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The interpretation of abdominal wall muscle recruitment strategies change when the electrocardiogram (ECG) is removed from the electromyogram (EMG)

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Abstract

The purpose of this study was to determine the effect of the ECG artifact on low-level trunk muscle activation amplitudes and assess the effectiveness of two methods used to remove the ECG. Simulations were performed and percent error in root mean square (RMS) amplitudes were calculated from uncontaminated and contaminated EMG signals at various ECG to EMG ratios. Two methods were used to remove the ECG: (1) filtering by adaptive sampling (FAS) and (2) Butterworth high pass filter at 30 Hz (BW-30 Hz HPF). The percent error was also calculated between the ECG removed and the uncontaminated EMG RMS amplitudes. Next, the BW-30 Hz HPF method was used to remove the ECG from 3-bilateral external oblique (EO) muscle sites collected from 30 healthy subjects performing a one handed lift and replace task. Two separate ANOVA models assessed the effects of ECG on the statistical interpretation of EO recruitment strategies. One model included EMG data that contained the ECG and the other model included EMG data after the ECG was removed. Large percent errors were observed when the ECG was not removed. These errors increased with larger ECG to EMG ratios. Both removal methods reduced the errors to below 10%, but the BW-30 Hz HPF method was more time efficient in removing the ECG artifact. Different statistical findings were observed among the muscle sites for the ECG contaminated model compared to the ECG removed model, which resulted in different conclusions concerning neuromuscular control.

Keywords

Electrocardiogram; Electromyography; Trunk muscles; Simulation; Criterion methodology

Introduction

Surface electromyography (EMG) is commonly used to assess the neuromuscular demand on trunk muscles while performing various tasks. For tasks that only require low-level trunk muscle activation, the ECG artifact is often visible within the EMG. This ECG contamination results from the relative close proximity of the surface electrodes to the heart and the volume conducting properties of human tissue (Farina et al., 2002). The presence of the ECG within the EMG signal influences both amplitude and frequency domain measures of the true EMG (Kumar and Mital, 1996, Soderberg, 1992 and Hu et al., 2007). How much the artifact affects the

amplitude of the EMG signal depends on the level of muscle activation, which is the main focus of this study. For example, large ECG to EMG amplitude ratios can occur when muscle activation is less than 5% of its maximum voluntary isometric contraction (MVIC) and the electrodes are in close proximity to the heart such as the case with the trunk musculature (Cholewicki et al., 1997 and Moreside et al., 2007). In this case, the presence of the ECG could result in an overestimation of the reported EMG activation levels. Although these EMG activations are small, they are of functional importance since low-level muscle activations (1–3% MVIC) are required to maintain spinal stability (Cholewicki and McGill, 1996 and Cholewicki et al., 1997). Thus, understanding the effect of the ECG artifact is important since ECG contamination could lead to overestimations of EMG amplitudes and misinterpretation of the functional role of abdominal and back extensor muscles.

To reduce the effects of the ECG artifact, the ECG should be removed, however, removal of the ECG is complicated since the EMG and the ECG frequency spectra overlap (surface EMG 20-500 Hz; ECG 0-200 Hz) (Aminian et al., 1988 and Christov and Daskalov, 1999). One difference is that the majority of the power of ECG is found at frequencies less than 45 Hz (Aminian et al., 1988) whereas the peak power for EMG is approximately 100 Hz (Winter, 2005). As a result, several studies have presented methods to remove the ECG from the electromyogram, including: digital filtering (Drake and Callaghan, 2006, Redfern et al., 1993 and Zhou et al., 2007) and subtraction methods (Aminian et al., 1988, Bartolo et al., 1996 and Deng et al., 2000). However, in many of these studies they could not directly determine the effect of the ECG or how effective the removal method was at eliminating the ECG artifact. To accurately quantify the effect of the ECG on EMG amplitudes and the effectiveness of the removal method, the methodology should include the creation of a contaminated signal by combining an uncontaminated ECG with an uncontaminated EMG signal (criterion methodology). Depending on the removal method, either the ECG or EMG signal could be used as the criterion measure. To determine the effect of the ECG artifact, the criterion (uncontaminated EMG) is compared to the contaminated EMG signal. To determine the effectiveness of the removal method, the method is first applied to the contaminated signal. The performance of the removal method can then be determined by the error between the criterion (uncontaminated EMG) and the signal after the ECG has been removed. This methodology has not been used in many studies where the ECG artifact has been removed.

Previous work by Aminian et al. (1988) used the ECG signal as the criterion measure to determine the effectiveness of a subtraction method to remove the ECG artifact. The removal method included reconstruction of the ECG signal by adaptive filtering which was later subtracted from the combined EMG and ECG signals. Comparison of the criterion measure (uncontaminated ECG) with the reconstructed ECG resulted in 17–21% root mean square (RMS) errors associated with the reconstructed ECG signal. Although the results were based on a study from a rat muscle, they quantified the error associated with the removal method, which is an important consideration when comparing different methods. Other authors have used this subtraction method to remove the ECG artifact from the electromyogram during low activation levels from trunk muscles, however, the effect was not determined using the criterion methodology (Cholewicki et al., 1997 and Cholewicki et al., 2002). Therefore, it is necessary to determine the error associated with the removal method on human trunk muscle EMG in order to

determine the most appropriate method for removing the ECG artifact in studies examining low-level trunk muscle activations.

Recent studies using the criterion methodology determined the effectiveness of a number of different methods commonly used to remove ECG from EMG recorded from human muscle (Drake and Callaghan, 2006 and Zhou et al., 2007). Drake and Callaghan (2006) used the uncontaminated EMG from the biceps brachii as the criterion measure. Four different methods were used to remove the ECG from EMG signals of different activation levels (10–25% MVIC). Comparison between the criterion measure (uncontaminated EMG) and the contaminated EMG signals resulted in increased errors as muscle activation levels decreased. This suggests that the *relative* effect of the ECG artifact was greatest at lower level EMG amplitudes. In addition, comparison of the various removal methods showed that the errors associated with many of the removal methods were less than the errors associated with the ECG contamination. Based on higher performance rankings, lower errors and less time investment for removal, they recommended using a recursive second order Butterworth high pass filter at 30 Hz (BW-30 Hz HPF) for activation levels between 10% and 25% MVIC. However, the effectiveness of the removal method at lower activation levels (<10% MVIC) remains unknown. Thus, it is necessary to investigate the impact of ECG contamination on antagonist muscles of the trunk muscles since the activation levels of these muscles commonly occur below 10% MVIC (Davidson and Hubley-Kozey, 2005, Lavender et al., 1992, McGill et al., 1995 and Vezina and Hubley-Kozey, 2000).

