Effect of gait cycle selection on EMG analysis during walking in adults and children with gait pathology

A. De Stefano a,∗, J.H. Burridge b, V.T. Yule c, R. Allen a

a Institute of Sound and Vibration Research, University of Southampton Highfield, Southampton, SO17 1BJ, UK.
b Level E, Centre Block, Southampton General Hospital, Southampton, SO16 6YD, UK.
c School of Health Professions & Rehabilitation Sciences, University of Southampton Highfield, Southampton, SO17 1BJ, UK.

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Abstract

This paper presents the results of a project to evaluate different methods of gait cycle selection on the analysis of electromyography recorded during gait. Electromyography (EMG) describes the electrical activity associated with the muscle and is often interpreted in gait analysis using a simultaneously obtained signal to identify phases of the gait cycle. Phase transitions are often selected manually from reference signals derived from additional instrumentation, such as pressure platforms, footswitches and video cameras. We propose two methods (automatic and semi-automatic) as an alternative to the more traditional manual selection, and analyse how the gait cycle selection affects the EMG analysis. To quantify the differences between the gait cycles obtained using each method and to classify each cycle, three indices have been introduced. The effect of the gait cycle selection has been evaluated with respect to the EMG step profiles and temporal gait descriptors. An asymptomatic adult, an asymptomatic child and two children with cerebral palsy were examined using telemetric EMG devices and pressure footswitches. The results obtained showed that the method of gait cycle selection did not have a major influence for the adult, but it altered considerably the analysis in the case of the children with cerebral palsy.

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1. Introduction

Electromyography (EMG) has been widely used as a tool to understand and distinguish between normal and pathological gait in adults and in children. The timing and intensity of the EMG during a phase or the entire gait cycle can tell us much about neurological control and muscle weakness [1].

Temporal and spatial parameters such as stride length, cadence [2–5], and the timing of stance and swing periods [5–11] are commonly recorded along with EMG to describe, classify or identify normal and pathological gait. In the clinical environment, gait cycle determination is often performed by manually selecting the key points of foot contact and toe off at the beginning and end of the phases. To assist in this selection, pressure transducers applied under the feet of the subject are commonly used. Such methods are time consuming and may be unreliable particularly in young children and those with and pathological gait where a heel–toe contact pattern is not present. They are dependent on the subjective judgement of the operator and even very experienced users may lack repeatability. Automatic or semi-automatic methods to select the gait cycle are desirable because they could speed up the procedure, be more repeatable and permit the extraction of user independent parameters characterising the gait. Ghoussayni et al. [12] compared three techniques using ground pressure platform, visual inspection and velocity of reflective markers. Wall and Crosbie [13] instead compared videotape film marking, pressure plates and footswitches. The overall Centre of pressure [14] and kinematic data [15–17] extracted with camera motion analysis systems have also been employed to determine the gait cycle. A problem with these methods is that it is necessary to ensure a means of synchronising the video system with the EMG acquisition system.

The majority of the work presented in the literature concentrates on the determination of gait cycle events for asymptomatic adults and little attention has been given to normal children and those with pathological gait. These are often the most difficult subjects to analyse because...
even in normal children, below the age of 3 years, walking patterns have not yet matured and differ from those of normal adults [18]. EMG differences are primarily evident in children of 12–18 months and also in children with pathology where large variations in the gait pattern are evident [4].

We wished to examine the difficulties and limitations in using automatic and semi-automatic methods to select the gait cycle in normal and pathological gait. We also compared the errors measured in the present study with those measured previously [12,14] for asymptomatic adults.

2. Methods

Four participants were invited to take part in the investigation. One normal adult aged 31 years and one normal child aged 13 months were recruited from the staff and relatives of the University of Southampton. A further two children with cerebral palsy (both aged 2 years) were recruited by a local paediatrician. The Southampton and South West Hants Local Research Ethics Committee gave ethical approval for this investigation. Assessments were conducted in one session where, following skin preparation with an alcohol wipe, 3M™ Red Dot™ Ag/AgCl surface electrodes were positioned on the tibialis anterior (TA) and lateral gastrocnemius (LG) muscles of both legs in accordance with the recommendations of SENIAM [20]. In addition two auto-calibrating force sensitive resistors (FSRs) were placed on the plantar surface of the shoes in the toe and heel positions. The FSR input circuitry auto calibrates so there is no fixed force threshold for detecting footfall. The absolute maximum sensitivity is set by the hysteresis in the system and how quickly the force on the switch is changed. The system is less sensitive to more slowly changing forces, even if they are big changes. Subjects were required to walk along a 10 m walkway at a self-selected speed during which time EMG data were recorded.

