Title: The relationship between submental surface electromyography and hyo-laryngeal kinematic measures of Mendelsohn Maneuver duration

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Abstract

Purpose: The Mendelsohn maneuver (MM) is a commonly prescribed technique that is taught to individuals with dysphagia to improve swallowing ability. Due to cost and safety concerns associated with videofluoroscopy (VFS) use, submental surface electromyography (ssEMG) is commonly used in place of VFS to train the MM in clinical and research settings. However it is unknown whether ssEMG accurately reflects the prolonged hyo-laryngeal movements required for execution of the MM. The primary goal of this study was to examine the relationship among ssEMG duration, duration of laryngeal vestibule closure, and duration of maximum hyoid elevation during MM performance.

Method: Participants included healthy adults and patients with dysphagia due to stroke. All performed the MM during synchronous ssEMG and VFS recording.

Results: Significant correlations between ssEMG duration and VFS measures of hyo-laryngeal kinematic durations during MM performance ranged from very weak to moderate. None of the correlations in the group of stroke patients reached statistical significance.

Conclusions: Clinicians and researchers should consider that the MM involves novel hyo-laryngeal kinematics that may be only moderately represented with ssEMG. Thus, there is a risk that these target therapeutic movements are not consistently being trained.

Introduction

Swallowing maneuvers are widely incorporated into dysphagia therapy because of known immediate physiological changes that can improve airway protection kinematics (Bulow, Olsson, & Ekberg, 2001; Hind, Nicosia, Roecker, Carnes, & Robbins, 2001; Kahrilas, Logemann, Krugler, & Flanagan, 1991; Lazarus, Logemann, & Gibbons, 1993; Masako, 1996; McCullough et al., 2012; Nagaya, Kachi, Yamada, & Sumi, 2004; Ohmae, Logemann, Kaiser, Hanson, & Kahrilas, 1996). The Mendelsohn Maneuver (MM) is a swallowing maneuver that involves volitionally prolonging the duration of hyo-laryngeal elevation during swallowing, which also impacts upper esophageal sphincter opening durations, according to some reports (Boden, Hallgren, & Witt Hedstrom, 2006; Hoffman et al., 2012; Kahrilas, et al., 1991). Since the kinematics of swallowing are internal, hyo-laryngeal movements during MM performance have been viewed with videofluoroscopy (VFS) (Kahrilas, et al., 1991). VFS, however, has known disadvantages including high cost, reduced accessibility, and exposure to ionizing radiation.

Surface EMG offers a low cost, easily accessible alternative that eliminates the negative health impact associated with VFS. Thus, investigations of long-term effects of MM training in patients have used submental surface electromyography (ssEMG) to teach the MM and as biofeedback during training (Crary, Carnaby Mann, Groher, & Helseth, 2004; McCullough, et al., 2012). The submental region is targeted for EMG recording during swallowing because it houses muscles that play an integral role in hyo-laryngeal elevation; namely the mylohyoid, geniohyoid, and anterior belly of the digastrics

(Pearson, Hindson, Langmore, & Zumwalt, 2013). However, ssEMG lacks specificity for defining hyo-laryngeal function during swallowing because it records submental muscle activation during other swallowing events, in addition to hyo-laryngeal excursion. For example, it records submental muscle activation that occurs when stabilizing the floor of mouth during tongue movements (Palmer et al., 2008). Furthermore, ssEMG is unable to record activity of other muscles that contribute to hyo-laryngeal elevation during the MM, such as the longitudinal pharyngeal muscles (Pearson, et al., 2013). At this time, the relationship between swallowing hyo-laryngeal kinematics and ssEMG during performance of swallowing maneuvers, such as the MM, warrants more investigation.

Several investigations have shown strong relationships between ssEMG activity and swallowing kinematics during natural swallows (swallowing without a therapeutic technique) (Alfonsi et al., 2013; Chi-Fishman & Sonies, 2000; Crary, Carnaby Mann, & Groher, 2006, 2007; Dantas & Dodds, 1990; Zamir, Ren, Hogan, & Shaker, 1996). Wheeler-Hegland et al (2008) conducted an insightful study that correlated hyoid kinematics (seen on VFS) and ssEMG during MM performance (Wheeler-Hegland, Rosenbek, & Sapienza, 2008). Significant correlations were found between hyoid displacement and ssEMG activity during MM performance for discrete events such as time of maximum EMG and maximum hyoid displacement. However, the purpose of the MM training is for patients to prolong hyo-laryngeal displacement for at least 1.5 seconds (Ding, Larson, Logemann, & Rademaker, 2002; McCullough, et al., 2012), but duration of the MM was not examined in the Wheeler-Hegland study. Thus, given the

prolongation goal of the MM, the relationship between ssEMG and kinematic durations is pertinent and clinically relevant.