The first objective of this study was to evaluate the influence of the ECG artifact using the criterion methodology with low-level activation amplitudes from human abdominal wall muscle. Secondly, this study used the same methodology to examine two removal methods: a modified version of filtering by adaptive sampling (FAS) method (Aminian et al., 1988) and a Butterworth 30 Hz high pass filter (Drake and Callaghan, 2006 and Zhou et al., 2007). Finally, the third objective of this study was to investigate whether the interpretation of the amplitude recruitment strategy among the external oblique (EO) muscle sites change between an experimental dataset containing ECG and when the dataset was processed to remove the ECG. In addition, the statistical effect of the removal method on the datasets was determined.

Methods

2.1. Participants

For the simulation analysis in Parts 1 and 2, the uncontaminated EMG signal was collected from one 30-year old female subject (163 cm height; 73.7 kg mass) and the uncontaminated ECG signal was collected from one 31-year old male subject (171 cm height; 63.3 kg mass). For Part 3, 30 healthy, right-hand dominant individuals aged 20–50 years participated in the study (30.9 ± 9.1 years; 171.3 ± 8.6 cm height; 69.2 ± 13.6 kg mass). All subjects signed a written consent consistent with the policies of the Health Sciences Research Ethics Board at Dalhousie University.

2.2. Experimental design

The study was divided into three parts. In Part 1, a simulation of an ECG signal was combined with an uncontaminated EMG signal (EMG_{uncon}) of varying amplitudes to produce contaminated signals (EMG_{con}). The EMG_{con} and EMG_{uncon} signals were compared to determine the effect of the ECG artifact. For Part 2, the EMG_{con} signal was then subjected to different methods that attempted to remove the ECG (EMG_{rem}). The EMG_{uncon} signal was then compared to the EMG_{rem} signal for two different ECG removal methods. For Part 3, one method was used to remove the ECG in experimental amplitude data recorded during a lifting task that produced low-level activation in abdominal muscle sites. A series of maximum voluntary contractions were used to normalize the lifting trial data in Part 3. Comparisons were then made between the original EMG data ($EMG_{original}$) without the ECG removed and the EMG data with the ECG removed (EMG_{filter}). Details for each part are explained in the subsequent sections.

2.3. Surface electromyography

Collection and recording of the myoelectric signals were in accordance with published standards (Merletti, 1999). Following standard skin preparation, pairs of Ag/AgCL (Meditrace 10 mm) electrodes with 3 cm inter-electrode distance were placed in a bipolar fashion parallel to the fiber direction of eight abdominal wall muscle sites. All sites were based on standard placements, but were adjusted for individual anthropometrics and validated with manual resistance tests.

For Parts 1 and 2, the left lower and upper rectus abdominis sites were used. Electrodes were placed on the muscle belly midway between the umbilicus and the pubis for the lower site and centred on the muscle belly midway between the sternum and the umbilicus for the upper site (Gilleard and Brown, 1994).

For Part 3, three bilateral-sites on the external oblique (EO) muscles were used. The electrodes for the EO1 site were placed over the 8th rib adjacent to the costal cartilage to represent the anterior fibers of the external oblique (Ng et al., 1998). The electrodes for the lateral fibers (EO2) were placed 15 cm lateral the umbilicus at a 45-° angle (McGill, 1991) and for EO3 the electrodes were placed at the midpoint between the lowest part of the ribcage and the iliac crest (Nouwen et al., 1987).

For normalization purposes, the subjects performed 2-trials of nine different maximum voluntary isometric contractions (MVIC). For details see Butler et al. (2006). Briefly, the exercises included supine sit-up and V-sit-up; sitting axial rotation to the right and left; side-lying lateral bend to the right and left; prone back extension and coupled back extension with axial rotation to the right and left (Butler et al., 2006 and Davidson and Hubley-Kozey, 2005). Resistance was provided to the subjects. The exercises were randomized with a 2-min rest between trials.

The myoelectric signals were amplified using a Bortec AMT 8-channel amplifier (Bandpass 10-1000 Hz, CMRR = 115 db, input impedance ~10GΩ) and sampled at 1000 Hz with a 16-bit analogue to digital (A/D) conversion board (National Instruments (NI) CA-1000, Austin, Texas). The biases from the system as well as from the subject while lying supine were used to correct the raw EMG signal for DC offset. For Parts 1 and 2, the RMS amplitude was calculated during the entire data collection trial (4.0 s), whereas for part 3 only the duration of the lift (upward) phase was used. Using a 500 ms moving window, the maximum RMS amplitude from the

normalization trials was identified and then used to normalize the lifting trials to %MVIC in Part 3 (Vezina and Hubley-Kozey, 2000).

2.4. Part 1: Simulation: effect of the ECG artifact

The left lower rectus abdominis muscle site was selected from one female subject to represent EMG$_{uncon}$ (criterion measure) for the simulation trials, due to negligible ECG content (Fig. 1). For this trial, the subject was required to stand and lift (5 cm off the table) and replace a 3.0 kg load with both hands with their arms straight in front of their body while minimizing spine and pelvic motion. The total trial lasted 4.0 s and was used in the simulation analysis. The level of activation for EMG$_{uncon}$ normalized to the maximum voluntary isometric activation was calculated to be approximately 5.3% MVIC for this trial.
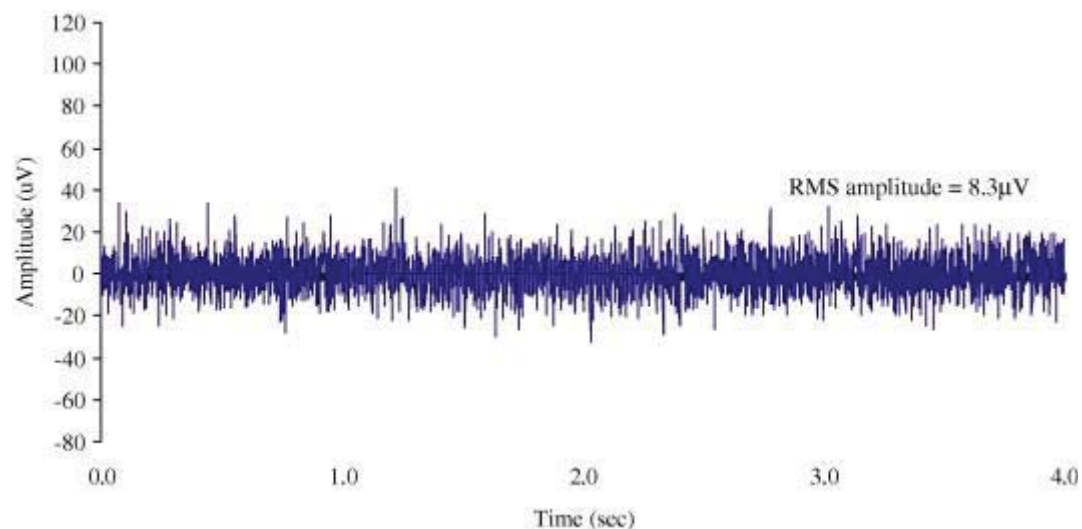

Fig. 1.

