Addition of a Cognitive Task During Walking Alters Lower Body Muscle Activity

Jordyn Vienneau, Sandro Nigg, and Benno M. Nigg
Human Performance Laboratory, Faculty of Kinesiology, University of Calgary, Calgary, AB, Canada

This study compared electromyography of five leg muscles during a single walking task (WALK) to a dual task (walking + cognitive task; COG) in 40 individuals (20 M and 20 F) using a wavelet analysis technique. It was hypothesized that muscle activation during the dual task would differ significantly from the walking task with respect to both timing (H1) and frequency (H2). The mean overall intensity for the COG trials was 4.1% lower for the tibialis anterior and 5.5% higher for the gastrocnemius medialis than in the WALK trials. The changes between the WALK and COG trials were short 50 ms bursts that occurred within 100 ms of heel strike in the tibialis anterior, and longer activation periods during the stance phase in the gastrocnemius medialis. No changes in overall intensity were observed in the peroneus longus, gastrocnemius lateralis, or soleus. Furthermore, no clear frequency bands within the signal could further characterize the overall changes in muscle activity during the COG task. This advances our understanding of how the division of attentional resources affects muscle activity in a healthy population of adults.

Keywords: dual task, gait, electromyography, attentional resources

The ability to perform multiple tasks simultaneously is a common component of daily living. Extensive research has demonstrated measurable effects on the motor cortex of dividing attention between a motor task and a cognitive task (for reviews, see Corp et al., 2014; Leone et al., 2017). Underlying mechanisms to explain these changes include (a) capacity sharing, (b) cross talk, and (c) the bottleneck theory, which together suggest that the brain has a restricted ability to integrate unlimited information (Pashler, 1994). Walking and talking simultaneously is frequently studied with the goal of understanding the division of cognitive processes. Various combinations of biomechanical variables (e.g., stride characteristics, muscle activity) and cognitive outcome measures (e.g., reaction time, accuracy) have been investigated in populations such as young adults (Abbud et al., 2009; Wrightson et al., 2016), aging adults (Hausdorff et al., 2008; Springer et al., 2006), and diseased populations such as individuals with Parkinson’s disease (Yoge et al., 2005) or multiple sclerosis (Hamilton et al., 2009).
The study of muscle activation using electromyography (EMG) provides insights into mechanisms behind observed differences in cognitive outcomes. For example, differences in stride characteristics, such as step frequency, can be explained and understood more fully by studying the changes in muscle activity that cause the varied step pattern. Research into the effects of dual tasking on lower body EMG has shown significant effects; however, the findings have been conflicting. For example, one study found an increase in EMG during a dual task, but only when the auditory cognitive stimulus occurred during the double support phase of gait (Li et al., 2012). Conversely, a similar study found a decrease in muscle activity during the stance phase of walking in five of eight investigated leg muscles during a dual task (Fraser et al., 2007). A third study found a significant reduction in peroneus longus activation and a trend of a similar reduction in the vastus lateralis activation during a dual task (Abbud et al., 2009).

The cited studies have used traditional EMG analysis techniques (rectifying the signal and/or normalizing it to maximum voluntary contractions), which provide an indication into the amplitude of the activation. However, EMG signals contain additional information related to timing and frequency content of the activation. Investigations into these additional aspects of the data may provide increased clarity into the nuanced differences between single- and dual-tasking muscle activation that have been previously overlooked; this may help to clarify the discrepancy in the previous findings.

A wavelet analysis technique has been developed that enables EMG signals to be transformed into intensity (a measure of power represented in both time and frequency domains simultaneously [von Tscharner, 2000]). It has been used previously in classifying low- and high-effort running (Stirling et al., 2011), characterizing rhythmic fluctuations called the Piper rhythm while running at different speeds (Maurer et al., 2013), understanding the low- and high-variability components of muscle activity during cycling (Enders et al., 2013), and detailing clusters of runners with similar activation patterns using the vastii muscles (von Tscharner et al., 2018). With wavelet analysis, one can investigate specific frequency bands, as well as time windows during the activation phase, rather than only quantifying the total amplitude of the signal during a step. Previous research has suggested that muscle activation in different frequency bands may indicate differences in activation patterns from slow and fast motor unit action potentials, such as during a fatiguing task (Wakeling & Syme, 2002). By investigating both time and frequency domains, the possibility of missing key components of the differences between test conditions by means of averaging the amplitude over a long-time window is reduced.

