Short communication

Assessment of spatio-temporal gait parameters using inertial measurement units in neurological populations

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Laboratory based gait analysis techniques are expensive, time consuming and require technical expertise. Inertial measurement units can directly measure temporal parameters and in combination with gait models may provide a solution to obtain spatial gait measurements within daily clinical assessments. However it is not known if a model and standard correction factor determined by Zijlstra and Hof \cite{8} to estimate step and stride length parameters in typically developed adults (TDA) can be accurately used in neurologically impaired gait.

This research estimated the stride length over two 10 m walks at self selected walking speed in people with neurological conditions, using a previously established model and correction factor for TDA. The relation of the correction factor to walking speed was explored.

We recruited TDA (n = 10) and participants with Parkinson’s disease (PD; n = 24), muscular dystrophy (MD; n = 13), motor neuron disease (MND; n = 7) and stroke survivors (n = 18) for the study who twice walked 10 m at a self-selected pace. Stride length correction factors, for TDA (1.25 ± 0.01), PD (1.25 ± 0.03), and MD (1.21 ± 0.08) (p = 0.833 and p = 0.242) were the same as previously reported in TDA \cite{8}. Correction factors for stroke (1.17 ± 0.42) and MND (1.10 ± 0.08) were different (p < 0.01 and p = 0.028 respectively). However there was a high level of variability for correction factors within groups, which did not relate to walking speed.

Our findings support that correction factors should be determined for each individual to estimate average step/stride length in patients suffering from a neurological condition.

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1. Introduction

Neurological populations such as Parkinson’s disease (PD), muscular dystrophy (MD), motor neuron disease (MND) and stroke survivors make up about three million individuals in the UK \cite{1}. Maintaining mobility is a key concern for people with these conditions \cite{2}. Objective measurement of mobility and gait can be a critical marker for clinicians to monitor disease progression \cite{3}. Not all clinicians have access to a gait laboratory but inertial measurement units (IMU), can be used during standard clinical tests such as the 10 m or 6 min walking tests \cite{4}, to provide information on underlying gait performance which can be used to direct rehabilitation \cite{2}. Centre of mass (CoM) motion during walking can be measured by IMU, which combine gyroscope, accelerometer and magnetometer data to provide accurate vertical acceleration, speed and position measurements in the global frame \cite{5}. This data can then be used to determine accurate temporal gait parameters (i.e. step time), however spatial parameters (i.e. step length) need to be estimated utilizing mathematical equations such as

\begin{equation}
\text{d} = \gamma(2\sqrt{2lh - h^2})
\end{equation}

where (d) is the step length, (h) is the CoM vertical excursion, (l) is the leg length and (\gamma) is the correction factor \cite{6,7}. This model is suitable for routine clinical use, because it requires only one additional measurement (leg length). Previous research \cite{8} has shown that in typically developed adults (TDA) the model underestimates step length by 25\%, because the anterior–posterior movement during double stance is not included \cite{6}. Therefore, a correction factor of 1.25 is required to estimate step length with the model in TDA \cite{8}. However, it is unclear if the model accurately estimates the step length in populations where gait is affected by a neurological condition \cite{9}.

Considering the utility of measuring gait using IMUs in individuals with neurological conditions, the correction factor should now be explored. Previous investigations have shown that
walking speed, relates to the time in double stance [2]. We propose that in neurological populations the correction factor may be different in people with altered gait patterns and that there will be a negative correlation between walking speed and the required correction factor.

This study sets out to determine the correction factor required for people with different neurological conditions.

2. Method

We recruited TDA and participants with Parkinson’s disease (PD), muscular dystrophy (MD), motor neuron disease (MND) and stroke survivors (n = 18) for the study. Participants were included who were able to walk 10 m independently. The study was conducted in accordance with the Declaration of Helsinki and approved by a local National Health Services ethics committee.

To determine functioning in daily living, the lower limb section of the Fugl-Meyer [10] (FM) was conducted for stroke survivors and the Barthel Index [4] [8I] for the remaining conditions. All participants were asked to perform a standard clinical 10 m walk test twice at self-selected walking speed. A commercially available IMU (MTx, Xsens, The Netherlands) was attached over the skin of the 4th lumbar vertebra. A lower spine marker has been shown to be a valid indicator of CoM displacement in healthy and pathological gait [11,12]. The time taken to walk 10 m from a standing start to a standing finish, as defined as the start and finish of forward movement of the CoM, was manually recorded with a stopwatch and also determined from IMU Z acceleration data.

Participant walking speed ($V_w$) was calculated by dividing walking distance by the time taken to cover the 10-m as measured with a stopwatch. Tri-axial accelerometer, gyroscope and magnetometer signals from the IMU, were processed with quaternion rotation matrices and integrated to yield vertical excursion of the CoM in the global frame (see for further detail [5]). Step time was taken as the time interval between trough-to-though CoM excursions during one gait cycle. Step length was calculated $[6,7]$ from Eq. (1) with the initial correction factor set at 1.25 for all groups [8]. Predicted walking speed ($V_p$) was derived by dividing average step length by average step time from each walk in its entirety. The correction factor for each participant was optimised by manipulating it until $V_p$ matched $V_w$. An average group correction factor for each patient group was calculated from the individual correction factors.

A paired sample t-test and intra class correlation coefficient (ICC3.1) was employed to expose IMU to stopwatch timing with adequate test–retest reliability defined as ICC $\geq$ 0.75. [13] Descriptive statistics were conducted on the spatio-temporal gait parameters for both 10 m walks. Group correction factors from each patient group were submitted to a one-way ANOVA with significance set at 0.05. Tukey’s test was used for post-hoc analysis. Additionally, Spearman’s rank correlation coefficient was calculated to evaluate the relationship between correction factor and walking speed.

