Accelerometry based assessment of gait parameters in children

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Abstract

The objective of this study was to examine if spatio-temporal gait parameters in healthy children can be determined from accelerations measured at the lower trunk as has been demonstrated in adults, previously. Twenty children aged 3–16 years, participated in a protocol that involved repeated walks of different distances in an indoor environment. During walking, accelerations were measured by three orthogonally mounted acceleration sensors in a small wireless device (DynaPort MiniMod) that was attached to the lower back. Based on an inverted pendulum approach, spatio-temporal gait parameters and walking distances were computed from the acceleration signals. Results were compared to video observations and known walking distances and durations. Steps were successfully detected in 99.6% of all observed steps (n = 5554). On average, walking distance was accurately estimated (100.6 ± 3.3%, range 93–106.7%). No correlation was found between the number of miscounted steps and the total number of steps or the age of the subject. It can be concluded that the use of an inverted pendulum model provides the possibility to estimate spatio-temporal gait parameters in children as well as in adults. The method allows an inexpensive and comfortable assessment of gait parameters in children, is applicable in controlled, indoor environments and could be tested for applicability under free living conditions.

Keywords: Accelerometry; Children; Inverted pendulum model; Steps; Walking distance

1. Introduction

The value of computerised gait analysis is generally accepted [1,2]. In particular, gait analysis in children helps clinicians to identify the underlying causes of abnormal gait, providing additional information to simple visual inspection of gait [3,4].

However, it is questionable, whether or not the data collected in a laboratory setting are representative of natural walking performance in daily life [5]. Clinical gait analysis assesses the walking pattern of a subject at a given time but does not provide information on subject performance during daily activities [1]. Recently, new measurement devices based on accelerometers, gyroscopes or goniometers have been developed for specific motion assessment tasks. These devices offer information on basic gait parameters and can be used when conventional gait analysis systems are not applicable due to limitations in space, time and funding [6]. The new systems focus on body fixed sensors to enable non-obtrusive gait assessment in non-laboratory settings [7–9], measuring acceleration of the trunk, thigh, shank or foot. These systems are relatively inexpensive, lab-independent and can be easily integrated into the clinical routine. Compared to a lab-based 3D motion analysis, they offer less data but focus on specific parameters, e.g. number of steps and walking distance.

Recent studies demonstrated that in healthy adult subjects spatio-temporal gait parameters can be estimated from trunk accelerations [10,11]. If applicable, the approach would allow simple, unobtrusive gait assessments in children. However, this approach assumes that lower trunk accelerations during
walking correspond to an inverted pendulum type of movement. It is not known, however, if this is the case in children and further evaluation is required. Previous research [12] has demonstrated that spatio-temporal gait parameters in children after the age of 3.5 years are similar to those in adults when corrected for differences in height. Thus, it can be expected that an accelerometry based method for gait assessment (e.g. refs. [10,11]) could be applied in children. The present study aimed at assessing whether essential spatio-temporal gait characteristics in children (including young ones) can be determined by accelerometry methods.

2. Methods

2.1. Subjects

Personal contacts were used to invite 20 children (11 boys and 9 girls) to participate in this study. For all children, written informed consent was obtained by the parents. All procedures of the study were in accordance with the Declaration of Helsinki by the World Medical Association. The subjects were between 3 and 16 years old (mean 9.0, standard deviation (S.D.) 4.2). The leg length, measured from the greater trochanter to the ground, ranged from 49.0 to 90.5 cm (mean 69.9 cm, S.D. 13.1 cm).

2.2. Equipment and data acquisition

Accelerations were measured by the DynaPort MiniMod, a small and lightweight measurement device (5.6 cm x 6.1 cm x 1.5 cm, 54 g, McRoberts BV, The Hague, The Netherlands). The MiniMod consists of three orthogonally mounted accelerometers and a local memory card for data storage. The unit is powered by two AAA 1.5 V batteries. Data are collected at 100 Hz and stored on the SD card. For this study, the accelerometer was firmly fixed to the skin over the lower lumbar spine, close to the sacrum, using double-sided adhesive tape to avoid movement artefacts. On average, the system was placed 79.5 cm (S.D. 14.2) above the ground.