The purpose of this study was to compare lower body muscle activation patterns using a wavelet analysis technique during a WALK to the muscle activity during a COG in order to quantify differences in activation timing and frequency. The hypothesis, based on changes in the cognitive loads between tasks, was that muscle activation during the COG would differ significantly from the WALK with respect to both timing (H1) and frequency (H2). Results of this study will further our understanding of how divided attention changes gait in healthy adults, which can be used as a foundation for other populations, such as aging or diseased groups.
Methods

Participants

Forty individuals (20 males and 20 females) participated in this study (mean ± SD: age = 29.0 ± 8.1 years, body height = 169.0 ± 8.1 cm, and body mass = 66.5 ± 11.7 kg). All subjects were currently active and free from injury. All participants gave written informed consent to the study protocol, which the University of Calgary’s Conjoint Health Research Ethics Board (REB17-2247) approved.

Procedures

Participants performed two 2-min treadmill walking trials (Quinton Q65, Quinton Instruments Co.) at a self-selected “comfortable walking speed” in a randomized order. The WALK trial consisted of normal walking, with no further instructions given to the participant. During the COG trial, participants also performed the SERIAL-7 test, which involves counting aloud, backward in increments of seven starting from a number between 591 and 595 while walking on the treadmill (Wrightson et al., 2016). Before performing the data collection trials, all participants performed a practice COG trial in their own training shoes. All subjects wore the same footwear condition in order to mitigate any effects on the EMG.

EMG Analysis

Muscle activity was measured from five right lower leg muscles (tibialis anterior (TA), peroneus longus, gastrocnemius medialis (GM), gastrocnemius lateralis, and soleus (SO) using bipolar surface electrodes with preamplifiers (sampling rate: 2400 Hz, Biovision). Prior to the placement of electrodes, the skin was shaved and cleaned with an isopropyl wipe, and the electrodes were secured to the skin with medical tape. The electrodes were placed on each muscle’s belly, parallel to the assumed orientation of the muscle fibers based on the SENIAM guidelines (Hermens et al., 2000). A ground electrode was placed on the tibial tuberosity. A 1D accelerometer (ADXL 78, Analog Devices) was placed on the heel of the right shoe and synchronized with the EMG recording to determine the occurrence of heel strike (the onset of the rise in acceleration due to impact). From each 2-min trial, 80 steps were extracted and used for analysis.

A wavelet analysis technique (von Tscharner, 2000) with 13 nonlinearly scaled wavelets (center frequencies ranging from 6.9 to 542 Hz) was used to resolve the EMG signals into time–frequency space without using any normalization procedure. Raw EMG signals and wavelet transformed patterns were visually inspected for movement artifact or baseline noise and rejected from the analysis. The EMG signals were initially analyzed for a time window of 600 ms before and after heel strike. Later, the active time window was reduced to the primary timewise modulation of each muscle (TA: −500 to 150 ms; peroneus longus, GM, gastrocnemius lateralis: 100–600 ms; SO: 0–600 ms, where 0 ms is heel strike). The EMG signals were averaged across the total number of approved trials for each condition. From the wavelet-transformed signals, EMG total intensity for each
time sample was calculated as the sum of EMG intensities across frequencies from wavelets 3 to 11 (center frequencies = 37.7–395.4 Hz). EMG intensity from wavelets 1, 2, 12, and 13 (center frequencies = 6.9, 19.2, 465.9, and 542.1 Hz, respectively) are frequently associated with noise, and were therefore not considered in the analysis. The overall intensity of the EMG signal for each muscle during the trial was calculated as the area under the total intensity curve during the active time window of the EMG total intensities across time.

Post hoc, the changes in wavelet intensities were investigated more closely to assess and describe frequency and/or timing differences in muscle activation between the WALK and COG conditions. Specifically, contour plots of these differences were generated for the participants who responded in the direction of the overall mean significant results.

Statistics

All EMG data were processed and analyzed using MATLAB software (version R2016b, The MathWorks). In order to compare across subjects, the overall intensities for each muscle were normalized to the WALK condition. One-sample t tests were used to determine if COG differed from 100% (i.e., WALK) with a Bonferroni correction (α = .05/5 = .01).

