Measuring distance walked and step count in children with cerebral palsy: An evaluation of two portable activity monitors

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1. Introduction

Cerebral palsy (CP) is caused by damage to the motor control areas of the immature brain [1], and affects 1.5–2.5 children per 1000 births [2]. Many affected children have progressive musculoskeletal pathology, including spasticity, muscle weakness and shortening, and bone deformity, leading to impaired function and limitations in mobility [3,4]. Treatment options for children with CP include physiotherapy, orthoses, pharmacological interventions, orthopaedic and neurosurgical interventions [5]. One of the treatment goals is to improve functional independence in daily living.

Functioning in the home and community is an area of major interest in rehabilitation medicine. The International Classification of Functioning, Disability and Health (ICF) suggests describing body structures and functions, activities and participation in the context of environmental and personal factors [6]. A well-equipped gait laboratory can provide comprehensive gait assessment and monitor treatment outcomes in a laboratory setting [7], but how these measures translate to functioning in the home and community [8] has yet to be explored using objective measures [9]. Continuous, objective measurement at home, school and in the wider community, will give a more accurate indication of limitations and restrictions experienced by children with CP.

As an aim of treatment for children with CP is to increase step length, children may use fewer steps to walk a given distance in which case fewer steps may indicate improvement. Children may also increase walking distance because it is easier in which case more steps may indicate improvement. These possibilities make data interpretation difficult. The actual distance walked appears to be a more appropriate measure to reflect treatment outcomes.

Some pedometers [10,11] and the uptimer [12,13] have been used to measure the step count and time spent upright, these measures cannot fully reflect treatment outcomes in children with CP. As an aim of treatment for children with CP is to increase step length, children may use fewer steps to walk a given distance in which case fewer steps may indicate improvement. Children may also increase walking distance because it is easier in which case more steps may indicate improvement. These possibilities make data interpretation difficult. The actual distance walked appears to be a more appropriate measure to reflect treatment outcomes.

Some pedometers and accelerometers have been used to measure walking distance in adults [14,15] and typically developing children [9,16,17]. However, the feasibility of these activity monitors for children with CP has not been investigated. An easy-to-use gait assessment tool that provides accurate measurement for children with CP in daily living will help doctors and physiotherapists to evaluate the outcome of different surgeries and to tailor post-operative therapies more effectively. The aim of this preliminary study was to evaluate commercially available systems for measurement of the distance walked and step count in...
typically developing children and children with CP. A review of the commercial literature suggested two that appeared to offer the best potential to do this; the AMP 331 (AMP) and the DynaPort Minimod (Minimod).

2. Methods

2.1. Participants

A total of 40 children aged 4–16 years participated in this study. Twenty (13 boys; age 10.5 ± 3.0 years; height 140 ± 17 cm; weight 40 ± 17 kg) had diplegic CP of gross motor function classification system (GMFCS) levels I to III [18] and 20 typically developing children (10 boys; age 10.3 ± 2.8 years; height 144 ± 16 cm; weight 37 ± 12 kg) who have not experienced any significant musculoskeletal disorders or walking difficulties. Participants were recruited through the referrals to the Royal Children's Hospital and Hugh Williamson Gait Laboratory and the invitation to friends and families of staff members. Written informed consents were obtained from the parents or legal guardian which had prior approval from the Hospital's Ethics in Human Research Committee. The Functional Mobility Scale (FMS) [19] was administered in children with CP and use of orthoses recorded.

2.2. Activity monitor

Two small and lightweight activity monitors, AMP (71 × 24 × 37 mm, 50 g, 1600 Hz) and Minimod (62 × 41 × 18 mm, 53 g, 100 Hz) were used in this study. The AMP consists of a combination of inertial sensors, and was worn in a sleeve attached to the right lower leg just above the ankle. The Minimod consists of three orthogonally mounted accelerometers, and was worn on the lower back (just between and above the posterior superior iliac spines).

The Minimod was calibrated to two 10-m and two 20-m linear walks over level ground according to the manufacturer's instructions before starting the protocol. After calibration measurement, the Minimod remained turned on and continuously recorded all walks of the protocol. No calibration measurement was needed for the AMP. After inputting participant information (date of birth, gender, height and weight) in the AMP, each walk of the protocol was recorded by manually turning on and off the device before and after each activity.

2.3. Protocol

The protocol included three walking conditions, continuous walking (condition 1), structured activity lap walking (condition 2) and stair climbing (condition 3). If a child was unable to walk any of the required distances or climb stairs, these walking conditions were not conducted. The reference data on the distance walked was validated by a calibrated measuring wheel, and the reference data on the step count was obtained from simultaneous video recordings.

2.3.1. Condition 1

During continuous walking, participants walked a marked linear distance of 5, 10, 20 and 45 m within an indoor environment at their preferred walking speed using their everyday walking aids and/or orthoses. Each of these walks was repeated to give a total of eight walks for each participant. Participants also walked a distance of 100 m once by completing five laps of a 20 m oval track.