2.3. Procedures

2.3.1. Condition 1

To validate the accelerometer’s ability to detect the number of steps, the children walked four times along a marked distance of 40 m on a flat floor in an indoor hospital environment with no obstacles nearby. After each track, the children paused for a few seconds before turning around, paused again and started the next track. The data collection of the device was terminated when the subjects had stopped at the end of the distance for the fourth time. Video recordings of the subjects were obtained to enable counting of the steps after the procedure and identification of causes of error during data analysis.

2.3.2. Condition 2

To validate the accelerometer’s ability to measure walking distance, the subjects walked a marked distance of 25 m (n = 1), 24 m (n = 16) or 16 m (n = 3) within the indoor environment used in condition 1. The walking time was taken with a digital stopwatch. The acceleration signals collected by the device were stored in a separate file.

The subjects always wore their own comfortable clothing and shoes. No recommendations were given with respect to gait style or walking speed and the subjects were free to choose their preferred speed in both conditions.

Fig. 1. The change of sign (○) of the positive peak in the acceleration signal in anterior-posterior direction is taken as the instant of foot contact.
2.4. Data analysis

After finishing conditions 1 and 2, the raw data for each child were downloaded to a PC for analysis. The acceleration signals were then sent to the manufacturer for blinded analysis to avoid a conflict of interest. For condition 1, performed for step detection, the manufacturer was blinded for the number of steps. For condition 2, carried out for the calculation of walking distance and walking time, the manufacturer was blinded for the number of steps, distance and walking time of the subjects. Only name, age and leg length were provided to the manufacturer for each condition.

For step detection, the onset of the support phase was determined from the forward acceleration signal. Along the line of progression, the basic pattern of pelvic acceleration corresponds to a pattern predicted by an inverted pendulum model [11,13]. After low-pass filtering the acceleration signal in the walking direction with a cut-off frequency equal to the step frequency (as determined by a Fourier transformation), the remaining signal shows a basic pattern of acceleration after mid-stance and deceleration after foot contact. The peak forward acceleration preceding the change of sign was taken as the point of initial foot contact (Fig. 1) [10,11].

For the calculation of walking distance, step length can be estimated based on the amplitude of vertical pelvic displacement and leg length using a simple inverted pendulum model of walking [10,11]. Changes in vertical position were calculated by double integration of the superior-inferior acceleration signal. After high-pass filtering to correct for integration drift (4-th order zero-lag Butterworth filter at 0.1 Hz), the amplitude of changes in vertical position was determined as the difference between the highest and lowest position during a step cycle. Then, subsequent step lengths were calculated as $\sqrt{2l^2 - h^2}$, with $l$ as the individual leg length and $h$ being the amplitude of vertical displacement during a step cycle. Walking distance was estimated by multiplying mean step length over a certain duration by the number of steps. As the use of an individual correction factor can improve the estimation of step length [10], the estimated distances were multiplied by an individual constant ($c$) that was calculated as the ratio between the known and the predicted distance from the first 40 m track in condition 1.

The results of the blinded analyses were sent back to the Movement Analysis Lab in Muenster via email for comparison with the video documentation. Spearman-rho was computed with SPSS 11.0 to evaluate correlations between the parameters.

3. Results

For the validation of step detection, each child completed the four walking tracks in condition 1, so that 80 data sets were available. On average, the children needed 273.7 steps (S.D. 45.1, range 207–377) for the distance of 160 m in condition 1, as counted from the video. Each incorrectly classified step from the software (under- or overestimated) was counted as an error. Thus, the accuracy of the software reached 99.6%. In nine cases, the software counted one step less, twice a loss of three steps occurred. Sixty out of 80 tracks of condition 1 were analysed precisely. In eight cases, the software overestimated one step, once three steps were overestimated (Fig. 2).

All children completed condition 2; therefore 20 data sets were available. The measured walking distance and duration were compared to the calculated ones. The algorithms calculated 100.6% of the actual distance resulting in a slight
Table 1  
Comparison between calculated values from acceleration and observation (video/stop watch)  
<table>
<thead>
<tr>
<th></th>
<th>Mean (%)</th>
<th>S.D. (%)</th>
<th>Range (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of steps</td>
<td>99.6</td>
<td>0.6</td>
<td>98.5–100</td>
</tr>
<tr>
<td>Walking distance</td>
<td>100.6</td>
<td>3.3</td>
<td>93–106.7</td>
</tr>
<tr>
<td>Walking time</td>
<td>101.3</td>
<td>2.8</td>
<td>94.5–106.6</td>
</tr>
<tr>
<td>Walking speed(^a)</td>
<td>100.4</td>
<td>4.2</td>
<td>89.8–110.2</td>
</tr>
</tbody>
</table>

\(^a\) Walking distance divided by the walking time (from acceleration) compared to the actual walking distance divided by the walking time (stop watch).