Results

The self-selected treadmill walking speeds ranged from 2.7 to 5.6 km/hr (mean speed: 4.1 km/hr). The mean overall intensity for the COG trials was significantly lower than in the WALK trials for the TA (p = .003; d = −0.505). Twenty-nine out of 39 participants (74.3%) responded to the COG task with a decrease in EMG overall intensity for this muscle. The TA data from one participant were excluded due to motion artifacts. Inspection of the wavelet intensities for this group of responders (n = 29) illustrated that in most participants (86.2%), the timing differences in muscle activation occurred (a) fully or mostly between 100 ms before heel strike and 100 ms after heel strike and (b) for short durations (~50 ms or less; Figure 1). With respect to the frequencies where the differences occurred, no distinct pattern emerged across a majority of the participants.

Conversely, the mean overall intensity for the COG trials was significantly higher than in the WALK trials for the GM (p = .002; d = 0.541). Twenty-eight out of 37 participants (75.7%) responded to the COG task with an increase in EMG overall intensity. The GM data from three participants were excluded due to motion artifacts. Inspection of the wavelet intensities for this group of responders (n = 28) did not show clear timing or frequency patterns across a majority of participants. However, compared to the TA intensities, the differences in activation between the WALK and COG trials for the GM tended to be much longer in duration (Figure 2). The primary differences in activation were longer than 50, 100, and 200 ms in 85.7%, 64.3%, and 21.4% of responders, respectively. Only 14.3% of the responders did not have a primary difference in activation longer than 50 ms.

There were no differences observed in the other muscles, however there was a trend for increased SO activity in the COG trial (p = .021; d = 0.390; Table 1).
Figure 1 — Contour plot of difference in wavelet intensities for the TA between the two tested conditions for three exemplary participants. Darker shades indicate higher muscle activity in the WALK condition. Dark vertical line indicates heel strike (time = 0). WALK = treadmill walking; TA = tibialis anterior.
Figure 2 — Contour plot of difference in wavelet intensities for the GM between the two tested conditions for three exemplary participants. Darker shades indicate higher muscle activity in the COG condition. COG = walking while performing a cognitive task; GM = gastrocnemius medialis.
The objective of this study was to compare lower leg muscle activity between a single task (treadmill walking) and a dual task (walking while counting backward) using a wavelet analysis technique. Hypothesis 1 was supported as there was a significant decrease in muscle activity in the TA, and a significant increase in muscle activity in the GM during the COG task compared to the WALK task. The timeframe corresponding to lower TA activation in the COG condition tended to be 50 ms or less, and usually within 100 ms of heel strike. In the COG condition, the GM demonstrated longer periods of higher activation than the WALK condition, up to 200 ms. Hypothesis 2 was not supported, as no consistent trends with respect to the frequency component of the EMG signal were observed.

Similar research by Frazer et al. (2007) found a decrease in EMG in five of eight leg muscles during a treadmill walking dual task. They proposed that dual-task costs were only observed in muscles that could be depleted without compromising the motor task. In the current study, the longer and higher GM activation demonstrated by the participants while their attention was divided indicates that they may have plantarflexed their ankle joints more forcefully during the propulsion portion of the gait cycle. This speculation is further supported by the trend for increased muscle activity in the SO, which primarily acts to plantarflex the ankle joint. The decrease in TA activity surrounding heel strike suggests that the foot may have been in a flatter (less dorsiflexed) position at heel strike compared to during the WALK task.

Increased GM activity occurring late in stance may also suggest changes at the knee joint. For example, the GM, in concert with quadriceps muscles, has been shown to act as a stabilizer during weight-bearing tasks in an unstable population (Kvist & Gillquist, 2001), especially during mid-stance when the center of mass is shifting over the ground contact point, which corresponds to the time point where differences were observed in the wavelet patterns in the current study. Previous research demonstrated no kinematic effects of a COG on walking stability, but did result in a decrease in lower body variability (Kao et al., 2015). This finding supports the speculation presented here that an increase in GM, an increase in GM activity, and potentially hamstring EMG, may result in increased knee joint coactivation, and thus a maintained movement pattern when compared to normal walking.