Our study was also motivated by inclusionary criteria reported in the methods of Wheeler-Hegland et al (2008). Participants were initially taught the MM with ssEMG, which was defined as increased ssEMG signal for at least 2 seconds. Then, the investigators confirmed proper MM performance with VFS. Although ssEMG training indicated that all participants performed the MM successfully, VFS identified that 24% of the participants were incorrectly performing the MM. These individuals were performing "partial" MM, which is defined as prolonged hyoid elevation, but no laryngeal vestibule closure (LVC). Furthermore, one participant in the Wheeler-Hegland had "successful" ssEMG MM training, but did not prolong hyoid elevation or LVC, and was subsequently excluded from the study (see Table 2, page 1078). These discrepancies were described as inclusionary criteria, but the relationship between ssEMG and hyo-laryngeal kinematics were not directly examined and reported in the results of the Wheeler-Hegland study.

The goal of this investigation is to assess the relationship among the durations of ssEMG duration, hyoid elevation, and LVC during MM performance in healthy adults and in stroke patients. We hypothesize that the relationship between ssEMG signals and hyo-laryngeal kinematics will be weak when measuring MM swallow durations for two reasons: (1) ssEMG is not specific to hyo-laryngeal movements, as it also records activity when stabilizing the floor of the mouth during tongue movements (Palmer, et al., 2008), and; (2) ssEMG does not record other major contributors to hyo-laryngeal elevation, including posterior belly of the digastrics, stylohyoid, stylopharyngeus, and palatopharyngeus (Pearson, et al., 2013). Therefore, ssEMG may not represent the extent of the activity of hyo-laryngeal elevators required for the maneuver, impacting accurate measures of MM swallow duration.

Methods

Ethical considerations

The Johns Hopkins University Institutional Review Board (IRB) approved this study. Written informed consent was obtained from all participants.

Participants

Participants included 21 healthy adults (mean age 32, range 18-54, 8 females) and 3 participants with dysphagia due to cortical stroke (mean age 68.3, range 60-80, 1 female). All healthy adults reported a negative history of speech, language, swallowing and cognitive impairment. One stroke patient had oropharyngeal dysphagia that lead to regular deep penetration due to delayed laryngeal vestibule closure onset. The other

two stroke patients frequently aspirated due to reduced upper esophageal sphincter opening as well as delayed laryngeal vestibule closure onset.

Procedures

Training participants to achieve the MM - Participants were seated upright in view of a monitor displaying real-time VFS. First, a lateral view still-shot of the participants' oropharyngeal anatomy was used to orient them to the oral cavity, the pharynx, and the larynx. They were then instructed to palpate their thyroid notch to feel its movement during a saliva swallow. Instructions on how to perform the MM were "swallow and hold your Adam's apple up as high and as long as possible". Participants swallowed their saliva during all MM trials in this study.

Performing the MM – Once participants demonstrated the first accurate MM performance, healthy participants performed an additional 6 MM trials. Stroke patients performed an additional 16 MM trials, to increase their chances of learning the behavior. Healthy adults were told to hold the MM for as long as possible. Patients were instructed to hold the maneuver for no longer than 6 seconds to prevent fatigue. Although clinical training of the MM does not require MM performance up to 6 seconds, we were interested in understanding the relationship among VFS and ssEMG in a wide range of MM durations.

Recording and Analyzing ssEMG and VFS

Recording: ssEMG and VFS were synchronously recorded during all MM swallows. All swallows were recorded with continuous VFS, acquired in the sagittal plane with a video capture rate of 30 frames per second. The image intensifier included the oral cavity, pharynx, larynx, cervical vertebrae, and cervical esophagus. A time code was simultaneously recorded and facilitated frame-by-frame data analysis. Bipolar ssEMG electrodes (Motion Lab Systems, Inc.) were placed on the left and right sides of the submental muscle group, approximately half way between the hyoid bone and the mentalis of the mandible. We expect that we were recording floor of mouth muscles (primarily anterior belly of the digastrics, mylohyoid, geniohyoid) and it is also possible that we recorded activity from hyoglossus and genioglossus. In order to ensure accurate surface EMG interpretation, there are technical data acquisition settings that must be considered. The rate of sampling is an important factor. Using a low sampling frequency can result in distortion of the signal and affect the reliability of the study (Ives & Wigglesworth, 2003). Therefore, we also considered the effects of sampling frequency on the data obtained, comparing the results in two groups with different sampling rates, 1kHz (low sampling frequency) vs. 10kHz (high sampling frequency)(Figure 1). Submental surface EMG was recorded throughout the study at a sampling rate of 1000 Hz (1kHz) for 78 of swallows and 10,000 Hz (10kHz) for the 117 swallows (including inter-swallow intervals)(rationale provided in EMG section below).