EMG$_{uncon}$ for the left lower rectus abdominis used in the simulation trials during a light lift and replace task (4.0 s).

The ECG trace used for the simulations was selected based on visually clear ECG signals with minimal EMG. The ECG trial was recorded from one male subject's left upper rectus abdominis during the same lift and replace protocol as described above, but using only the right hand. The subject lifted the load close to the body at a 45° angle from the body's midline. Because the trial contained EMG, the baseline was manually zeroed outside of the QRS portions of the ECG signal and the signal was then smoothed so that the resulting ECG signal contained minimal levels of EMG during the four-second trial (Fig.2).
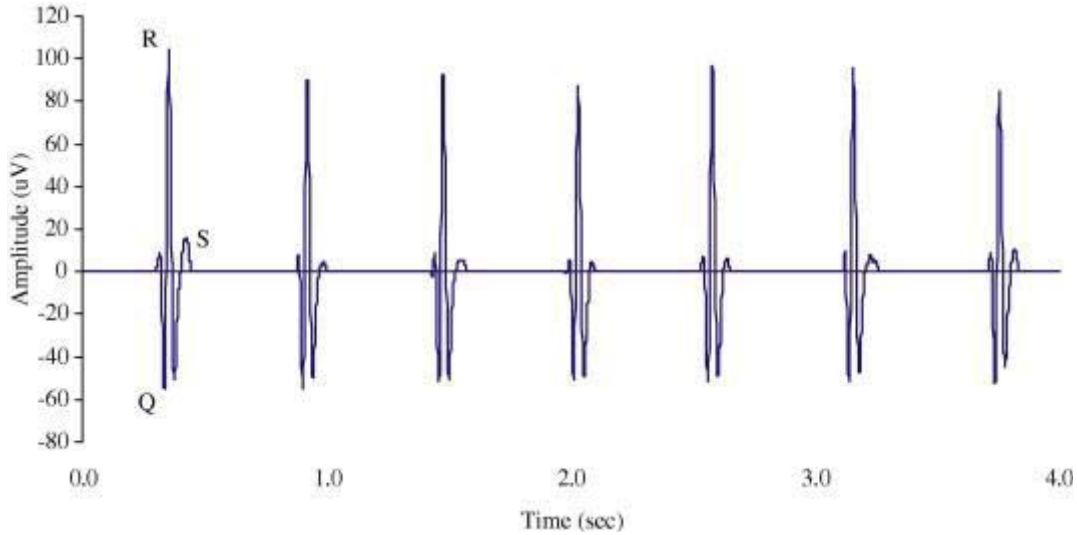
Fig. 2.

ECG waveform used in the simulation trials with the QRS portions identified on the first heartbeat.

To determine how the amplitude of the ECG affects the EMG RMS amplitude for different signal amplitudes, ratios between the ECG and EMG signals were manipulated. The ratios were calculated using the peak-to-peak amplitude (range from maximum peak to minimum peak) of the ECG and EMG after the signals was combined. The EMG amplitude was digitally scaled to produce six ratios ranging from 1:1 to 3.5:1 in 0.5 increments for the simulations. These ratios were similar to the magnitudes observed in the experimental data.

To calculate the percent error associated with the ECG presence in the EMG signal (effects of not removing the ECG signal from the contaminated signal), the RMS of the EMG_{uncon} and EMG_{con} signals were compared during the total movement (4.0 s) for the six ECG:EMG ratios using Eq. (1):

$$\%RMSE_{ECG} = (RMS_{EMGcon} - RMS_{EMGuncon})/(RMS_{EMGcon})^{*}100 \qquad (1)$$

where

$\%RMSE_{ECG}$ percent error in RMS amplitudes due to ECG artifact

RMS_{EMGcon} RMS of the EMG_{con} signal

$RMS_{EMGuncon}$ RMS of the EMG_{uncon} signal

2.5. Part 2: Simulation: effect of the ECG removal methods

The two methods that were used to remove the ECG signal from EMG_{con} included the filtering by adaptive sampling method (FAS) similar to that used by Aminian et al. (1988) and

Butterworth high pass filtering at 30 Hz (BW-30 Hz HPF) ([Drake and Callaghan, 2006](#) and [Zhou et al., 2007](#)). These two removal methods were selected based on previous studies that used the criterion methodology to quantify the effect of the ECG and the removal method. However, these removal methods have not yet been directly compared to each other.

2.5.1. Method A: FAS algorithm development

A modified version of the method described by [Aminian et al. (1988)](#) was applied to the EMG_{con} signal. This method first identifies and reconstructs the ECG signal from the contaminated data. In order to detect the QRS portion of the ECG signal, the data were windowed using a threshold value (L). This threshold was used to separate the ECG and EMG signals by identifying the threshold of the R portion of the QRS component of the ECG. The value of L was chosen such that any amplitude with more than four consecutive points above the threshold was identified as the R portion of the ECG. Since there was still a great deal of EMG in the reconstructed ECG, the algorithm was modified so that the data were smoothed using a quintic smoothing spline (with an error tolerance of 0.01). Although the smoothing of the data distorted the magnitudes at this tolerance, the timing of the QRS events was unaffected. Therefore, the QRS portions of the ECG could be identified where the derivative of the spline crossed zero (reflecting a change in slope). This removal method required the user to visually determine the threshold value, L, for each trial and each muscle.

The reconstruction of the ECG was an iterative process based on the fact that the motor unit action potential components are more variable than the ECG ([Basmajian and De Luca, 1985](#)). This algorithm suppresses the rapidly changing components of the EMG signal and identifies samples that do not reflect a slope change within a consecutive three-sample window. The samples that do not contain a slope change are saved and represent the ECG. Since the algorithm skips over rapidly changing points, missing data were interpolated using a linear interpolation technique resulting in an ECG array that was equal in length to the EMG trace. Although this process was repeated 5 times, a substantial amount of EMG still remained in the ECG signal. As a result a final smoothing spline was performed on the data with 0.001-error tolerance (this tolerance did not distort the magnitude of the data markedly). Finally, the reconstructed ECG was then subtracted from the EMG_{con}, so that the resultant EMG_{rem} signal theoretically contained no ECG. A customized program was written in MATLAB® to develop and test the algorithm (MathWorks, Inc., Natick, MA. Version 7.3).

