\text{max}}$/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  |

Note: Results are given as mean (SD).
extremities can result in longer step (Cavagna et al. 1963). This indicates that it is important to standardise the conditions, especially when serial assessments of the same participant are planned. In most clinical settings, it is probably easier to standardise 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 $F_{\text{max}}$ was lower in shod walking is consistent with our previous study on adults but in contrast with a study by Keenan et al. (2011), who found that maximal vertical ground reaction forces were slightly higher when wearing shoes. The characterisation of differences between barefoot and shod walking warrants further study.

5. Conclusions
In conclusion, gait analysis in healthy children and adolescents 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.

Acknowledgements
Louis-Nicolas Veilleux is a member of the MENTOR training programme supported by the Canadian Institutes of Health Research (CIHR) and from the Réseau Provincial en Adaptation-Réadaptation (REPAR). Laurent Ballaz is a member of the MEDITIS training programme supported by the Natural Sciences and Engineering Research Council of Canada (NSERC). Maxime Robert is supported by the CIHR. Martin Lemay is supported by NSERC. Frank Rauch is a Chercheur-Boursier Clinicien of the Recherche en Santé du Québec. This study was supported by the Shriners of North America and by the Research Institute of the Sainte-Justine University Hospital Center.

References
Atkinson G, Nevill AM. 1998. Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. Sports Med. 26(4):217–238.

Atkinson G, Nevill AM, Webster K. 2003. Concurrent related validity of the GAITRite walkway system for quantification of the spatial and temporal parameters of gait. Gait Posture. 17(1):68–74.

Bollens B, Crevecoeur F, Detrembleur C, Guillery E, Lejeune T. 2012. Effects of age and walking speed on long-range autocorrelations and fluctuation magnitude of stride duration. Neuroscience. 210:234–242.

Cavagna GA, Saibene FP, Margaria R. 1963. External work in walking. J Appl Physiol. 18:1–9.

Coutts F. 1999. Gait analysis in the therapeutic environment. Man Ther. 4(1):2–10.

Dierick F, Penta M, Renault D, Detrembleur C. 2004. A force measuring treadmill in clinical gait analysis. Gait Posture. 20(3):299–303.

Diop M, Rahmani A, Belli A, Gautheron V, Geyssant A, Cottalorda J. 2005. Influence of speed variation and age on ground reaction forces and stride parameters of children’s normal gait. Int J Sports Med. 26(8):682–687.

Gluer CC, Blake G, Lu Y, Blunt BA, Jergas M, Genant HK. 1995. Accurate assessment of precision errors: how to measure the reproducibility of bone densitometry techniques. Osteoporos Int. 5(4):262–270.

Hausdorff JM, Zemany L, Peng C-K, Goldberger AL. 1999. Maturation of gait dynamics: stride-to-stride variability and its temporal organization in children. J Appl Physiol. 86(3):1040–1047.

Kadaba MP, Ramakrishnan HK, Wootten ME, Gainey J, Gorton G, Cochran GV. 1989. Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. J Orthop Res. 7(6):849–860.

Keenan GS, Franz JR, Dicharry J, Della Croce U, Kerrigan DC. 2011. Lower limb joint kinetics in walking: the role of industry recommended footwear. Gait Posture. 33(3):350–355.

Krebs DE, Edelstein JE, Fishman S. 1985. Reliability of observational kinematic gait analysis. Phys Ther. 65(7):1027–1033.

Lythgo N, Wilson C, Galea M. 2009. Basic gait and symmetry measures for primary school-aged children and young adults whilst walking barefoot and with shoes. Gait Posture. 30(4):502–506.

Macfarlane PA, Looney MA. 2008. Walkway length determination for steady state walking in young and older adults. Res Q Exerc Sport. 79(2):261–267.

McGraw KO, Wong SP. 1996. Forming inferences about some intraclass correlation coefficients. Psychol Methods. 1(1):30–46.

Menz HB, Latt MD, Tiedemann A, Mun San Kwan M, Lord SR. 2004. Reliability of the GAITRite walkway system for the quantification of tempo-spatial parameters of gait in young and older people. Gait Posture. 20(1):20–25.

Senden R, Grimm B, Heyligers IC, Savelberg HH, Meijer K. 2009. Acceleration-based gait test for healthy subjects: reliability and reference data. Gait Posture. 30(2):192–196.

Stansfield BW, Hillman SJ, Hazlewood ME, Lawson AA, Mann AM, Loudon IR, Robb JE. 2001. Normalized speed, not age, characterizes ground reaction force patterns in 5-to 12-year-old children walking at self-selected speeds. J Pediatr Orthop. 21(3):395–402.

Steinwender G, Saraph V, Scheiber S, Zwick EB, Hackl K. 2000. Intrasubject repeatability of gait analysis data in normal and spastic children. Clin Biomech (Bristol, Avon). 15(2):134–139.

Sutherland D. 1997. The development of mature gait. J Orthop Res. 15(2):134–139.

Veilleux LN, Robert M, Ballaz L, Lemay M, Rauch F. 2011. Gait analysis using a force-measuring gangway: intrasession repeatability in healthy adults. J Musculoskelet Neuronal Interact. 11(1):27–33.

Webster KE, Wittwer JE, Fella JR. 2005. Validity of the GAITRite walkway system for the measurement of averaged and individual step parameters of gait. Gait Posture. 22(4):317–321.

White R, Agouris I, Selbie RD, Kirkpatrick M. 1999. The variability of force platform data in normal and cerebral palsy gait. Clin Biomech (Bristol, Avon). 14(3):185–192.