Changing filtering parameters affects lower extremity pre-landing muscle activation onset times

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Abstract:

Surface electromyography(sEMG) is extensively used to examine muscle activation. Although raw sEMG signals are often filtered using Root-Mean-Square(RMS) algorithms, little agreement exists as to the time window over which signals should be processed. We examined the effects of differing RMS filtering windows on muscle onset times. Fifty-five participants performed 5 drop jumps from a 45 cm box and lateral gastrocnemius(LG), medial and lateral hamstring(MH, LH) and lateral quadriceps(LQ) muscle activity were acquired. Signals were collected at 1000 Hz and RMS filtered using 3 ms, 10 ms, 20 ms and 25 ms windows. Muscle onset times differed by RMS windows for the LG(p= 0.01), MH(p= 0.002), and LH(p= 0.000), but not for the LQ(p=0.14). Pairwise comparisons indicated that LG onsets were earlier with the 3 ms vs. 20 ms window, MH onsets were earlier with the 3 ms vs. 20 ms and 25 ms windows, and LH onsets were earlier with the 3 ms, 10 ms, and 20 ms windows than the 25 ms window. Gastrocnemius and hamstring muscle onset times were substantially earlier when filtering raw sEMG data with 3 ms versus wider RMS windows(> 20 ms) during landing. Changing filtering parameters affects data interpretation when analyzing sEMG data using differing window widths. Additional research should determine optimal RMS window widths that maximize signal fidelity but still retain meaningful time differences.

Keywords: Surface electromyography | root mean square | signal processing | drop jumps

Article:

1. Introduction

Surface electromyography (sEMG) is extensively used in movement sciences research to obtain physiological or clinical information about muscle function [13], pathology [4,38], performance related issues [2,37], injury risk [8], and the effect of intervention programs [7,17,39]. An important application of sEMG is the detection of muscle activation onset times i.e. whether the muscle was active or not at a particular point in time following a period of inactivity [9,

19,21,23]. Researchers have examined muscle onset times in various activities including step downs [13, 20], landings [8,14,24,25,32], walking [21,27,35], and cutting [30].
Before muscle onset times are identified, the raw sEMG signals are typically filtered [18]. Although several techniques have been described in the literature for filtering raw sEMG signals, Root Mean Square (RMS) is a processing technique that is becoming increasingly popular when examining sEMG during dynamic activities [16,29,34,40]. As the RMS value is a measure of the power of the signal, it has a clear physical meaning and is recommended for sEMG data processing [3,10]. When using RMS as the filtering technique to process raw sEMG data: (1) the raw signal is squared; (2) a moving mean value is obtained over specified window widths (a function of time); and (3) the root of this value calculated [18]. The width of the RMS smoothing window needs to be small to detect subtle yet clinically significant onset time differences between groups. This is because using wider time windows to smooth raw data can lead to oversmoothing, causing subtle phasic changes in muscle activation to be washed out from the original signal [26]. Additionally, wider windows may also cause time and phase shifts in the data, actually changing temporal parameters [26]. A compromise is therefore needed to keep the window wide enough to allow for adequate data smoothing, while not making the window so wide as to over smooth the data.

To determine whether a muscle is truly active, it needs to exceed a pre-defined threshold. Pre-defining this threshold value helps to consistently determine muscle activation onset times by clearly identifying when the muscle activity deviated from baseline sEMG activity. Previous researchers [1,5,11,13,15,24,25,28, 35] have used a range from ± 1 to ± 5 SD (standard deviations) above baseline activity to determine muscle onset. DeLuca [9] suggested that a ± 2 SD from baseline would allow one to be 95% confident that the muscle onset time has been accurately recorded. As baseline activity might differ across muscles, it may be necessary to individually set the threshold value for each muscle [33]. Further, the muscle activation needs to be sustained over a certain time period (25 ms) [9, 11,13,33] to ensure that the recorded time truly signi- fies the actual onset of muscle activity and not just an erroneous spike in the activity.