2.5.2. Method B: Butterworth 30 Hz high pass filter (BW-30 Hz HPF)

The second method to remove the ECG applied a fifth-order recursive high pass Butterworth filter with a 30 Hz cut-off to the EMG_{con} signal. The use of a fifth-order filter recursively produced a 10th order filter and was based on better performance at removing frequencies below 30 Hz with little affect on the EMG signal ([Zhou et al., 2007](#)). To ensure that the initial unstable response characteristic of the filter did not alter the data, 10 padding points were added (at both the beginning and end) to the data and then removed after filtering.

2.6. Comparison between ECG removal methods

The EMG$_{uncon}$ signal was combined with an ECG signal (as in Part 1) to test the effectiveness of each removal method. Multiple simulations were performed to represent the same six ECG:EMG ratios used in Part 1. The percent errors in RMS amplitude were calculated based on the RMS from the EMG$_{uncon}$ and EMG$_{rem}$ signals for each removal method during the total movement (4.0 s) using Eq. (2):

$$\%RMSE_i = (RMS_{EMGuncon} - RMS_{EMGrem})/(RMS_{EMGuncon})^*100 \qquad (2)$$

where

$\%RMSE_i$ percent error in RMS amplitudes due to removal method i

$RMS_{EMGuncon}$ RMS of EMG$_{uncon}$ signal

RMS_{EMGrem} RMS of EMG$_{rem}$ after the ECG has been removed by removal method i

2.7. Part 3: Impact of filtering ECG on experimental data

The removal method associated with lower percent errors and processing time was selected as the method to remove the ECG from the experimental data in Part 3. The data consisted of normalized activation amplitudes from the EO muscle sites.

Thirty healthy right-handed subjects performed three trials of an asymmetric lift and replace task with the right hand. From a standing position with the right arm straight and reaching in front of the body, the subjects were required to perform a lift and replace movement using a 3.0 kg load located at 45° to body midline (Fig. 3). Subjects were asked to lift the test container vertically 4-5 cm off the table's surface in a slow and controlled manner while minimizing trunk and pelvis motion. The timing of the task started when the test container was lifted off the table (1-s count), the maximum lift height was attained on 2-s count and the end of the task corresponded to the replacement of the container (3-s count). In the present study, normalized RMS amplitudes during the lift or upward phase were examined. The duration of the lift was identified using event markers triggered by a pressure transducer located at the bottom of the test container and from a photoelectric relay system.
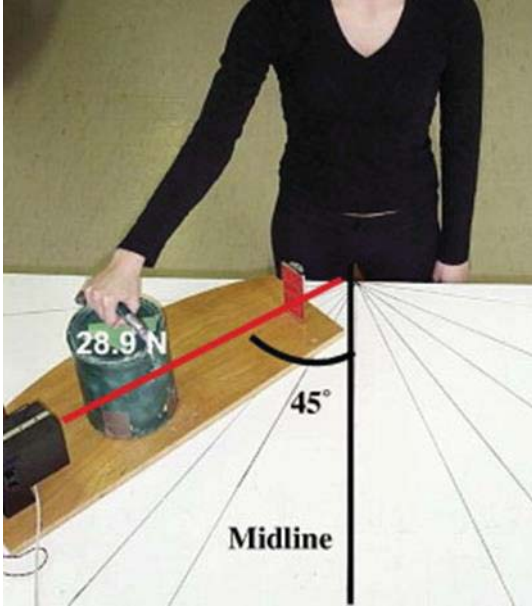
Fig. 3.

Experimental set-up and subject position during the asymmetric lift and replace task.

2.8. Data analysis

For the simulation trials, the percent error in RMS amplitudes represented the performance indicator for each removal method and was also used to determine the influence of leaving the ECG in the EMG signal. For the experimental data, two-factor repeated measures ANOVA first tested the main effects of side (right, left) and muscle site (EO1, EO2, EO3) for the $EMG_{original}$ and EMG_{filter} datasets separately ($\alpha = 0.05$). To assess whether the ECG influenced the interpretations of the amplitude recruitment strategy, comparisons of significant pairwise comparisons were made between the two datasets. To determine the effect of the removal method on experimental datasets, a three-factor repeated measure ANOVA tested the main and interaction effects of side (right, left), muscle site (EO1, EO2, EO3) and dataset ($EMG_{original}$, EMG_{filter}) ($\alpha = 0.05$). Bonferonni adjustments were performed for post-hoc analysis.

3. Results

For Part 3 an outlier ($n = 1$) was identified given the large residuals. The outlier was removed from the dataset based on the associated large BMI (35 kg/m^2) and waist girth (107 cm) measures, which may have influenced the stability of the EMG signal. Thus, the statistical analyses were performed on the remaining 29 subjects.

3.1. Part 1: Simulation: effect of the ECG artifact

For the simulation trials the effect of not removing the ECG artifact from the EMG is shown in Fig. 4. As the ECG:EMG ratio increased, the percent errors associated with not removing the

ECG quickly increased. The percent errors ranged from 14% to 68% for the six ratios tested (1–3.5). When the peak-to-peak amplitude of the ECG was equal to the peak-to-peak amplitude of the EMG (1:1 ratio) there was 14% error (or 5 µV absolute RMS difference) associated with not removing the ECG. Moreover, when the ECG was three times that of the EMG (3:1 ratio) the percent error was approximately 62% (or 11 µV absolute RMS difference).
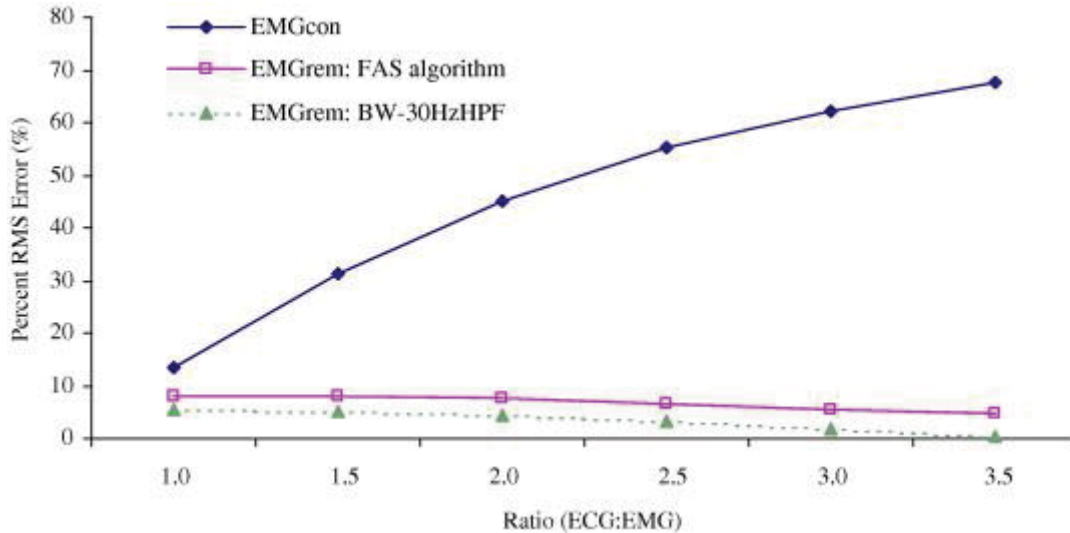

Fig. 4.

