Activity mapping of lower leg muscles using a circumferential electrode array

Aurel Coza, Vinzenz von Tscharner & Benno Nigg

To cite this article: Aurel Coza, Vinzenz von Tscharner & Benno Nigg (2009) Activity mapping of lower leg muscles using a circumferential electrode array, Footwear Science, 1:3, 135-143, DOI: 10.1080/19424280903535421

To link to this article: https://doi.org/10.1080/19424280903535421

Published online: 26 Feb 2010.

Article views: 80

Citing articles: 3 View citing articles
Activity mapping of lower leg muscles using a circumferential electrode array

Aurel Coza*, Vinzenz von Tscharner and Benno Nigg

Faculty of Kinesiology, Human Performance Laboratory, University of Calgary, Calgary, Alberta, Canada T2N 1N4

(Received 5 August 2009; final version received 7 December 2009)

The timing of muscle activity during walking and standing is crucial for the understanding of normal and pathological functioning of the human body. All muscles crossing the ankle joint are an essential part of balance control during walking or standing. However, EMG measurements concentrate typically on the large muscles and neglect the small ones. An array of EMG electrodes was proposed to measure the circumferential EMG activity of the lower leg muscles. A wavelet based method was designed to generate muscle activity maps. The findings of this study showed that: (a) the individual activity of selected small muscles crossing the ankle joint can be measured with the proposed array; (b) both timing and intensity of the muscle activity during movement can be visualized simultaneously with the proposed activity maps; and (c) the time and space resolution is suitable for the study of multiple muscle activity interplay during standing or walking. Possible applications of this technique range from gait and stability analysis to sports equipment and clinical testing.

Keywords: electromyography; EMG-array; muscle activity; balance; walking

1. Introduction

Timing and intensity of large and small muscles activity during walking and standing is crucial for the understanding of normal and/or pathological functioning of the human body (Winter and Yack 1987, Hesse et al. 2001, Warren et al. 2004). The muscle activity is typically assessed by quantifying the electromyographic (EMG) signal of large muscles using bipolar electrodes. Another method used to noninvasively quantify muscle activity is the electrode array. An electrode array usually consists of a large number \( n \gg 2 \) of electrodes arranged in one or a number of rows. Depending on the individual electrode and whole array dimensions, the arrays can be employed to quantify individual muscle activity or the activity of (usually large) adjacent muscles within a given area of the body. Thus, large arrays of electrodes have been used to localize active muscles on body parts such as the torso (Finneran et al. 2003, Zwarts and Stegeman 2003). Small EMG electrode arrays were also used to quantify characteristics of single motor units within a muscle (Merletti et al. 2003, Lapatki et al. 2004). However, these electrode arrays were either not able to simultaneously detect the activity of multiple individual muscles, or were not able to simultaneously measure the activity of large and small muscles. The most mentioned reasons for these limitations are the large electrode surface and inter-electrode distance or (as in the case of small linear arrays) the array is too small to cover more than one muscle.

A number of studies emphasized the essential role played by the activity of large and small lower leg muscles during tasks such as walking and balance and the importance of quantifying the activity for the understanding of the neuro-muscular control of leg joints movements (Neptune et al. 2001, Nielsen 2003, Loram et al. 2009, Torres-Oviedo and Ting 2007). Quantifying the muscular control of the ankle joint during walking or standing, involves simultaneously monitoring of a large number of small and large muscles. This is generally hard to achieve using standard, relatively large, electrode pairs. Furthermore, due to the poor localization of certain small muscles that control the ankle joint, a method that could simultaneously record the muscle activity along the circumference of the lower leg would be preferable to a small number of localized electrodes. A circumferential array would be less sensitive to the relative position of individual electrodes in respect to the underlying muscles since at all times there would be at least one electrode on top of a given muscle. Therefore, the purposes of this study were to develop a device and an analysis method that allows for: (a) assigning the muscles to the electrode pairs and (b) quantifying the activity and timing of small muscles and regions of larger muscles of the lower leg in static and dynamic conditions related to locomotion.

*Corresponding author. Email: acoza@kin.ucalgary.ca
The device was primarily designed for studying the muscular control of the ankle joint during activities such as standing and walking for normal and pathological situations. Possible applications for this device include the study of normal and pathological gait and balance and also the quantification of the effect of footwear on lower leg muscles activity during standing or walking. Two examples – normal walking and the effect of footwear design on muscle activity – were investigated in this study.