EMG data and FSRs signals were collected using a CBS5000 telemetric system (Custom Biotelemetry Solutions, UK) which allowed the subjects to walk free of cables. A sensor module located over the bipolar electrodes amplified the signals before transmitting them using ISM UHF frequencies. Data were recorded using a Biopac MP100 system and Acknowledge software (Biopac Systems Inc., CA, USA). The signals were sampled at a rate of 2000 Hz, processed by a 16-bit A/D converter, band pass filtered (20–500 Hz) and full wave rectified.

2.1. Footswitches signal processing

The signals provided from the footswitches were used to determine the stance and swing phases during the gait cycle. Three different methods to determine the phases were used and their performances with respect to the same dataset are described by Figs. 1 and 2 (healthy adult).
2.1. Method 1

In the first automatic method (Fig. 1), the pressure switch signals are treated using a variable and adaptive threshold generated using the local signal maximum and minimum values. This approach generates two binary signals that are combined to define the gait cycle. A median filter can be applied to reduce false steps due to signal spikes generated with the switches. This method does not require much intervention or knowledge from the user and in this research has been implemented in the hardware acquisition device.

2.1.2. Method 2

In the second, semi-automatic, method (Fig. 2) the two signals from the pressure footswitches were normalised, rectified and smoothed with a moving average filter (100 points window). Normalisation facilitates the thresholding while rectification and smoothing are aimed at reducing the high frequency components in the signal, which can be considered as artefacts and distortion. Two threshold levels were then selected and applied to extract two binary signals from the two FSRs signals, indicating the conditions on and off for each pressure switch. To reject spikes, median filtering (100 points window) was used on each of these signals. The two binary signals were finally combined to extract a single binary signal describing the gait cycle (0 = stance; 1 = swing), this signal was median filtered again (200 points window) to reject other artefacts.

2.1.3. Method 3

The third (manual) method (Fig. 3) used the pressure switch signals as a reference for manually selecting the gait cycle sequence by visual inspection. These signals were normalised, rectified and smoothed with a moving average filter (100 points window) to facilitate selection. The user can select the gait sequence by selecting the start and end events of the stance phase corresponding to the heel down and toe up points.

To evaluate the differences between the gait cycles obtained with the three methods, three indices were defined. The first and the second indices are

\[ \Delta 1 = \frac{\sum_{i=1}^{N_1} |t_{1i} - t_{2i}| + \sum_{j=1}^{N_2} |t_{3j} - t_{4j}|}{N_1 + N_2} \]
\[
\Delta_2 = \frac{\sum_{i=1}^{N_{B1}} \text{abs}(t_{ik}^1 - t_{ik}^3) + \sum_{j=1}^{N_{B2}} \text{abs}(t_{jk}^1 - t_{jk}^3)}{N_{B1} + N_{B2}}
\]

where \(N_{A1}\) is the number of toe off events common for methods 1 and 3, \(N_{B1}\) the number of heel down events common for methods 2 and 3, \(N_{A2}\) the number of heel down events common for methods 2 and 3, \(t_{ik}\) the instants of toe off events using the \(k\)th (\(k = 1, 2, 3\)) method, \(t_{jk}\) is the instants of heel down events using the \(k\)th (\(k = 1, 2, 3\)) method.

These indices describe the similarity of the gait cycles obtained with automatic and semi-automatic methods with respect to the cycle obtained manually. They can be interpreted as the average absolute timing error (in ms). Large values of \(\Delta_1\) (or \(\Delta_2\)) indicate that the walking cycle obtained using the automatic (or semi-automatic) method has phase durations different from the cycle obtained using the manual method.

\[
\Delta_3 = \frac{\Delta_1 + \Delta_2}{2}
\]

The third index is the average between the two errors and provides a general measure of the reliability of the walking cycle describing the similarity of the results obtained using the three methods. The index \(\Delta_3\) is used to classify the acquisitions in to three groups. Small values (less than 100 ms) for this index indicate that the method used for the identification of the gait cycle has little influence on the results because the durations of swing and stance phases are similar.

### 2.2. EMG signal processing

The techniques to extract amplitude information from the raw EMG are, in general, based on the application of non-linear functions (using single or double threshold levels) followed by low pass filtering [21–23]. The major problem with these techniques is the subjectivity in the selection of the non-linear function (threshold levels) and of the filter characteristics. In the present study, the DC components were suppressed and the signals rectified and normalised with respect to their mean value. The two EMG amplitude envelopes were identified by applying a percentile filter [24].