Percent error associated with leaving the ECG in the EMG signal. Percent errors associated with EMG_{con} and EMG_{rem} using two removal methods: FAS algorithm (filtering by adaptive sampling) and BW-30 Hz HPF (Butterworth 2nd order 30 Hz high pass filter)

3.2. Part 2: Simulation: effect of the removal methods

Fig. 4 also illustrates the percent error in RMS amplitudes associated with the two ECG removal methods. The BW-30 Hz HPF method consistently produced lower percent error than the FAS algorithm method. The BW-30 Hz HPF produced percent errors that ranged from 1% to 5% for the different ratios, where the percent errors associated with the FAS algorithm were 5–8%. The difference in absolute RMS values between the removal methods were small as indicated in Fig. 5 and Fig. 6 for ratios 3:1 and 1:1, respectively.

A EMGcon

B EMGrem: FAS algorithm

RMS amplitude = 6.4 μV

C EMGrem: BW-30HzHPF

RMS amplitude = 6.6 μV

Fig. 5.

Ratio 3:1 for EMG$_{con}$ (A) and EMG$_{rem}$ using two removal methods: (B) FAS algorithm (filtering by adaptive sampling) and (C) BW-30 Hz HPF (Butterworth 30 Hz high pass filter).
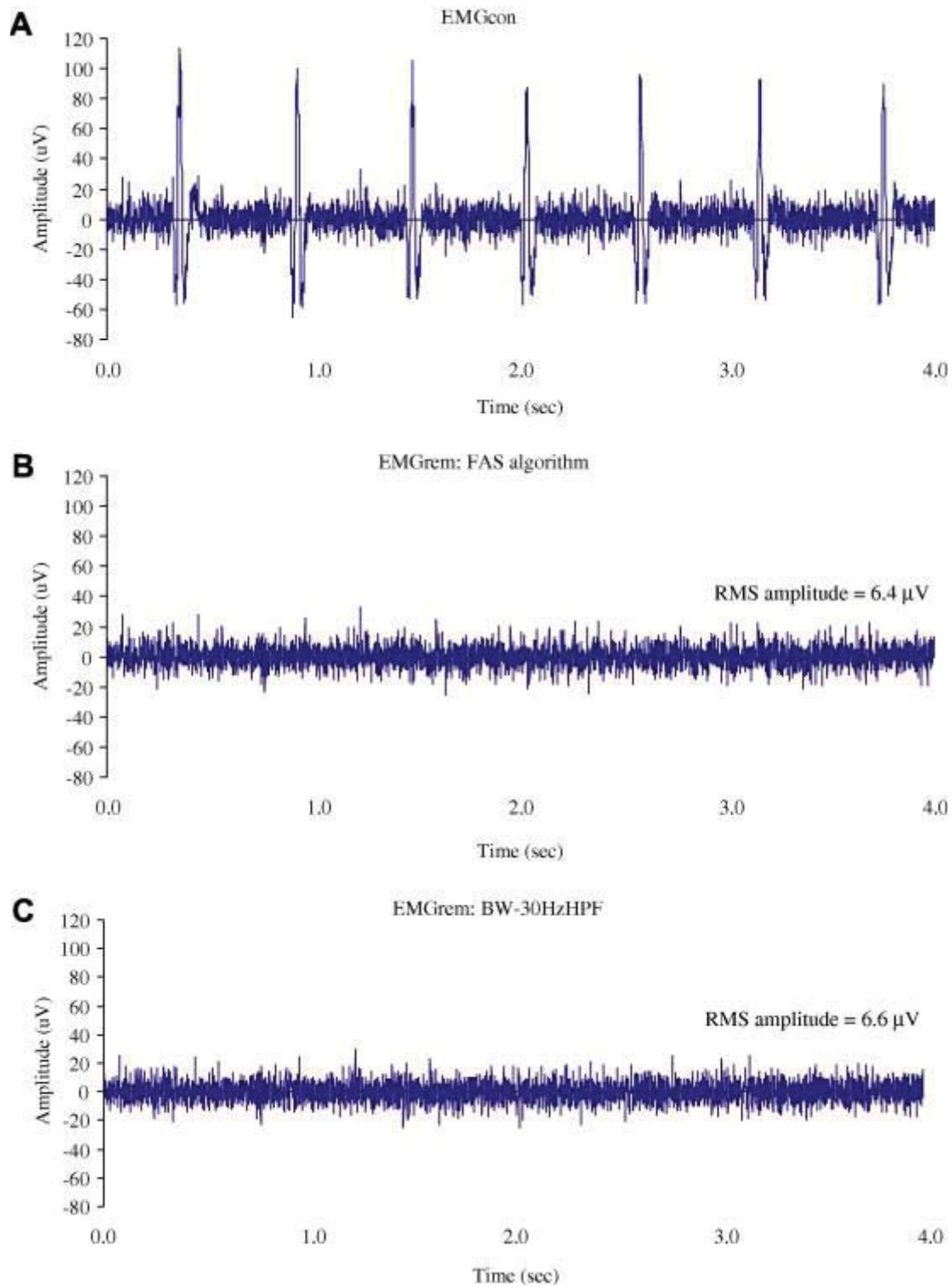

Fig. 6.