Table 2  
Spatio-temporal parameters and their relation to the age of the children  
<table>
<thead>
<tr>
<th></th>
<th>Mean (S.D.)</th>
<th>Range</th>
<th>(r_{age}^{a})</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of steps</td>
<td>273.7 (45.1)</td>
<td>207–377</td>
<td>0.92**</td>
</tr>
<tr>
<td>Step duration (s)</td>
<td>0.45 (0.04)</td>
<td>0.39–0.52</td>
<td>0.75**</td>
</tr>
<tr>
<td>Step length (cm)</td>
<td>60.0 (9.7)</td>
<td>42.4–77.3</td>
<td>0.92**</td>
</tr>
<tr>
<td>Velocity (m/s)</td>
<td>1.35 (0.18)</td>
<td>0.98–1.7</td>
<td>0.62**</td>
</tr>
<tr>
<td>Step length/(l_0)</td>
<td>86.4 (6.0)</td>
<td>77.8–100.3</td>
<td>0.37, n.s.</td>
</tr>
</tbody>
</table>

\(l_0 = \) leg length (m), measured from the trochanter major to the ground.  
\(^a\) Calculated Spearman-rho between gait parameter and age of the subjects.  
\(^{**}\) \(p < 0.01.\)

overestimation (Fig. 3). Further comparisons between values calculated from acceleration signals and observations and impressions of the walking behaviour that was observed in this study are given in Tables 1 and 2, respectively.

Computation of Spearman-rho revealed no significant correlation between the age of the subjects and the number of miscounted steps in condition 1 \((r = 0.3, p = 0.2)\) and no significant correlation between the number of miscounted steps and the number of steps each child had taken in condition 1 \((r = -0.4, p = 0.7)\).

The correction factor for the calculation of the walking distance in condition 2 averaged 1.3 ± 0.1 and showed no correlation to the age of the subjects.

4. Discussion

In this study, spatio-temporal gait characteristics in children were accurately determined using accelerometry of the lower back.

Regarding the step detection in condition 1, the method reached a high accuracy of 99.6%. The computed distance was accurately estimated at 100.6% of the actual distance the subjects walked in condition 2. There was variability of the correction factor, which suggests that an individual correction factor in the calculation of walking distance is required.

Based on the analysis of the video data, a number of errors in the detection algorithms could be clarified. The underestimation of three steps during track four of the youngest subject could be explained by a short shuffling before starting the fourth track followed by a short back-stepping: the subject took three small steps, paused for a few seconds, and restarted walking on demand. The three small steps were counted by the video observer but were not included in the analysis of the acceleration data, leading to the difference between observer and analyst.

The overestimation of three steps in one track of another subject occurred as a consequence of turning around without pausing after the second track. These steps were not included in our counting because they were not used for forward progression. Nevertheless, they were automatically detected by the software.

In three subjects, the error in the calculated walking distance was greater than ±5% of the real distance. Again, this happened in the case of the youngest children, which could be explained by non-compliance with the instructions. For subjects two and three, no obvious reasons for the discrepancies were identified.

The error in walking time calculated from the acceleration signals and the sample frequency averaged 1.3%, which is equivalent to 0.2 s. This difference is negligible taking the measurement inaccuracy of a manually operated stopwatch into account. However, in one case the overestimation was 1.4 s. The difference between stopwatch and calculated walking time could be explained by a significant slowdown of the subject to reach the marked distance exactly.

We are not aware of any previous reports using video observation for comparison or recruiting children as subjects. Therefore, it was not established whether the basic models for estimation of spatio-temporal gait parameters would be applicable and reliable in children. The high success rate for step detection, computation of distance and walking time in the present study confirmed the reliability of the use of the described pendulum model to estimate spatio-temporal gait parameters in children. This new approach offers an easy and time-saving assessment of general gait parameters in controlled indoor environments.

Further research is required to validate the applicability of this method during activities of daily living and to achieve acquisition of more complex gait parameters. The calculation of step length, duration of stance and swing phase and the variability between steps and strides in non-laboratory settings will be investigated in the future.

References