2. Methods

2.1. Array construction

Sixteen EMG electrode pellets (Ag-AgCl coated) were sealed between two double side tape ribbons (200 x 30 mm). Holes were perforated in both ribbons and the connecting heads of the electrode pellets were inserted through the upper band (Figure 1B) while the contact surface of the electrode (2 mm diameter) was visible through the lower ribbon holes (Figure 1A). The inter- and intra-electrode distance was 11 mm, similar to other array dimensions (Farina and Mesin, 2005). A drop of approximately 1 µl of conducting gel was placed on the visible contact surface of the electrodes to ensure proper conduction.

2.2. Array positioning

The protective sheet of the lower (inside), adhesive tape ribbon was removed prior to attaching it to the skin (Figure 1A). Thus, the array was taped around the distal third of the lower leg and secured to the skin by the intrinsic adhesive tape (Figure 2B) Magnetic resonance imaging (MRI) cross-sectional images of the lower leg (Figure 2A) and palpation were used to find the position where the flexor digitorum longus (FDL), the soleus (SOL), the peroneus brevis (PB) and the tibialis anterior (TA) were most distinctly arranged under the skin. The first electrode pair was placed at the edge of the tibia adjacent to the FDL muscle (Figure 2A).

2.3. Testing

Three males (age 23.3 ± 2.8 years; mass 72.2 ± 7.6 kg) and three females (age 22.8 ± 4.3 years; mass 61.0 ± 4.5 kg) participated and gave informed consent corresponding to the guidelines of the University of Calgary Ethics Committee. Out of the six subjects, five were used to calibrate the array and one subject was used for a pilot footwear study. Two conditions producing task dependent muscle activities were used to assign the muscles to the electrodes: (a) 5 s isometric contractions: dorsiflexion, eversion, toe-curling and standing on toes, (b) clockwise unloaded foot rotation starting in dorsiflexion followed by a lateral movement, plantar flexion, inversion and returning to the starting position through dorsiflexion. Following the muscle assignment to the electrode pairs, a barefoot walking task consisting of walking 20 steps on a track was performed. The comparative footwear test consisted in 30 s balance task for three testing conditions: barefoot, wearing

Figure 1. (A) Interior side of the EMG array. The electrodes and the partially detached protective sheet are visible. (B) Exterior side of the array. The electrode connectors protruding through the upper tape are visible.
standard running shoes (control) and wearing unstable shoes (MBT). The balance task consisted in maintaining a quiet stance posture with the eyes open and the feet 25 cm apart.

2.4. EMG recording and processing

The EMG activity recorded by the 16 electrode pairs within the array, were used for the calibration. During the walking and balance trials pair 16 was deactivated and replaced by an accelerometer used to synchronize the gait phases with the EMG activity. The EMG signals were amplified by 1500, using pre-amplifiers (Biovision D-61273, Wehrheim, Germany) and sampled at 2400 samples/s by an A/D converter (National Instruments-6128). EMGs were submitted to a wavelet analysis. The wavelet analysis consists of decomposing the signal into a number of temporal sequences, each of them corresponding to a frequency band. A detailed description of the method was given by von Tscharner (2000). The total EMG intensity for each time point was obtained by summing the intensities across the wavelet spectra covering the frequency range from 19 to 466 Hz. Lower frequencies were excluded to minimize contributions from movement artifacts (Conforto et al. 1999). The total EMG intensity represents the filtered and time compressed initial signal.

2.5. Activity maps and circumferential intensity distributions

A muscle activity matrix was created for each trial using the total intensity time series corresponding to each electrode pair as a row in the matrix. Activity maps were created by generating contour plots of an activity matrix. A circumferential intensity distribution (CID) was obtained by averaging the intensities of the activity maps over time.

2.6. Electrodes assignment

The assignment of muscle to an electrode pair was determined in two steps:

(a) Muscles of interest were activated using isometric muscle activations that are known to activate specific muscles and monitoring the activity in the CID. Thus, dorsiflexion, plantarflexion, inversion and curl toes and eversion were used to selectively activate the TA, SO, FDL and PB muscles, respectively.

(b) The cross-correlation (least square) between the time-series of total intensity for all combinations of electrode pairs revealed correlated muscular events. A correlation matrix was computed by correlating the muscular events measured during unloaded foot rotation. High correlations ($r > 0.6$) in adjacent electrode

![Figure 2. (A) Cross-sectional MRI image at the distal third of the right leg and the corresponding circumferential positioning of the electrodes and (B) An example of an electrode array placed on the lower leg. The electrodes (bottom) and the preamplifiers (top – covered by tape) are visible in this picture.](image-url)
pairs represented domains of the same muscle. Lower, but significant correlations, indicated synchronous CNS generated activation signals or a certain amount of cross-talk.