Ratio 1:1 for EMG_{con} (A) and EMG_{rem} using two removal methods: (B) FAS algorithm (filtering by adaptive sampling) and (C) BW-30 Hz HPF (Butterworth 30 Hz high pass filter).
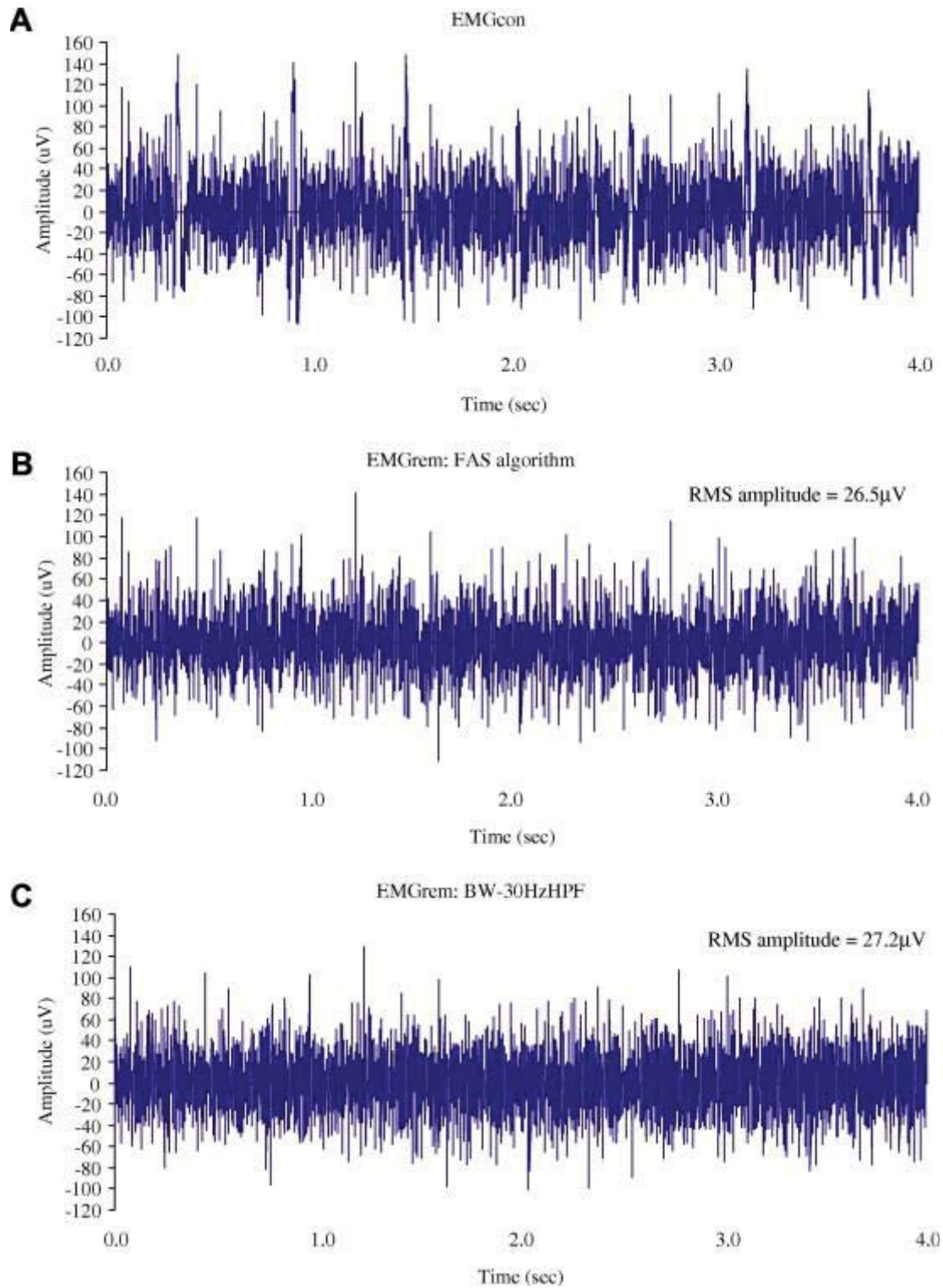
For the simulation analysis, the percent error associated with not removing the ECG was always greater than the error associated with either removal method (Fig. 4). Furthermore, the BW-30 Hz HPF method produced less percent error, however slight, than the FAS algorithm method across the different ratios. Because the BW-30 Hz HPF method was easier to implement and was more time efficient to remove the ECG from the contaminated signal, it was selected as the method to remove the ECG for the interpretation analysis in Part 3.

3.3. Part 3: Impact of filtering ECG on experimental data

When the datasets were analyzed separately, the ANOVA results showed a significant muscle-by-side interaction for both $EMG_{original}$ ($p = 0.000$) and EMG_{filter} ($p = 0.000$) datasets (Table 1). Comparing the statistical results from the $EMG_{original}$ dataset with the EMG_{filter} dataset, five different significant pair-wise comparisons were found. For the EMG_{filter} dataset, the right EO1 was not different from EO2 and EO3 as well, no differences were found between the right EO2 and left EO2. However, significant differences were observed for the left EO1 and left EO2 as well the left EO2 and right EO3 for EMG_{filter} dataset. These different statistical pairwise outcomes created different interpretations of the recruitment strategies for the external oblique muscle sites.

Table 1.

Side-by-muscle site comparison of the mean normalized amplitudes (%MVIC) for the EMG_{filter} and $EMG_{original}$ datasets during the right asymmetric lift and replace task

Muscle site		$EMG_{original}$ (% MVIC)		EMG_{filter} (% MVIC)	
		Right	Left	Right	Left
EO1	mean	6.2	5.1	5.3	4.1
	(SD)	(2.6)	(2.6)	(2.2)	(2.2)
EO2	mean	4.6	6.1	4.8	6.0
	(SD)	(2.7)	(4.0)	(3.0)	(4.0)
EO3	mean	4.7	6.7	4.6	6.3
	(SD)	(2.3)	(3.4)	(2.3)	(3.2)

*$=p < 0.05$.

When the datasets were combined to determine the statistical effect of the removal method, the ANOVA results showed significant main effects for side ($p = 0.030$) and dataset ($p < 0.000$) and significant two factor interaction effects for muscle site-by-side ($p < 0.000$) and muscle site-by-dataset ($p < 0.000$). Since there was not a significant three-factor interaction (muscle site, side, dataset), the changes in muscle site activation amplitudes with side were similar for both datasets

(EMG$_{original}$, EMG$_{filter}$). However, the magnitude of the muscle activation amplitudes changed as a function of whether the ECG was removed (EMG$_{filter}$) or not (EMG$_{original}$) as demonstrated by a significant muscle-by-dataset interaction. Table 2 shows the mean activation amplitude for muscle site and dataset (EMG$_{original}$, EMG$_{filter}$). Comparison between the two datasets revealed that when the original EMG amplitude data was filtered using a BW-30 Hz HPF to remove the ECG artifact, the amplitude significantly decreased for EO1 (1.0% MVIC) and EO3 (0.3% MVIC). As expected, greater decreases in normalized activation amplitudes were observed for muscle sites closest to the heart (EO1). However, what was not expected was a slight increase in EO2 activation amplitude for EMG$_{filter}$. Further examination of the data showed that for some trials the BW-30 Hz HPF removed relatively more signal from the normalization trials than the lift trials resulting in slight, but non-significant increased normalized values.