ssEMG Analysis: No standard method for analyzing the onset and offset of the MM with ssEMG has been reported in previous studies. Ding et al (2002) compared

ssEMG signals between normal and MM swallows and determined that the onset for both normal and MM swallows is 2 standard deviations (SD) above the pre-swallow baseline. Crary et al (2004) used ssEMG to demonstrate the effects of biofeedback in patients learning the MM, but did not report EMG analysis methods. Wheeler-Hegland et al (2008) defined sEMG activity as a "departure of the sEMG signal from a resting baseline level associated specifically with biomechanical events occurring on the fluoroscopic image indicative of the beginning of each task". Finally, McCullough et al (2012 and 2013) used "an SEMG target line for amplitude was then set at 5 microvolts above their mean established from three baseline swallows".

Our aim was to investigate an ssEMG method that is typical for clinicians who train this maneuver in a clinical setting (i.e. ssEMG in the absence of complex analyses). However, in the current study, some ssEMG analyses were necessary to ensure that our measures of ssEMG duration were valid. The ssEMG data were digitally rectified and filtered at a low and high pass filter of 450Hz and 20Hz, respectively. The rationale for our settings are based on known theories about use of surface EMG on the submental region for speech and swallowing tasks (Stepp, 2012). Specifically, in

sEMG signals for speech and swallowing systems, most of the power of the signal is in the 0-450Hz range, thus our low-pass filter cut off of 450Hz. Furthermore, movement artifacts are found in the 0-20Hz range, thus our high-pass filter cut off at 20Hz. Stepp et al (2012) also indicated that when a low pass filter is set at 500Hz, ssEMG should be acquired at least 2x higher than the highest frequency, which is approximately 1kHz in our data, to prevent under sampling. However, since 1kHz is the lowest allowable frequency, we also sampled at 10kHz to prevent aliasing (under sampling). The electrode (left or right) with the cleanest signal was used for analysis. MM onset was defined as the point at which the ssEMG signal breached a threshold of 4 times the magnitude of rest ssEMG. MM offset was defined as the point at which the ssEMG signal breached this same threshold on its return to rest. The threshold of 4x the baseline signal was used to ensure that we were determining onset and offset points of the MM in our subjects and not some other movement that was not swallowing. For example, an anticipatory postural adjustment of the tongue or a throat clear just prior to MM performance increased the EMG signal twice or even three times from the baseline. Setting our onset point at 2x or 3x the baseline level

would result in non-swallowing tasks being mistakenly identified as the onset of the MM. Baseline ssEMG was obtained by averaging a rest period of 1 second following the completion of the maneuver. VFS was used to ensure no tongue or swallow related movements occurred during the time we derived the baseline. Post-maneuver rest was preferred to pre-maneuver rest to avoid anticipatory muscle activations that could influence the baseline ssEMG signal. VFS was not viewed for the purpose of determining MM onset or offset of ssEMG data.

Our ssEMG methods are similar to Wheeler-Hegland, because we compared MM ssEMG signal to baseline and considered VFS. However, in our case, VFS was considered after each ssEMG analysis was complete (blinded to VFS) by confirming that the ssEMG signal that was analyzed actually occurred during the time of MM performance (as opposed to some other task, i.e. speaking, yawning). We did not adjust our ssEMG measures to match hyo-laryngeal kinematics as in the Wheeler-Hegland study. Similar to Ding et al (2002), we also determined the threshold that best suited onset and offset based on our baseline signals.