While RMS filtering is commonly employed by researchers, the RMS smoothing window widths used to filter data have ranged from 3 to 40 ms [21,36,40]. The differences in data filtering windows can be confusing for clinicians using evidence-based research for their clinical practice. In a recent systematic review and meta analyses of the relative timing of medial and lateral quadriceps muscle onsets in patients with anterior knee pain, Chester et al. [6] noted that although trends were noted towards earlier medial quadriceps onsets, no conclusions could be drawn due to the heterogeneity in methodology including sEMG data collection and processing techniques. While the International Society of Electrophysiology and Kinesiology (ISEK) suggests that filtering at time constants (window widths) higher than 25–30 ms introduces detectable delays and should not be used when investigating any muscle timing relationships with other events [26], relatively little research has examined the effect of changing sEMG filtering parameters on muscle onset times. Gabel and Brand [15] reported the effects of different sEMG signal conditioning on statistical analyses of sEMG noting that filtering sEMG data differently does affect muscle onset time values. Morey-Klapsing et al. [28] also observed that muscle onset times changed based on the thresholds (± 2 SD, ± 3 SD or ± 4 SD) and the window widths (13 ms or 26 ms) used to determine onsets. However, we could not find specific

consensus in the published literature as to the time constant to be used when filtering raw sEMG data using RMS to calculate muscle onset times during activity.

Thus, our purposes were to examine the effect of different RMS filtering windows on lower extremity muscle onset times during drop jumps and to quantify the extent of muscle onset delays that are introduced due to the differing filtering windows.

2. Methods

2.1. Participants

Fifty-five healthy females (20.4 ± 2.2 yrs, 166.5 ± 7.1 cm, 66.0 ± 12.1 kg) with no musculoskeletal injury to either lower extremity for six months prior to data collection, no previous surgery on either lower extremity, no history of cardiovascular or neurological problems, and no pre-existing conditions that would have detracted from the ability to land or jump participated in the study.

2.2. Instrumentation

All sEMG data were collected using a 16-Channel Myopac surface EMG unit (Run Technologies, Mission Viejo, CA). The sEMG unit had an amplification of 1mV/V with a frequency bandwidth of 10 to 1000 Hz, a common mode rejection ratio of 90 dB min at 60 Hz, an input resistance of 1 MHz and an internal sampling rate of 8 KHz. Bipolar, Ag/Ag-Cl surface electrodes (Blue Sensor N-00-S; Ambu Products, Ølstykke, Denmark; skin contact size 30 × 22 mm) with a centerto-center distance of 20 mm were used to collect the sEMG data. sEMG data were acquired, stored, and analyzed using the Datapac 2K2 Lab Application Software (Run Technologies; Mission Viejo, CA). SEMG activity were synchronized with a type 4060 non-conducting forceplate (Bertec Corporation; Columbus, OH) using a trigger sweep mode. Foot contact exceeding 10 N triggered collection of the sEMG data. All sEMG were sampled at 1000 Hz.

2.3. Procedures

Participants completed a university approved informed consent form after which demographics were recorded. All measurements were taken on the preferred landing leg. The preferred leg was determined by asking participants to perform 3 single-leg landings from a 45 cm box placed above two forceplates. The leg that the participant used to land 2 out of 3 times was chosen as the preferred landing extremity. All subsequent recordings were done on this extremity.

Electrodes were placed on the skin over the LG, LH, MH, and LQ muscles of the preferred leg after shaving and wiping the areas with alcohol swabs [34]. The electrodes were oriented perpendicular to the length of the muscle fibers and placed midway between the motor point and the distal muscle tendon of the lateral quadriceps, and the mid bellies of the medial hamstrings, lateral hamstring, and the lateral gastrocnemius muscles as previously reported [34]. The reference electrode was attached over the flat anteromedial bony aspect of the tibia, midway between the tibial tuberosity and the intermalleolar point. Absence of crosstalk between the

electrodes was then visually confirmed with manual muscle testing using the scope mode of the data acquisition software. To prevent any pulling or twisting of the wires during activity that potentially could affect the sEMG signal the electrodes and wires were secured to the skin using stress loops with pre-wrap and regular white athletic tape.