Table 2.

Average (standard deviation) normalized amplitude muscle site-by-dataset comparison for the right asymmetric lift and replace task

Muscle site	Dataset	
	EMG$_{original}$ (%MVIC)	EMG$_{filter}$ (%MVIC)
EO1	5.7 (2.6)	4.7 (2.3)[a]
EO2	5.3 (3.4)	5.4 (3.5)
EO3	5.7 (3.0)	5.4 (2.8)[a]

a

Statistically different from EMG$_{original}$.

4. Discussion

This study established that the presence of an ECG artifact had an effect on low-level abdominal wall muscle activation amplitudes during a functional lifting task. Two ECG removal methods were compared to determine their effectiveness to reduce the influence of the ECG artifact in simulated data. The Butterworth high pass filter at 30 Hz method was selected as the better method to remove ECG from an experimental dataset since it produced slightly lower errors and required less processing time. For the experimental data, the significant pairwise comparisons from the ECG removed dataset differed from the original contaminated dataset, which resulted in different interpretations of the neuromuscular recruitment of the external oblique muscle sites. When the effect of the dataset was tested, lower external oblique activation amplitudes for sites that were located closest to the heart were observed. Together these results suggest the removal of the ECG artifact when analyzing low-level abdominal wall muscle activation is necessary to obtain accurate EMG amplitude measures.

4.1. Part 1: Simulation: effect of the ECG artifact

Application of the criterion methodology that compared uncontaminated EMG signals and EMG signals contaminated with ECG allowed us to directly determine the effect of the ECG artifact on activation amplitudes. This methodology is important and should be used to compare various techniques for similar work. While research has documented the importance of constant low-level trunk muscle activations (Cholewicki and McGill, 1996, Granata and Orishimo, 2001a, Granata and Wilson, 2001b and McGill et al., 1995), many studies have not addressed the ECG issue nor described the methodology used to deal with ECG contamination in low-level trunk activations. The inconsistent reporting of ECG removal in previous studies may be related to the lack of evidence for the direct effect of the ECG on the amplitude of the EMG signal. For the few studies that have used ECG removal methods, they did not compare the signal with the ECG removed to an uncontaminated signal (criterion measure) (Cholewicki et al., 1997). Thus, the true effect of the removal method has remained unclear.

In the present study, the ECG artifact resulted in signals with overestimated activation amplitudes. Greater percent errors were observed when the amplitude of the ECG was considerably larger than the amplitude of the EMG. This scenario of large ratios can commonly occur in experimental data for muscle sites located close to the heart during low-level activations. When evaluating the influence of the ECG on these low-level activations, concern arises when small changes occur in these small amplitude signals since it can have a large effect on the relative estimates of change or errors. Therefore, the magnitude of change in the absolute RMS values must be considered along with the magnitude of the relative percent errors in order to address the ECG issue in the context of practical implications. The relative percent errors associated with examining the effect of the ECG on EMG in Part 1 of this study ranged from 14% to 68% across different ratios, whereas the difference in absolute RMS values ranged from 5 to 12 µV between EMG_{uncon} and EMG_{con} signals. While these absolute changes are small, the magnitude of the change in absolute values can reflect changes in the neural drive that may have practical and clinical implications for low-level muscle activations observed in antagonistic muscles. Results from this study and from other researchers (Aminian et al., 1988, Drake and Callaghan, 2006 and Zhou et al., 2007) using an uncontaminated signal as the criterion measure provide evidence that the ECG can influence EMG amplitude.

4.2. Part 2: Simulation: effect of the ECG removal methods

In order to determine a suitable removal method, it is necessary to determine whether the error associated with the EMG signal with the ECG is larger than the error associated with the method used to remove it. Our results showed that the ECG contamination induced larger percent errors compared to the errors related to the removal method. This is in agreement with previous studies Drake and Callaghan, 2006.

Direct comparisons of our results to other studies are difficult due to the use of different performance indicators, parameters and method modifications. However, general comments can be made. For the FAS method, Aminian et al. (1988) reported errors when comparing the original ECG to the reconstructed ECG, whereas our results are based on comparing the EMG signals. One may assume that similar errors would be noted since only a subtraction of the ECG from the EMG occurs for this method. Nevertheless, we observed less error for our EMG amplitude data using the FAS algorithm than previously reported. This may be the result of

modifications made to the algorithm. We used a unique approach to identify the QRS portion of the ECG. We feel that this modification improved the algorithm's ability to subsequently subtract the ECG, and thus decreased the errors associated with this subtraction method. Although, this method had the advantage to process subject specific data, it required the visual identification of a threshold level for the ECG of each trial and each muscle site. This process appreciably increased user time for ECG removal. While this procedure was effective in reducing the errors associated with the ECG ratios, the time it would require the user to process a dataset of 29 subjects with multiple muscle sites makes the method not suitable for large datasets.

Since the FAS method considerably increased the processing time, high pass filtering used in the present study offered a promising alternative method to remove the ECG artifact. However, no removal method has been shown to be 100% effective in removing the ECG without altering the EMG signal. This is mainly due to the overlapping power spectra of the ECG and EMG signals. Thus, each ECG removal method affects the EMG signal with varying degrees of distortion. For instance, using a second order Butterworth high pass filter (Zhou et al., 2007) showed that greater distortion of the EMG signal occurred at cut-off frequencies greater than 40 Hz. In fact, when filtering at 100 Hz the resulting EMG amplitude was 49% of the uncontaminated EMG signal, much of this change would be related the loss of the EMG signal itself. The greatest amount of the ECG artifact was eliminated when filtering at 40 Hz compared to 20 Hz than when comparing subsequently higher cut-off frequencies (Zhou et al., 2007). Drake and Callaghan (2006) observed that a second order Butterworth high pass filter at 30 Hz was effective in removing the ECG artifact for bicep muscle activations between 10% and 25% MVIC. Our results provide further evidence for the suitability of using a fifth order Butterworth high pass filter with a cut-off frequency at 30 Hz to effectively remove the ECG with low percent errors for abdominal wall muscle activation amplitudes below 10% MVIC.

In the present study, both methods reduced the relative errors associated with the ECG signal. When comparing the percent errors from the removal methods, the Butterworth high pass filter at 30 Hz produced lower errors in Part 2 of this study. However, only differences of 3–4% errors were observed between the removal methods across the different ratios. This translates, in terms of absolute RMS values, to changes less than one microvolt between the removal methods. In this context, both removal methods performed similarly, however, the less computational time associated with the Butterworth filter made it the superior method to be used in Part 3. In fact, Zhou et al. (2007) indicated that implementing a high pass filter to remove the ECG was 30,000–50,000 times faster than when adaptive filtering was utilized.