2.3.2. Condition 2

During structured activity lap walking, the child started from sitting, and walked between four separate points of interest alternating between chairs and tables (Fig. 1). The distance between each point of interest was known and varied between 2 and 6 m. The child visited each point of interest in sequence, and completed a simple task before walking to the next point. The child continuously walked around the lap for approximately 4 min. This condition was aimed at determining accuracy of the activity monitor during short bouts of low intensity activity.

2.3.3. Condition 3

During stair climbing, the child ascended and descended a flight of 16 steps (17.7 cm height, 26.6 cm depth) while accompanied by two researchers. The calculated length (5.1 m) of the slope of 16 steps was used as the reference distance.

2.4. Data analysis

Independent t-tests were computed with SPSS 16.0 to compare the difference in age, height and weight between two groups of children. Statistical significance was set at the P < 0.05. The method of the Bland and Altman plot [20] was modified to examine the accuracy of both activity monitors for the measures of distance walked and step count. This involved graphing the difference between the monitor's output and the reference data under consideration against the reference data. If there is no systematic variation with the measurement pairs, the mean difference should be small and centred around zero. The 95% limits of agreement (mean difference ± 2 standard deviations) were also calculated to indicate random errors.

3. Results

There were no statistically significant differences noted in age (t = 0.16, 95% CI = 1.7–2.0, P = 0.9), height (t = −0.78, 95% CI = 14.6–6.5, P = 0.4) or weight (t = 0.76, 95% CI = 5.9–13.0, P = 0.5) between the two groups of children. Table 1 summarizes the characteristics of children with CP. A procedural oversight led to Minimod data from one typically developing child and three children with CP not being processed along with the rest of the data, and this data was not included in the analysis. Data for some other walks was not included in the analysis. Data for some other walks was

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Number (percentage)</th>
</tr>
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<tbody>
<tr>
<td>GMFCS Level I</td>
<td>5 (25%)</td>
</tr>
<tr>
<td>GMFCS Level II</td>
<td>12 (60%)</td>
</tr>
<tr>
<td>GMFCS Level III</td>
<td>3 (15%)</td>
</tr>
<tr>
<td>Does the patient usually wear their AFO/s when walking?</td>
<td>Yes 11 (55%)</td>
</tr>
<tr>
<td>On which leg does the patient have an AFO, if any</td>
<td>Left 1 (5%)</td>
</tr>
<tr>
<td>What type of AFO is worn, if any</td>
<td>Hinged left 1 (5%)</td>
</tr>
</tbody>
</table>

5 m 50 m 500 m

FMS score

| Use wheelchair | 0 | 0 | 4 (20%) |
| Use crutches | 0 | 2 (10%) | 2 (10%) |
| Use sticks | 3 (15%) | 4 (20%) | 3 (15%) |
| Independent on level surfaces | 13 (65%) | 10 (50%) | 8 (40%) |
| Independent on all surfaces | 4 (20%) | 4 (20%) | 3 (15%) |
Fig. 2. Modified Bland and Altman plots for the measure of distance walked during continuous walking (left) and structured activity lap walking (right) in both groups of children.
Fig. 3. Modified Bland and Altman plots for the measure of step count during continuous walking (left) and structured activity lap walking (right) in both groups of children.
Table 2
Mean differences in actual and measured distance walked and step count during stair climbing.

<table>
<thead>
<tr>
<th>Measurement/group</th>
<th>Stair descent</th>
<th>Stair ascent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AMP</td>
<td>Minimod</td>
</tr>
<tr>
<td>Rate of activity detection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Children with CP</td>
<td>85%</td>
<td>19%</td>
</tr>
<tr>
<td>Typically developing children</td>
<td>100%</td>
<td>84%</td>
</tr>
<tr>
<td>Distance (m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Children with CP</td>
<td>−1.3 ± 2.5</td>
<td>8.9 ± 2.5</td>
</tr>
<tr>
<td>Typically developing children</td>
<td>0.7 ± 1.0</td>
<td>7.5 ± 2.8</td>
</tr>
<tr>
<td>Step count (step)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Children with CP</td>
<td>−10.1 ± 9.5</td>
<td>−1.0 ± 1.0</td>
</tr>
<tr>
<td>Typically developing children</td>
<td>−1.3 ± 1.6</td>
<td>−1.8 ± 2.5</td>
</tr>
</tbody>
</table>

Values are mean ± standard deviation for mean difference.

recorded as ‘inactive’ in the AMP or was not detected by the Minimod. Trials missing for this reason are listed in the sections below.

3.1. Condition 1

The AMP did not detect walking for two (5%) 5 m walks, one (3%) 10 m walk, and three (8%) 45 m walks in children with CP and for three (8%) 5 m walks in typically developing children. The Minimod did not detect walking for 12 (10%) walks in typically developing children and 3 (3%) walks in children with CP.