Participants then performed 5 double-leg drop jumps from a 45 cm box. Participants dropped off the box and then immediately upon ground contact performed a vertical jump as high as possible and landed back onto the forceplate. Throughout the landing trial, participants looked forward, and kept their hands on their hips at all times. Participants also were asked to maintain their balance upon landing and not move off of the forceplates until told to do so by the investigator. Suf- ficient practice was allowed for participants to become comfortable with the task. A rest interval of 10 seconds was provided between each trial. A trial was discarded and participants were asked to repeat the trial if they lost their balance, if their hands came off of their hips at any point during the trial, or if they failed to land back onto the forceplate. The trigger sweep acquisition mode was used to obtained identically timed trials 500 ms prior to contact with the forceplate (> 10N) the initial landing and 2500 ms after the initial landing. The law of constant acceleration ensured that the estimated time of free fall from the box (45 cm) was ~262.5 ms, ensuring that participants were not on the box 150 ms before ground contact, and collecting muscle activity 2500 ms post initial landing allowed us to ensure that all participants successfully completed the drop jump.

2.4. Data processing and analysis

The sEMG signals were digitally processed with a band pass filter from 10 Hz to 350 Hz, using a fourthorder, zero-lag Butterworth filter. SEMG signals were then digitally filtered using a centered RMS algorithm with time windows of 3 ms, 10 ms, 20 ms and 25 ms. Five trials for each participant were then ensemble averaged to obtain one composite representative trial for each participant for each window width [33] (Fig. 1). The ensemble average of 5 trials for each RMS window was used for analyses. Muscle onset (ms) was defined as time prior to ground contact when muscle activity exceeded 2 standard deviations above quiet standing baseline activity for at least 25 ms [13,33]. Baseline sEMG data were collected for 2 seconds in quiet standing prior to task performance. As our research question was a within repeated-measures temporal (onset times) one and not amplitude-based, we did not normalize sEMG data to maximum voluntary isometric contractions.

2.5. Statistical analyses

Four separate repeated measures ANOVAs for each muscle (LG, MG, LH, and LQ) compared muscle onset times across the four RMS window widths (3 ms, 10 ms, 20 ms and 25 ms). An alpha level of 0.05 was used for all tests. Post-hoc analyses consisted of pairwise comparisons with Bonferroni corrections. All analyses were conducted using the SPSS 15.0 version for Windows software (Statistical package for Social Sciences, Chicago, IL).

3. Results

Muscle onset times for the four muscles using the different window widths are presented in Table 1. Muscle onset times were earlier with wider RMS windows for the lateral gastrocnemius ($F_{3,162} = 4.48$, $p = 0.01$), the medial hamstrings ($F_{3,162} = 5.22$, $p = 0.002$), and the lateral hamstring ($_{F3,162} = 8.76$, $p = 0.000$) muscle. However, no significant change in onset times was observed for the lateral quadriceps muscle across the 4 RMS windows ($F_{3,162} = 1.50$, $p = 0.14$). Pairwise comparisons indicated that LG onsets were 22 ms later when using a 20 ms vs. 3 ms ($p = 0.001$) window. MH onsets using 20 ms and 25 ms windows were 13 ms ($p = 0.01$) and 16 ms ($p < 0.001$) later than the onset obtained with a 3 ms window. LH onsets were 30 ms ($p = 0.01$), 36 ms ($p < 0.001$), and 20 ms ($p = 0.04$) later at 10 ms, 20 ms and 25 ms windows, respectively, compared to the 3 ms window. A graphical representation of muscle onset time shift with increasingly wider RMS window widths is presented in Fig. 2.

Muscle	3 ms window	10 ms window	20 ms window	25 ms window
LG	133.3 ± 32.4*	145.3 ± 32.0	155.6 ± 41.1	141.5 ± 44.1
MH	114.5 ± 22.9*†	122.0 ± 22.1	127.6 ± 27.9	130.4 ± 36.8
LH	95.5 ± 43.9†	88.6 ± 42.1†	104.7 ± 42.7†	124.4 ± 42.9
LQ	38.3 ± 26.3	42.6 ± 22.2	46.8 ± 26.7	45.2 ± 26.3

LG = Lateral Gastrocnemius Muscle, MH = Medial Hamstrings Muscle LH = Lateral Hamstring Muscle, LQ = Lateral Quadriceps Muscle.
*Significantly Different compared to 20 ms window.
†Significantly Different compared to 25 ms window.