3. Results

Descriptive measurements, group correction factors and derived data from the inverted pendulum model are given in Table 1. The stopwatch time (9.5 $\pm$ 1.9 s) agreed with the time derived from IMU acceleration signals (9.6 $\pm$ 2.0 s), no significant difference was found ($p = 0.28$) with a high significant correlation (ICC = 0.996, $p < 0.001$).

A one-way ANOVA showed a significant difference between groups ($F = 22.21$, $p < 0.01$) for the group correction factors. A Tukey post-hoc analysis ($p = 0.05$) showed no significant difference between TDA and PD ($p = 0.998$) or MD ($p = 0.907$). Stroke and MND group correction factors were significantly different compared to those for TDA ($p < 0.001$ and $p = 0.028$ respectively).

Table 1
Mean and standard deviation values of outcome measures for the typical developed adults (TDA), Parkinson’s disease (PD), muscular dystrophy (MD), stroke survivors (stroke) and motor neuron disease (MND) groups. Median and range values are given for disability level measured by the Fugl-Meyer (FM) for stroke survivors and Barthel’s Index (BI) for the other patient groups. Group adjusted correction factors are displayed as $\gamma$ for each individual group.

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>n</th>
<th>Sex</th>
<th>BI or FM scores</th>
<th>Age (years)</th>
<th>Diagnosis</th>
<th>n</th>
<th>Sex</th>
<th>BI or FM scores</th>
<th>Age (years)</th>
<th>Step time (ms)</th>
<th>Adjusted</th>
<th>Stride length (m)</th>
<th>Speed ($V_a$) (ms$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDA</td>
<td>10</td>
<td>M = 6</td>
<td></td>
<td>66.4 ± 4.4</td>
<td>487 ± 22</td>
<td>1.25 ± 0.01</td>
<td>1.37 ± 0.08</td>
<td>1.36 ± 0.13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PD</td>
<td>29</td>
<td>M = 25</td>
<td>20 (16–20)</td>
<td>63.4 ± 7.7</td>
<td>551 ± 47</td>
<td>1.25 ± 0.03</td>
<td>1.21 ± 0.23</td>
<td>1.08 ± 0.22</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MD</td>
<td>13</td>
<td>M = 4</td>
<td>20 (16–20)</td>
<td>44.0 ± 12.3</td>
<td>627 ± 111</td>
<td>1.21 ± 0.08</td>
<td>1.22 ± 0.34</td>
<td>1.02 ± 0.41</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stroke</td>
<td>18</td>
<td>M = 14</td>
<td>23 (15–34)</td>
<td>68.7 ± 7.9</td>
<td>598 ± 123</td>
<td>1.47 ± 0.21</td>
<td>1.17 ± 0.42</td>
<td>0.81 ± 0.47</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>MND</td>
<td>7</td>
<td>M = 4</td>
<td>18 (16–19)</td>
<td>63.4 ± 6.9</td>
<td>862 ± 439</td>
<td>1.10 ± 0.08</td>
<td>1.16 ± 0.21</td>
<td>0.82 ± 0.41</td>
<td></td>
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</tr>
</tbody>
</table>

Fig. 1. Relationship between the individual correction factors and walking speed for people with (A) Parkinson’s disease, (B) muscular dystrophy, (C) motor neuron disease and (D) stroke survivors. The horizontal dotted line represents the correction factor of 1.25 for typically developed adults as proposed by Zijlstra and Hof [8].
No strong relationship was found between correction factors and walking speed for PD ($r^2 < 0.01$), MD ($r^2 = 0.40$), MND ($r^2 = 0.45$) or stroke survivors ($r^2 = 0.51$; Fig. 1), or between correction factors and $V_a$ for TDA (rho = 0.38; p = 0.10), PD (rho = –0.03; p = 0.89), MD (rho = 0.03; p = 0.93), stroke survivors (rho = 0.57; p = 0.018) or MND (rho = 0.643; p = 0.12).

4. Discussion

We found a correction factor of 1.25 for TDA as previously reported [8], which was similar to that of the PD and MD groups. However, in stroke survivors and people with MND an alternative correction factor value was required in order to accurately model gait. We found that none of our groups showed a relationship between walking speed and the size of the calculated correction factor. This suggests that there is a dissociation between walking speed and the required correction factor. We included participants with a range of disability thus heterogeneity existed within groups. Variability in the adjusted correction factor indicates that a group correction factors for specific neurological conditions may therefore not be appropriate.

Stopwatch measurements were used for the timing of the 10 m walk. This is standard practice within clinical environments in order to describe walking speed [14]. It has been reported before by Youdas et al. [15] that measurements performed by a stopwatch contribute to 1% total variance within gait measurements in persons with gait impairments. The comparison between IMU and stopwatch timing did not show any significant difference over the 10 m walk and as such was considered accurate for this application.

The current results are based on relatively small groups; therefore to generalise the results similar research needs to be performed in a wider population for each condition. Whilst our findings demonstrate that group correction factors are inadvisable, individual correction factors may be used to calculate average step/stride length to assess patients suffering from a neurological condition. In addition, as the stability of correction factors over time has not yet been established in these patient groups a correction factor should be determined for each use.

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Conflict of interest statement

The authors have a potential for a conflict on interest. PE, HD, JC and KH are inventors on a patent application for techniques of IMU analysis.

References