### Table 1 Normalized Overall Intensity (Mean ± SEM)

<table>
<thead>
<tr>
<th>Muscle</th>
<th>WALK (%)</th>
<th>COG (%)</th>
<th>p</th>
<th>Cohen’s d</th>
</tr>
</thead>
<tbody>
<tr>
<td>TA</td>
<td>100</td>
<td>96.3 ± 1.2*</td>
<td>.003</td>
<td>−0.505</td>
</tr>
<tr>
<td>PL</td>
<td>100</td>
<td>100.1 ± 2.1</td>
<td>.954</td>
<td>0.010</td>
</tr>
<tr>
<td>GM</td>
<td>100</td>
<td>105.4 ± 1.6*</td>
<td>.002</td>
<td>0.541</td>
</tr>
<tr>
<td>GL</td>
<td>100</td>
<td>100.0 ± 1.7</td>
<td>.993</td>
<td>−0.002</td>
</tr>
<tr>
<td>SO</td>
<td>100</td>
<td>102.6 ± 1.1</td>
<td>.021</td>
<td>0.390</td>
</tr>
</tbody>
</table>

*Note. TA = tibialis anterior; PL = peroneus longus; GM = gastrocnemius medialis; GL = gastrocnemius lateralis; SO = soleus; WALK = treadmill walking; COG = walking while performing a cognitive task.

*Statistical significance.
A primary difference between the current study and the cited studies is the style of the cognitive task. Specifically, in the current study, participants were constantly dividing their attentional resources between walking and counting backward for the duration of the trial. Conversely, the COG in many of the previous studies were variations on giving a verbal response to an auditory stimulus that was provided to the participant at random intervals. The working memory theory postulates that humans have a limited amount of cognitive resources (Baddeley, 2003; Just & Carpenter, 1992). Therefore, it could be that the continuous cognitive load required from participants in the current study demanded a larger portion of the working memory capacity compared to the discrete cognitive tasks used in earlier studies. As a result of this discrepancy in resource allocation for the cognitive task, the quantity of remaining attentional resources for walking (measured via EMG) may have differed. Furthermore, individuals are able to prioritize mental resources during a dual task (Gorgoraptis et al., 2011; Ma et al., 2014). While participants were not instructed to focus on either walking or the cognitive task, it is possible that the arithmetic challenge was sufficiently demanding that individuals prioritized this task over the walking task, and as a result, differences in muscle activity were observed.

It has been well documented that individuals naturally select a preferred walking speed (i.e., the WALK condition) that minimizes energy expenditure (Ralston, 1958; Selinger et al., 2015; Waters et al., 1988) and stride variability (Sekiya et al., 1997) and maximizes vertical and anterior–posterior head and pelvis stability (Latt et al., 2008). Therefore, any deviation from this natural movement path, such as the changes in EMG observed during the COG task, can be expected to decrease the efficiency of the movement. Interestingly, a post hoc analysis of the stride time using the heel mounted accelerometer found no difference between the mean WALK (1.126 s) and COG (1.127 s) conditions. This supports the theory that the participants did not alter their gross stride pattern during the COG. Rather, the changes in muscle activity may have been evidence of minor gait adjustments during the period of divided attention. It is of interest for future research studies to permit participants to modify their walking speed during the COG, such as by using a nonmotorized treadmill, to assess whether a new optimum speed and/or energy expenditure can automatically be established.

In conclusion, this study showed that performing a cognitive task while walking altered lower body muscle activity. Specifically, the TA activity decreased, while the GM activity increased. The use of a wavelet-based analysis approach demonstrated that the changes in EMG between the WALK and COG trials were short 50 ms bursts that occurred within 100 ms of heel strike in the TA, and longer (>100 ms) activation periods during the stance phase in the GM. No clear frequency bands within the EMG signal could further characterize the overall changes in muscle activity during the COG task. This study helps to further understand how the division of attentional resources affects biomechanical variables during gait. These results motivate the use of frequency-based analyses (e.g., wavelet analysis) when investigating muscle activity changes and motor control function during cognitively challenging tasks. Future research should investigate whether permitting participants to self-select their walking speed during a COG task would result in a reduction in altered muscle activity.
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References


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