Table 1
Muscle Onset Times (ms) using different Root Mean Square (RMS) Filtering window widths (3 ms, 10 ms, 20 ms, and 25 ms) during the Drop Jumps (Means ± SD)

4. Discussion

Our primary findings were that gastrocnemius and hamstrings muscle onset times increased as much as 20–30 ms when wider RMS windows were used to process raw sEMG data during drop jumps. The lateral quadriceps muscle was less sensitive to these changes in filtering parameters across the RMS windows.

The observed differences in muscle onset times were solely the result of altering filtering window widths. As changing window widths affects data extraction, it may also affect the subsequent interpretation of the data. Several examples exist in the literature of investigators deriving clinical implications based on differences of similar or even smaller magnitudes in lower extremity muscle onset times than those noted in the current study (i.e. differences of 30 ms). In an investigation of the effect of upper limb motion on lower limb muscle synchrony [8], differences of 15 and 22 ms respectively in the rectus femoris and medical gastrocnemius muscle onsets were interpreted as being significantly different when data were processed with 20 ms windows between ball catching versus no ball catching during landing. A difference of 12 ms in the medial gastrocnemius was interpreted as being significantly different between self-initiated and unexpected landings when processing data with 20 ms windows [14]. A close to significant association in vastus medialis oblique muscle onset times filtered with a 10 ms RMS smoothing window between individuals with and without patellofemoral pain during a step down task was

based on a difference of 16 ms in muscle onset times between the groups [13]. Finally, a change of 3–5 ms in vastus medialis and lateralis muscle onsets after simple full wave rectification of the raw sEMG data was interpreted as being significantly different and an indicator of the effect of a resistance training intervention during a sit to stand movement between controls and resistance trained individuals [39].

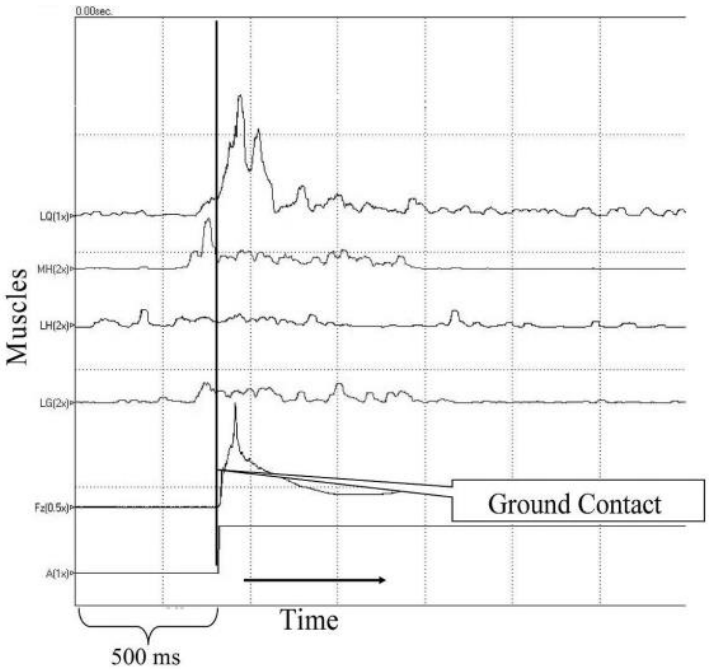

Fig. 1.
Representative Trial showing sEMG tracings of the Lateral Quadriceps (LH), Medial Hamstrings (MH), Lateral Hamstring (LH), Lateral Gastrocnemius (LG) muscles during the Drop Jumps. Fz = Ground Reaction Force, A = Ground Contact Event Marker.