Due to inherent differences between leg circumferences the electrode pairs detecting a given muscle were not always the same for different subjects. The mean positions were averaged over all five subjects and presented as a (integer rounded) mean and standard deviation.

3. Results
A CID was constructed from each of the four isometric contractions. A characteristic CID map for one subject is shown in Figure 3. Each contraction activated one muscle predominantly. For instance, eversion activated PB, standing on toes activated SOL, dorsiflexion activated TA and toe-curling activated the FDL muscle.

With the exception of electrodes 3 and 4, a smooth transition between the EMG intensity values corresponding to electrodes located on adjacent muscles was usually noticed.

This matrix allowed for the detection of groups of highly correlated EMG signals recorded on the same muscle (Table 1). The correlation matrix revealed high correlations between adjacent electrode pairs situated on the same muscle. Abrupt changes in the correlation coefficient were noticed when transitioning from one muscle to another or between muscle compartments within the same muscle (e.g. transition from electrode 14–15). Using a correlation threshold of 0.6, groups of correlated electrode pairs were formed for electrodes belonging to the same muscle/muscle compartment. The electrode assignment to the corresponding muscles was indicated by the light gray shading in Table 1. In this particular example a special situation was noticed for correlated pairs 10/9 and 10/11 where the correlation coefficient was very low probably due to the signal shielding caused by a tendon/blood vessel interposed between the electrode pair 10 and the muscle.

4. Electrode assignment
Electrode assignment to the muscles for each individual subject was done by combining the information from the CID and the correlation table. Thus, on average, the FDL muscle activity was detected by electrode pair 1; SOL muscle activity was detected by electrode pairs 3 (±0.70) to 11 (±1.18); PB muscle activity was detected by electrode pairs 12 (±1.32) to 14 (±1.38) and TA muscle activity was detected by electrode pairs 15 (±1.51) to 16 (±1.57). The correlation matrix showed that the activity of the soleus muscle had to be differentiated into three compartments: medial, central and lateral. With the exception of the FDL muscle activity, which was only detected in three out of five subjects all other muscles were detected in each of the five tested subjects.

5. Walking
The walking activity map showed similar activity patterns within the subject as well as between the subjects. A typical example of an activity map during walking for one subject is shown in Figure 4. On average the heel contact phase was characterized by high TA muscle activity and low muscle activity in all other muscles. During the stance phase two peaks of SOL and FDL muscle activity occurred at around 20 and 60% of the stance phase, respectively. Activity bursts in the lat-SOL compartment, the PB muscle and the FDL muscle were seen at 80% of the stance phase. At toe-off, the activity of all muscles ceased almost completely (Figure 4).

6. Footwear testing
The normalized circumferential EMG intensities corresponding to the three testing conditions (barefoot, running shoes and MBT shoes) showed large differences in both the intensity pattern and the relative muscle activity (Figure 5). Similar activity patterns were observed for the barefoot and running shoe standing. However, the EMG intensity for electrodes 4–7 was 40–50% higher for the barefoot condition. Standing in MBT shoes produced a muscle activity pattern different from the barefoot and running shoe conditions. High relative muscle activities were noticed across most of the electrode pairs (pairs 3–15).

7. Discussion
The main purpose of this study was to present a method for detecting the activity interplay of the lower leg muscles. The newly developed EMG electrode array has been shown to: (a) detect the activity of individual small muscles crossing the ankle joint and (b) simultaneously quantify a number of lower leg muscles activities at a high temporal resolution. EMG intensity profiles around the leg were quantified with this method during different tasks.

The presented data, using the described EMG electrode array combined with wavelet analysis yields information on timing of bursts of muscle activity
Figure 3. Illustration of the circumferential total intensity distribution (CID) for isometric contractions in eversion (top), standing on the toes (second from top), dorsiflexion (third from top) and inversion with curled toes (bottom) for one test subject (mean and SE for three trials). For the illustrated experimental results the muscles were visually assigned as illustrated by the top horizontal lines.
corresponding to muscular events (von Tscharner 2008). The wavelet method was used due to its superior time resolution over the root mean square method which is usually used to quantify the amplitude of the EMG signals. Furthermore, the applied wavelet method can be manipulated such that the time resolution is increased even further. The method can be simultaneously used as a signal filter thus eliminating the need for a separate filter. Also, the method provides the possibility for studying the neuro-muscular control of groups of muscles crossing the ankle joint during tasks such as walking or balancing (Laughton et al. 2003).