4.3. Part 3: Impact of filtering ECG on experimental data

Although the percent error associated with the ECG may seem large on low-level activation amplitudes, its effect on the interpretation from a statistical standpoint has been unclear to date. To the knowledge of the authors, this is the first study to investigate whether removing the ECG artifact has an impact on the interpretation of neuromuscular recruitment strategies from experimental data using abdominal wall muscles. However, a recent study showed that removing the ECG artifact from back muscle EMG amplitudes improved the discrimination between healthy controls and individuals with persistent low back pain (Hu et al., 2007).

In the present study when the experimental dataset was not processed to remove the ECG, different interpretations of the abdominal muscle amplitude recruitment strategy were found compared to the dataset that filtered the ECG. First, for the EMG$_{filter}$ dataset, the right EO sites were recruited to similar amplitudes compared to the differential recruitment observed for the EMG$_{original}$ dataset. Interestingly, several studies suggest that a bracing strategy that recruits more muscle sites to similar amplitudes may be a better balanced neuromuscular strategy for spinal stability than selective recruitment of individual muscle sites (Brown et al., 2006 and Grenier and McGill, 2007). Secondly, the left EO2 and EO3 activation increased compared to EO1 in response to the contralateral load for the EMG$_{filter}$ dataset, whereas only EO3 activation was significantly higher for the EMG$_{original}$ dataset. This finding may be explained by different functional roles of different muscle sites within the external oblique muscle (Wickham and Brown, 1998). The more vertical fibers of EO2 and EO3 are better suited to respond to external lateral flexion moments created by the asymmetrical loading (Huang et al., 2003 and Mirka et al., 1997). Therefore, if the ECG is not removed, different interpretations of the neuromuscular recruitment and functional actions of low-level abdominal wall amplitudes result.

When the effect of the ECG removal method was tested, the results revealed significant reductions in activation amplitude (1.0% MVIC) after the ECG was removed using the BW-30 Hz HPF method with greater decreases in muscle sites closest to the heart (EO1). While statistical differences were observed between the datasets, the clinical relevance of a 1.0% MVIC difference warrants further discussions. It has been suggested that a 1.0% MVIC change would be of little consequence when estimating global spinal loading and stability estimates (McGill et al., 1996). However, when considering the change in terms of an antagonist muscle, which is activated to low amplitudes, the relative effect may provide additional information. For instance, after prolonged standing, individuals who reported low back discomfort showed slight but significant increased amplitudes for the external oblique and erector spinae muscle sites (Gregory et al., 2007). They suggested these increases could be harmful to the spine in terms of cumulative spinal loading. The practical significance of these findings speaks to the potential for the reduction in endurance time to carry out occupational tasks while standing. In addition, several studies have shown 1–2% MVIC changes in activation amplitude among muscle sites within a muscle depending on the mechanical line of action for a given external moment direction (Brown et al., 2007, Mirka et al., 1997, Moseley et al., 2003, Vink et al., 1988 and Wickham and Brown, 1998). Based on these observations it has been suggested that the CNS can coordinate different regions within a muscle. At the present time it is unclear how the level of activation from different muscles affects force production and the resultant spinal loading and stability estimates. However, absolute small changes (1.0% MVIC) may provide interesting information in the neural drive to antagonist muscles that define functional roles and provide additional understanding of motor control strategies for low muscle activations. This information may be helpful in designing rest breaks for cumulative spinal loading and ergonomic prevention strategies in the workplace.

5. Limitations

Consistent with other simulation studies of this kind, data were collected on one subject and from one muscle. Although only one muscle was used, this study was the first to use an abdominal muscle from the human trunk to represent the criterion measure to which the contaminated

signals were compared. The fact that these results using an abdominal muscle support the use of the same method to remove the ECG as other researchers using muscles of the upper arm ([Drake and Callaghan, 2006](#)) and chest muscles. [Zhou et al. (2007)](#) suggests that the Butterworth high pass filter at 30 Hz method may be appropriate for all trunk muscles. However, this assumption remains unconfirmed.

The representative uncontaminated ECG signal was collected from the upper rectus abdominis muscle site during a light lifting trial. This method included some EMG signals and may have produced a different ECG signal than if collected using a standardized ECG electrode configuration. The resulting ECG signal may therefore include noise from the data collection system. However, the ECG profile was clearly shown and the EMG was digitally zeroed between the QRS portions of the ECG and slightly smoothed, and thus was a suitable representation. In addition, the uncontaminated EMG signal was the signal that was digitally adjusted for the different ratios. Thus the noise would be a systematic error across the trials and may not have a large effect.

While other studies compared up to four methods, this study only compared two removal methods, which were selected based on their ability to remove the ECG artifact. In fact, the Butterworth high pass filter at 30 Hz method was consistently ranked as the better method for ECG removal for amplitude levels between 10% and 25% MVIC compared to the other methods ([Drake and Callaghan, 2006](#)). The results from the present study provide additional support for its use for activation amplitudes less than 10% MVIC. Since performance indicators were based only on amplitude measures, the results are not necessarily appropriate for research questions regarding frequency content of the EMG signal. Thus, the effects of filtering on frequency characteristics should be further investigated.

Finally, for the interpretation analysis, only the lifting portion of the total movement was included. Although the lift typically took less than 1-s to perform, it is highly probable that the ECG was present within the time period since the average resting heart rate is 72 beats/min. Thus, the study's results would be conservative since longer time periods would include more ECG, which in turn would have a greater influence on the amplitude measures. The implication of this assumption is that for tasks in which the duration was long enough to capture more ECG signals, the differences would be larger between the $EMG_{original}$ and EMG_{filter} datasets. Nevertheless, the fact that different statistical results were observed between the data with and without the ECG removed for this short duration task (<1 s) provides support for the removal of the ECG artifact.

6. Summary and recommendations

In summary, since the effect of ECG on trunk muscle activation amplitudes was larger than the errors associated with its removal, it is recommended that the ECG be removed for low-level activation amplitudes. Furthermore, based on smaller errors and less computational time a 5th order Butterworth high pass filter at 30 Hz is recommended for trunk muscles over the FAS method for activations less than 10% MVIC. This study also revealed that interpretation of neuromuscular recruitment of abdominal wall muscles was dependent on whether the ECG was removed or not. These changes in interpretation associated with removal, along with the

substantial error associated with the ECG artifact suggests the need to remove ECG from EMG amplitudes during low-level abdominal wall muscle activation. With a multitude of research studies examining low-level trunk muscle activations, it is the recommendation of the authors that published guidelines for reporting EMG should include guidelines for reporting methods used to treat the ECG artifact contained in the EMG signal.

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