As can be seen in the abovementioned exemplar studies, differences to the magnitude of 3–25 ms between groups and/or intervention programs have been interpreted to be clinically different. We noted magnitude changes to the order of 30 ms in the current study with the differing smoothing window widths. Therefore, it is theoretically possible that had some of the abovementioned studies employed narrower or wider smoothing sEMG windows, the muscle onset times extracted could have differed up to 30 ms, possibly affecting statistical analysis results, and subsequent clinically significant interpretation of the results.

Another example of the importance of our findings is the observation that lateral hamstrings muscle onset times changed by as much as 36 ms when filtered using a 10 ms RMS window (88.6 ms) versus a 25 ms RMS window (124.4 ms). This magnitude represents almost a 33% change in the onset times, exclusively due to changing window widths. The hamstring muscles are known to be protective to the anterior cruciate ligament [12,22]. Therefore, with ligament rupture suggested to be possible as early as 73 ms after loading [31], a 36 ms difference in muscle onset may be interpreted as the difference between safe vs. unsafe absorption of impact

load absorption on body tissues during movement in an investigation of the effect of an injury prevention program on muscle activation parameters.

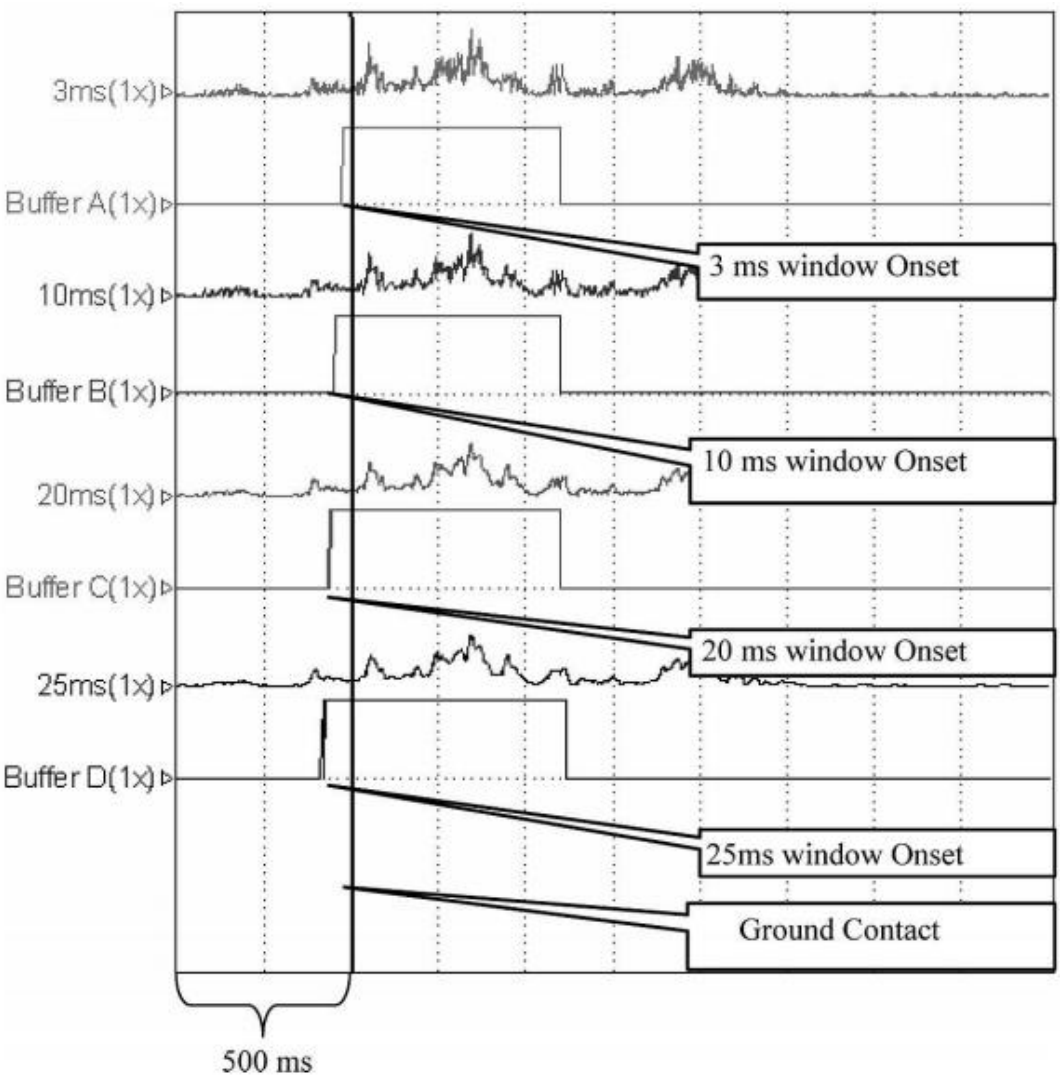

Fig. 2.
Graphical Exemplar Representation of the shift in Lateral Gastrocnemius Muscle Onset Times when using progressively wider Root Mean Square window widths (3 ms, 10 ms, 20 ms, and 25 ms) with buffers representing identified muscle onsets (x = magnification).

While the gastrocnemius and hamstrings were clearly affected with the changing window widths, the quadriceps did not appear to have similar magnitudes of change with the different windows. A possible explanation could be the activation pattern of the quadriceps muscle during the movement (initial landing during the drop jump). As can be seen in Fig. 1, the quadriceps were the last muscle to activate, with a rapid ramp up in activation levels very close to ground contact. The extraction of the quadriceps muscle onsets may therefore not have been affected as much as the other muscles by the filtering procedure.

Given the sizeable effect of changing window widths on muscle onset times it is important to determine the optimal window width to be used for RMS filtering of raw sEMG data. There is a need to compromise between maximizing signal fidelity while still retaining meaningful time differences when filtering raw EMG data. To examine this, it is important to review the technique of calculating RMS. When calculating RMS to smooth raw data, at least three points are needed; the raw data point to be filtered itself (n), one data point before (n−1) and one data point after (n+1) the raw data point [18]. The centered RMS algorithm then averages these