VFS

For VFS analysis, we obtained two temporal measures: duration of maximum hyoid elevation (dMHE) and duration of laryngeal vestibule closure (dLVC). The definition of dMHE was the time between the hyoid bone first reaching its maximum superior position after swallowing initiation, until the last frame before its descent, ending the MM. The definition of dLVC was the duration of contact between the arytenoids and epiglottis base during the swallow (Bisch, Logemann, Rademaker, Kahrilas, & Lazarus, 1994; J. A. Logemann et al., 1992; Park, Kim, Ko, & McCullough, 2010; Power et al., 2007a). We also differentiated between Full and Partial LVC MM swallows. Full LVC MM swallows were characterized by dMHE and dLVC that were different by less than 1.5 sec. Partial LVC MM swallows had differences between dMHE and dLVC that were equal to or greater than 1.5 sec. This differentiation is significant because hyoid elevation and laryngeal elevation co-occur to achieve LVC (B. R. Fink, 1974; B.R. Fink & Demarest, 1978; B.R. Fink, Martin, & Rohrmann, 1979; J. Logemann, Kahrilas, & Cheng, 1992). It is unknown whether ssEMG can differentiate between these two kinematic components involved in hyo-laryngeal excursion and laryngeal vestibule closure. Also, LVC duration is associated with penetration and aspiration in individuals with dysphagia (Park, et al., 2010; Power et al., 2007b) and, therefore, it is of clinical relevance to determine whether patients are learning to perform Partial or Full LVC MM, and whether ssEMG is sensitive to these differences. In the cohort sampled at 1kHz, there were 55 Full LVC MM swallows (43 healthy, 12 stroke) and 23 Partial LVC MM swallows (20 healthy, 3 stroke). For the 117 swallows sampled at 10kHz there were 104 Full LVC MM swallows (73 healthy, 31 stroke) and 13 Partial LVC MM swallows (9

healthy, 4 stroke).

Experienced research assistants conducted all analyses. The raters were blinded to participant information, but aware of the purpose of the study.

Statistical Analysis

Linear regression analyses assessed the relationships among dMHE, dLVC, and ssEMG durations in the following six comparisons: 1. Full MM swallows in all participants; 2. Partial MM swallows in all participants; 4. Full MM swallows in healthy participants; 5. Partial MM swallows in healthy participants; 6. Full MM swallows in stroke participants. Partial MM swallows were not considered in stroke patients because there were too few samples. Statistical significance was adjusted to an alpha level of $p \leq 0.008$ to correct for multiple comparisons (6 comparisons).

Results

All participants were able to complete all study tasks without an adverse event. Table 1 lists the results, including mean durations of ssEMG, dMHE, dLVC (seconds), correlations (R^2), probability values (p), and confidence intervals (CI) for each of the 2 comparisons in both sampling groups. Reliability was excellent for EMG and VFS measures (dMHE .996, dLVC=.999, ssEMG-.998).

Comparisons

All Partial LVC MM correlations were non-significant for all comparisons, therefore only Full LVC MM will be discussed.

Full LVC MM in all participants: The 1kHz ssEMG data were very weakly, but significantly correlated with dLVC (r=0.114) (Figure 2, Part A). This means that for any change in the duration of LVC, approximately 10% of that change is reflected by a change in the duration of the ssEMG signal. In the 10kHz ssEMG data, ssEMG duration was moderately and significantly correlated with dMHE (r= 0.428) and with dLVC (r= 0.432) (Figure 2, Part A). Thus, in the 10kHz data, for any change in the duration of a kinematic event (dMHE or dLVC), approximately 40% of that change is reflected by a change in the duration of the ssEMG signal. A significant strong positive relationship was found between dLVC and dMHE during Full LVC MM trials in all participants (r= 0.99)(Figure 2, Part B).

Full LVC MM in Healthy Adults (Figure 3): No 1kHz correlation was significant for this comparison. The 10kHz ssEMG data rendered a significant, moderate, positive relationship with both dMHE (r=0.423) and with dLVC (R=0.430). A significant, very strongly positive relationship between dMHE and dLVC was found for Full LVC MM swallows (r= 0.99).

Full LVC MM in Stroke Patients (Figure 3): No significant relationship was found for Full LVC MM swallows in stroke participants with either 1kHz or 10kHz ssEMG. A

significant, very strongly positive relationship between dMHE and dLVC was found for Full LVC MM swallows (r= 0.90).

Discussion

The goal of this investigation was to examine temporal relationships between hyo-laryngeal kinematics and submental muscle group activation during the Mendelsohn maneuver. Our main outcome is that, overall, the strength of the relationship between ssEMG duration and either dMHE and dLVC varies depending upon how the MM is performed (Full versus Partial LVC MM), the ssEMG sampling rate (1kHz vs 10kHz), and possibly the population being measured (stroke vs healthy). Under the best circumstances (Full LVC MM with 10kHz ssEMG in healthy adults), the duration of ssEMG signals demonstrate, a moderate, positive relationship (R^2=0.43) with dMHE and dLVC. This means that for every change in hyo-laryngeal kinematics, approximately 40% is reflected in ssEMG duration signal changes. In the stroke group, correlation reached statistical significance between ssEMG and hyo-laryngeal kinematics. A possible explanation for this finding is that weakness of the muscles in the stroke patients produced a less robust or even inconsistently robust signal on EMG. The threshold of four times the amplitude at rest to mark the onset and offset of the MM may not have been reached by the patient's weaker and more fatigable submental musculature.