EMG cross-talk could be a major limiting factor for dense EMG electrode arrays. In this study highly localized activity bursts occurred often while the intensity recorded by the adjacent electrodes remained close to zero. This contravenes with the cross-talk definition and can be seen as an indicator of a minimal cross-talk between neighboring muscles.

Table 1. Cross-correlation matrix between the 16 EMG channels for one subject, performing an unloaded foot rotation EMG electrode pair numbers are shown on the horizontal and vertical axis.

<table>
<thead>
<tr>
<th>EMG Electrode</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0.345</td>
<td>0.500</td>
<td>0.874</td>
<td>0.506</td>
<td>0.874</td>
<td>1</td>
<td>0.863</td>
<td>0.58</td>
<td>0.58</td>
<td>0.58</td>
<td>0.871</td>
<td>0.384</td>
<td>0.355</td>
<td>0.735</td>
<td>0.735</td>
</tr>
<tr>
<td>2</td>
<td>0.345</td>
<td>1</td>
<td>0.863</td>
<td>0.58</td>
<td>0.58</td>
<td>0.58</td>
<td>1</td>
<td>0.863</td>
<td>0.58</td>
<td>0.58</td>
<td>0.58</td>
<td>0.871</td>
<td>0.384</td>
<td>0.355</td>
<td>0.735</td>
<td>0.735</td>
</tr>
<tr>
<td>3</td>
<td>0.500</td>
<td>0.500</td>
<td>1</td>
<td>0.874</td>
<td>0.874</td>
<td>1</td>
<td>0.58</td>
<td>0.58</td>
<td>0.863</td>
<td>0.58</td>
<td>0.58</td>
<td>0.871</td>
<td>0.384</td>
<td>0.355</td>
<td>0.735</td>
<td>0.735</td>
</tr>
<tr>
<td>4</td>
<td>0.874</td>
<td>0.874</td>
<td>0.874</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.863</td>
<td>0.58</td>
<td>0.58</td>
<td>0.58</td>
<td>0.871</td>
<td>0.384</td>
<td>0.355</td>
<td>0.735</td>
<td>0.735</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.506</td>
<td>0.506</td>
<td>0.506</td>
<td>0.506</td>
<td>0.506</td>
<td>0.506</td>
<td>1</td>
<td>0.863</td>
<td>0.58</td>
<td>0.58</td>
<td>0.58</td>
<td>0.871</td>
<td>0.384</td>
<td>0.355</td>
<td>0.735</td>
<td>0.735</td>
</tr>
<tr>
<td>6</td>
<td>0.874</td>
<td>0.874</td>
<td>0.874</td>
<td>0.874</td>
<td>0.874</td>
<td>0.874</td>
<td>0.874</td>
<td>1</td>
<td>0.863</td>
<td>0.58</td>
<td>0.58</td>
<td>0.58</td>
<td>0.871</td>
<td>0.384</td>
<td>0.355</td>
<td>0.735</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.384</td>
<td>0.384</td>
<td>0.384</td>
<td>0.384</td>
<td>0.384</td>
<td>0.384</td>
<td>0.384</td>
<td>0.384</td>
<td>1</td>
<td>0.735</td>
<td>0.735</td>
<td>0.735</td>
<td>0.735</td>
<td>0.735</td>
<td>0.735</td>
<td>0.735</td>
</tr>
<tr>
<td>9</td>
<td>0.355</td>
<td>0.355</td>
<td>0.355</td>
<td>0.355</td>
<td>0.355</td>
<td>0.355</td>
<td>0.355</td>
<td>0.355</td>
<td>0.355</td>
<td>1</td>
<td>0.735</td>
<td>0.735</td>
<td>0.735</td>
<td>0.735</td>
<td>0.735</td>
<td>0.735</td>
</tr>
<tr>
<td>10</td>
<td>0.735</td>
<td>0.735</td>
<td>0.735</td>
<td>0.735</td>
<td>0.735</td>
<td>0.735</td>
<td>0.735</td>
<td>0.735</td>
<td>0.735</td>
<td>0.735</td>
<td>1</td>
<td>0.735</td>
<td>0.735</td>
<td>0.735</td>
<td>0.735</td>
<td>0.735</td>
</tr>
<tr>
<td>11</td>
<td>0.735</td>
<td>0.735</td>
<td>0.735</td>
<td>0.735</td>
<td>0.735</td>
<td>0.735</td>
<td>0.735</td>
<td>0.735</td>
<td>0.735</td>
<td>0.735</td>
<td>0.735</td>
<td>1</td>
<td>0.735</td>
<td>0.735</td>
<td>0.735</td>
<td>0.735</td>
</tr>
<tr>
<td>12</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>1</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
</tr>
<tr>
<td>13</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>1</td>
<td>0.378</td>
<td>0.378</td>
</tr>
<tr>
<td>14</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>1</td>
<td>0.378</td>
</tr>
<tr>
<td>15</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>1</td>
</tr>
<tr>
<td>16</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
<td>0.378</td>
</tr>
</tbody>
</table>

Shaded areas represent high values cross-correlations.