three data points to give the filtered data point. Obviously, the more data points that are included in the RMS algorithm (i.e. wider window width) the smoother the data. With a 1000 Hz sampling rate used in the current study, the minimum window width to perform RMS filtering sEMG data was 3 ms (i.e. 3 data points). We observed that using the 20 and 25 ms windows changed onset times in most muscles as compared to the 3 ms window (which would theoretically cause least raw data distortion as it had the least data points). It thus appears that using a 20 or 25 ms window width may be too wide, possibly causing over smoothing of raw sEMG data during movement in agreement with the recommendations of the ISEK [26]. Researchers thus should not filter raw sEMG data collected at 1000 Hz using window widths greater than 20 ms when examining timing variables. While the ISEK only recommends that window widths smaller than 25 ms should not be used when examining temporal variables, no specific recommendations for a filtering window width to be used are suggested. We noted that while using a 10 ms window did not result in any significant differences in muscle onset times as compared to using a 3 ms window, it did result in visually smoother data as compared to the 3 ms window (See Fig. 2). Thus, the 10 ms window needs to be investigated as a promising optimal window width when RMS filtering sEMG data collected at 1000 Hz.

A limitation of the current study is that the results are specific to the sampling frequency used to collect raw sEMG data (1000 Hz) and in a landing movement. Nevertheless, with several researchers [14,20,24,25,36]using a similar sEMG sampling rate previously, our findings provide an initial point for researchers to determine optimal RMS smoothing window widths across different activities. Further, as the task used in the study was a dynamic task using a healthy preferred landing leg, whether the results would remain the same across other tasks, types of contraction (e.g. isometric), and in pathological populations remains unclear and needs further investigation.

5. Conclusions

Overall, our findings suggest that extraction of lower extremity muscle activation onset times during activity can be substantially affected when filtering raw sEMG data using differing RMS windows. To limit the negative effects of signal processing on raw sEMG data, a compromise is needed between maximizing signal fidelity while still retaining meaningful time differences. Future researchers need to examine the extent to which changing RMS window widths affects muscle timing variables during other activities. Additional research is needed to determine the optimal RMS smoothing window widths to examine muscle timing variables during movement. These examinations will consequently assist clinicians to make appropriate clinical interpretations and recommendations from sEMG studies during activity.

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