The Minimod demonstrated excellent accuracy for measurement of the distance walked (Fig. 2) and step count (Fig. 3) for continuous walking in both groups of children. On the other hand, the AMP underestimated distance walked and step count in both groups of children and had greater random errors in assessing children with CP. As the child increased the walked distance to 100 m, both devices became less accurate and showed greater underestimation of actual distance walked and step count.

3.2. Condition 2

Walking during the structured activity laps was not identified by the AMP in one child (5%) with CP and by the Minimod data in one child (6%) with CP. Although the bias difference in detecting the distance walked was closer to zero for both groups with the Minimod compared to the AMP (Fig. 2), the Minimod had greater random error of measurement as evidenced by wider limits of agreement. In contrast to the result during continuous walking, the AMP demonstrated higher accuracy for measurement of step count than the Minimod in both groups of children for this particular condition (Fig. 3).

3.3. Condition 3

Thirty-nine children completed the protocol of stair climbing (fatigue prevented this for one child with CP). The Minimod did not identify stair descent in 13 (81%) children with CP and stair ascent in 10 (63%) children with CP. The problem of missing data with the Minimod also occurred in three (16%) typically developing children. In contrast, there was less missing data with the AMP. The AMP recorded data for stair climbing in all typically developing children and 17 (85%) children with CP.

The AMP underestimated the distance walked in children with CP (Table 2) whereas the Minimod overestimated. The AMP showed higher accuracy in measurement of the distance walked during stair climbing compared to the Minimod. For measurement of step count during stair climbing, the Minimod appeared to be more accurate for both groups of children. The AMP showed a similar level of accuracy as the Minimod in assessing step count in typically developing children, however step count was greatly underestimated during both stair ascent and descent in children with CP. In presenting these results of stair climbing it is important to note that the Minimod results were based on the smaller number of children where activity was appropriately detected.

4. Discussion

Measurement of distance walked using an accurate and easy-to-use activity monitor is important to reflect functioning in the home and community and improvement in the physical activity level following intervention in children with CP [21]. To the best of our knowledge, no study has evaluated activity monitors for measurement of the distance walked in children with CP during different walking conditions.

Neither monitor recorded all instances of walking 5, 10 and 45 nor of structured laps nor of stair ascent and descent. Detection of activities was less good in children with cerebral palsy but not perfect in typically developing children. Failure to detect such activities clearly limits the applicability of such devices regardless of the accuracy of measurements when activity is detected.

Results of this preliminary study showed that the Minimod provided more accurate measurement of the distance walked and step count during continuous walking in both groups of children, however the Minimod performed less well in measuring the walk around a structured activity lap and during stair climbing in children with CP.

Several factors can influence the accuracy of the activity monitor [10,15,22], such as placement of the device, calibration measurement, mode of physical activity and physical characteristics of the person. Most children with CP (55%) wore at least one ankle foot orthosis during data collection in this study. Although the ankle sleeve that held the AMP was tightly strapped around the orthoses in those children, the investigator observed that the ankle sleeve sometimes slipped out of the original alignment during the walks. The rotation of the AMP around the ankle foot orthoses and away from the sagittal plane may have contributed to greater underestimation in the distance walked for children with CP during continuous walking. In contrast, directly taping the Minimod to the skin of the sacrum reduced displacement of the device and this probably minimised measurement error. The need to calibrate the Minimod for known walked distance on level ground might be expected to improve accuracy of the device for measurement of distance walked under the similar walking condition, and may have led to excellent accuracy of the Minimod during continuous walking.

Both devices appear to underestimate the 100 m continuous walking. On reviewing the video recording, some children in both
groups were found to walk towards the inside of the lane of the oval track. Since the reference distance for the track was measured along the midline, the actual distance walked by those children would have been be shorter than 100 m. Measurement error may thus have been overestimated for both devices during this task.

Although the placement of the Minimod has the advantage of reducing measurement error associated with displacement of the device, placing the device closer to the centre of mass of the body minimised the detectable motion. As stair climbing is a slow activity in any children with CP, small movement of the sacrum and slow walking possibly affected the amount of acceleration generated to trigger the Minimod to record the movement in children with CP during stair descent and ascent. These possibly led to more missing data and increased measurement error for the distance walked in the Minimod.

The result of step count during stair climbing should be interpreted with caution. The larger bias difference for the AMP in children with CP was possibly related to data calculation based on a larger number of children. It may thus be unfair to conclude that the AMP is less accurate when in fact the Minimod failed to measure the step count at all. Greater vertical movement of the foot and ankle during stair climbing may have allowed the AMP to more successfully detect the activity of stair climbing and provide more ‘accurate’ measurement of the distance walked and step count.

It was unexpected that the Minimod performed less well in typically developing children during the structured activity lap walking. Different algorithms used by the manufacturers to calculate the distance walked and step count may explain this finding. According to the Minimod manufacturer, the device is limited in detecting the activity of stair climbing and provide more ‘accurate’ measurement of the distance walked and step count.

Acknowledgements

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Conflict of interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

References