When analysing EMG during walking it is useful to observe its profile averaged over a number of different steps (EMG step profile). The EMG signal has similar profiles over each individual step, but the steps have different time durations. Therefore, before averaging, a re-sampling operation is required to unify the length of the signals related to each step. The computation of a step-averaged EMG time profile can be obtained using the mean step duration [1,7,25]. In this study, the re-sampling method was based on the mean step duration and used an anti-aliasing filter compensating for the delays introduced by re-sampling. A moving average filter (100 points windows) was then applied to smooth...
the profiles. Using averaged profiles, the time duration of the averaged steps for all the acquisitions, and the duration of the swing phase as a percentage of the gait cycle, were calculated. Fig. 3 shows examples of EMG step profiles for TA and LG muscles. The dotted lines represent the standard deviation over the four gait cycles.

3. Results and discussion

Table 1 shows the subdivision of the data on the basis of the gait cycles obtained with the three methods. Group 1 (\(\Delta t < 100\) ms) includes the data where the gait cycles obtained with the three different methods are almost identical. Table 2 shows the effects of the gait cycle differences in terms of both stride and swing phase durations. Table 2 (data 1–5) shows that for the adult the three methods produce very similar results in terms of stride and swing phase durations.

4. Discussion

Electromyography is widely used in gait analysis to describe the muscular activity of the lower limbs. To analyse such data it is important to examine EMG concurrently with a signal describing the key events of the gait cycle. These events can be identified using different techniques and instruments with different grades of success depending on the type and condition of the subjects. Manual selection of the events by visual inspection of the signals is often used, although ideally automatic selection without any intervention from the operator is desirable. This study reported the effect of three methods of gait cycle selection on EMG analysis for a normal adult, one child and two children with cerebral palsy. The third group was compared with respect to their influence on the distribution of activity and the timing of key events in the signal. For asymptomatic adults, the average absolute timing errors measured (between 33 ms and 109 ms) are comparable with the sum of the heel contact and toe off average errors obtained in some recent works such as [12] (3–10 frames at 60 Hz) and slightly superior to the performances obtained in other works such as [14] (three frames at 120 Hz) Table 1, row 5. When the gait cycles obtained using the three methods are similar, the first method is preferable because it automatically provides a reliable gait cycle with no input from the operator. Table 1 shows this is the case in all the acquisitions related to the adult data collected. For the adult, the averaged time profiles obtained with the three methods (Fig. 5) only show differences in timing of events and no large amplitude differences. The EMG step profiles for the tibialis anterior muscle show the majority of the activity around terminal swing and early in the stance phase, while for the gastrocnemius muscle the activity is predominantly in the middle of the stance phase.

The reliability of the gait cycle signal obtained with the fully automatic method is directly related to the reliability of the footswitch signals. In the case of children, these signals are not always consistent because the normal heel-toe gait pattern is often absent or variable. When small footswitches are used their placement is crucial and key events in the cycle can often be misinterpreted. It is not surprising therefore, that for the normal child in this investigation, the fully automatic method was not always reliable, and the majority of the acquisitions belong to Group 2. For the normal child, the maximum tibialis anterior activity occurred before or after heel down depending on the gait cycle selection method used which is crucial in the determination of muscle activation patterns (Fig. 6).
Fig. 4. Comparison of gait cycles obtained using the three methods for data belonging to (a) Group 1, when differences are hardly detectable; (b) Group 2, when differences are visible; (c) Group 3, when the differences are dramatically evident.
For children with cerebral palsy, the selection of the method to be applied is even more critical. In such data not only is the normal heel-toe gait pattern regularly absent, but also the muscle activity patterns are varied and abnormal. The selection of the gait cycle not only affects both stride and swing phase durations (Table 2 acquisition 10–15), but it also changes the position of the maxima and the muscles activity distributions with respect to gait cycle phases (Fig. 7). Limited information can be extracted from the EMG step profiles using any of the gait cycle selection methods.