Figure 4. Activity map for one step of walking for one subject. The arrows on top of the figure indicate heel strike and toe off, respectively. Bright areas indicate high muscle activity; black areas indicate no muscle activity. The normalized intensity scale can be seen with ‘0’ representing no activity and ‘1’ maximum (normalized) intensity.
This interpretation is supported by other similar studies (e.g. Merlo et al. 2009). However, the contribution of the cross talk to the EMG intensity profile around the leg can not be completely ruled out in this setup. The relatively smooth transition between maxima of intensities (CID maps) supports the assumption that there is an overlap between the EMG fields created by adjacent muscles. Based on these observations the method emphasizes less on the detection of individual muscles and stresses more the use of the EMG field profile (pattern) around the leg.

The present study does not allow drawing final conclusions on the possibly of independent activity of the medial, central and lateral compartments of the soleus muscle. However, initial results strongly indicate that these compartments are separately activated or that muscle fibers located in these areas are activated in a task specific pattern. Previous studies have shown that both the structure and the activity of the soleus muscle indicates the existence of three (sometimes only two) distinct anatomical/functional compartments (Finni et al. 2003, Hodgson et al. 2006).

Given the muscle distribution in the lower leg the array used in this study did not allow for quantification of gastrocnemius muscle activity while simultaneously measuring the other surface muscles in the lower leg. It was shown that gastrocnemius muscles plays an important role in both walking/running and balance (Neptune et al. 2001, Loram et al. 2009, Torres-Oviedo and Ting 2007). Therefore, the method would have to be expanded in the future to cover the activity of this muscle too. Using multiple arrays to cover all the surface muscles in the lower leg would require no major changes in the method presented in this study.

It is known that EMG signals usually show large variations but they can be tolerated for most applications. However, when comparing small changes in muscle activity the quality and localization of the signal becomes very important. It is generally agreed that the larger the area of the EMG electrode the less localized the recorded activity (Merlo et al. 2009). Based on these results, and on the fact that the contact area of the electrodes used in this study was approximately 25 times smaller than that of standard bi-polar electrodes or other large electrode arrays currently in use, it is expected that this array would have superior activity localization (spatial resolution). This translates into a higher sensitivity when employed to detect minute changes in muscle activity induced by, for instance, small changes in footwear design.

Since, to the best of our knowledge, a similar device was not used before to investigate the muscle activity of the lower leg there are very few comparisons that can be made between this study and previous studies.
However, the results obtained in this study regarding the timing of a number of muscles activation during walking for instance were similar with previous studies (Winter et al. 1987, Warren et al. 2004). Given the detailed representation of muscle activity generated by this method the comparison is limited to comparing the inception and termination time of muscle activation only and no direct comparisons between the actual activation patterns can be made.

Preliminary footwear testing revealed the fact that the method can discriminate between the muscle activity patterns corresponding to different footwear conditions. However, given the fact that only one subject was tested, no statistical significance can be attached to these data; nor is the result significant for the effect of shoes design on the muscle activity. The results shown here were only used to exemplify a possible application of this method. Furthermore, the results shown here capture only a static image of the muscle activity corresponding to the tested conditions. However, the method can be employed to generate a dynamic activity map that can reveal even more subtle differences between different testing conditions as shown in previous studies (von Tscharner 2008).

In this study the emphasis was on method rather than the absolute muscle activity values, therefore, the examples shown here are usually for one subject only. However, average values within subjects can be easily computed providing that the data are normalized prior to averaging. Averaging across subjects and different time scales (such as different walking/running speeds) is also possible if the appropriate pattern extraction methods are used, however, this could constitute the topic of a separate study.

The presented new EMG electrode array provides the possibility to study new aspects of muscle coordination such as the correlation between muscular events corresponding to different muscles or different muscle compartments. It also opens the possibility to study muscle interactions in sports, equipment testing and/or in clinical applications by simultaneously monitoring the activation intensity and timing of a large number of muscles and the changes induced by different apparel of footwear designs.

References