In conclusion, for the adult data the three methods had no influence on the EMG analysis in terms of the phase durations or the EMG step profile. For the normal child, the method used to select the gait cycle events produced some differences concerning the duration of the phases but the

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**Table 2**

Stride durations in seconds (SD1, SD2 and SD3) and swing durations (SW1, SW2 and SW3) as a percentage of the total gait cycle (TGC) for the three methods of gait cycle selection

<table>
<thead>
<tr>
<th>Acquisition No.</th>
<th>Leg</th>
<th>Subject</th>
<th>SD1 (s)</th>
<th>SD2 (s)</th>
<th>SD3 (s)</th>
<th>SW1 (% TGC)</th>
<th>SW2 (% TGC)</th>
<th>SW3 (% TGC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Left</td>
<td>Adult normal</td>
<td>1.003</td>
<td>0.999</td>
<td>0.993</td>
<td>43</td>
<td>40</td>
<td>37</td>
</tr>
<tr>
<td>2</td>
<td>Left</td>
<td>Adult normal</td>
<td>1.061</td>
<td>1.058</td>
<td>1.049</td>
<td>46</td>
<td>44</td>
<td>41</td>
</tr>
<tr>
<td>3</td>
<td>Left</td>
<td>Adult normal</td>
<td>1.028</td>
<td>1.024</td>
<td>1.021</td>
<td>42</td>
<td>40</td>
<td>37</td>
</tr>
<tr>
<td>4</td>
<td>Right</td>
<td>Adult normal</td>
<td>1.103</td>
<td>1.103</td>
<td>1.104</td>
<td>45</td>
<td>41</td>
<td>37</td>
</tr>
<tr>
<td>5</td>
<td>Right</td>
<td>Adult normal</td>
<td>1.143</td>
<td>1.142</td>
<td>1.148</td>
<td>43</td>
<td>40</td>
<td>36</td>
</tr>
<tr>
<td>6</td>
<td>Left</td>
<td>Child normal</td>
<td>0.765</td>
<td>0.796</td>
<td>0.791</td>
<td>43</td>
<td>45</td>
<td>39</td>
</tr>
<tr>
<td>7</td>
<td>Left</td>
<td>Child normal</td>
<td>0.872</td>
<td>0.871</td>
<td>0.864</td>
<td>50</td>
<td>46</td>
<td>40</td>
</tr>
<tr>
<td>8</td>
<td>Right</td>
<td>Child normal</td>
<td>0.569</td>
<td>0.724</td>
<td>0.722</td>
<td>47</td>
<td>37</td>
<td>31</td>
</tr>
<tr>
<td>9</td>
<td>Right</td>
<td>Child normal</td>
<td>0.714</td>
<td>0.626</td>
<td>0.717</td>
<td>51</td>
<td>35</td>
<td>33</td>
</tr>
<tr>
<td>10</td>
<td>Left</td>
<td>CP child 1</td>
<td>1.341</td>
<td>1.339</td>
<td>1.335</td>
<td>39</td>
<td>39</td>
<td>35</td>
</tr>
<tr>
<td>11</td>
<td>Left</td>
<td>CP child 1</td>
<td>1.084</td>
<td>1.089</td>
<td>1.094</td>
<td>35</td>
<td>33</td>
<td>29</td>
</tr>
<tr>
<td>12</td>
<td>Right</td>
<td>CP child 1</td>
<td>0.582</td>
<td>0.584</td>
<td>1.247</td>
<td>66</td>
<td>50</td>
<td>29</td>
</tr>
<tr>
<td>13</td>
<td>Right</td>
<td>CP child 1</td>
<td>0.651</td>
<td>0.648</td>
<td>1.298</td>
<td>74</td>
<td>47</td>
<td>27</td>
</tr>
<tr>
<td>14</td>
<td>Right</td>
<td>CP child 2</td>
<td>0.864</td>
<td>0.859</td>
<td>0.939</td>
<td>51</td>
<td>40</td>
<td>36</td>
</tr>
<tr>
<td>15</td>
<td>Right</td>
<td>CP child 2</td>
<td>0.768</td>
<td>0.771</td>
<td>0.753</td>
<td>56</td>
<td>42</td>
<td>38</td>
</tr>
</tbody>
</table>
Fig. 5. Comparison between EMG step profiles obtained using the three methods for data belonging to Group 1. The continuous line represents the automated (first) method, the dashed line represents the semi-automated (second) method, and the dotted line represents the manual (third) method. The differences are only due to time delays.

Fig. 6. Comparison between EMG step profiles obtained using the three methods for data belonging to Group 2. The continuous line represents the automated (first) method, the dashed line represents the semi-automated (second) method, and the dotted line represents the manual (third) method. The differences are due to time delays but note that the point of toe off is before the maximum of the tibialis anterior muscle activity using the automatic method while it is after the maximum activity using the semi-automatic and manual methods.
distribution of the EMG step profiles remained similar. For the children with cerebral palsy, the method of selection had a significant influence on both the phase duration and EMG step profiles. The results demonstrate that, while for adults it is possible to determine and utilise an automatic method to segment the gait cycle, this may produce problems in young children and in particular pathological cases. Care should therefore be taken when determining key events of the gait cycle and a combination of methods considered.

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References