We have also examined the two behavioral patterns of MM performance including LVC maintained throughout the MM (Full LVC MM) and LVC ending before hyoid elevation

has terminated (Partial LVC MM) noted by Wheeler-Hegland et al. 2008. Partial LVC MM swallows did not have statistically significant relationships between ssEMG and either kinematic measure or between the two kinematic measures. During Partial MM LVC performance, our data show that ssEMG durations (10kHz) were shorter than dMHE. Thus, it is possible that not achieving LVC lead to decreased submental muscle activation that caused the ssEMG signal to breach our specified threshold, reducing the ssEMG duration measures.

Our data also highlight the importance of sampling frequency in ssEMG data as evidenced by the variations in comparison strength between the 1kHz and 10kHz groups. The correlation of ssEMG to laryngeal kinematics in Full LVC MM trials from healthy adults was strengthened by using a higher sampling frequency. A review of the use of surface EMG in the swallowing system suggests that to ensure signal integrity, data acquisition of at least 2kHz is recommended (Stepp 2012). It is possible that sampling at a frequency of 1kHz was under sampling the data resulting in a signal that is not truly representative of the muscle activity, an effect known as aliasing. Increasing the sampling frequency to 10kHz appeared to improve ssEMG to hyo-laryngeal kinematic correlations, likely because the baseline could more clearly be differentiated from the signal increase of MM swallows (Figure 1).

Overall, submental ssEMG likely did not demonstrate strong correlations with hyo-laryngeal kinematics during MM swallowing because longitudinal pharyngeal muscles, also involved in hyo-laryngeal elevation during MM swallowing, are not included in

recordings from this region (Pearson, et al., 2013). Longitudinal pharyngeal muscles are infrequently measured during swallowing because they are inaccessible for non-invasive ssEMG recordings. Their role in airway protection is poorly characterized by the research literature and warrants more scientific investigation. Furthermore, laryngeal vestibule closure is a phenomenon that occurs due to epiglottic inversion (also impacted be pharyngeal squeeze and the bolus), arytenoid adduction, and aryepiglottic fold bunching, not just hyo-laryngeal elevation (Ekberg, 1982; Ekberg & Sigurjonsson, 1982; B. R. Fink, 1974; B.R. Fink & Demarest, 1978; B.R. Fink, et al., 1979; J. A. Logemann, et al., 1992). These many mechanistic contributors cannot all be reflected in the ssEMG signal. Despite frequent, accepted use of ssEMG for both research and clinical purposes when training the MM, no previous study has determined whether duration of ssEMG signals accurately represent duration of hyo-laryngeal movements for the goal of prolonged hyo-laryngeal elevation and/or LVC. Understanding the relationship among the durations of hyoid elevation, LVC and ssEMG are important because ssEMG is widely used to initially teach the MM and as biofeedback tool, aimed to improve MM performance over time in dysphagia rehabilitation (Crary, et al., 2004; McCullough, et al., 2012). The goal of biofeedback is to provide information about movement accuracy so that motivation and faster learning are increased while losses in intrinsic feedback (i.e. proprioception) are supplemented over the long term (Salmoni, Schmidt, & Walter, 1984; Sidaway et al., 2008; van Vliet & Wulf, 2006). Thus it is critical that ssEMG accurately reflects the target kinematic events of the therapeutic task that is being trained. Our findings are significant because we show that without imaging swallowing kinematics when training novel movements, there is a risk that the target therapeutic

movements (i.e. hyo-laryngeal elevation, LVC) are not consistently being reflected in ssEMG data. For example, if the goal is for patients to perform Full LVC MM swallows, then ssEMG might not be able to distinguish them from Partial LVC MM swallows. Since the goal of therapy is to induce beneficial changes over time, it is possible that ssEMG used in isolation for acquisition or training of novel movements could misrepresent improvement, stagnation, or decline.

We conclude that ssEMG is, at best, moderately correlated with the hyo-laryngeal kinematics of the MM. Our findings also point to an important, but addressable, barrier to dysphagia management. That is that complicated internal swallowing events are best visualized with expensive and potentially harmful instrumentation that is not widely accessible. Although VFS presents a number of challenges, it is still the gold standard for imaging hyo-laryngeal swallowing kinematics. More studies are needed to explore the ways in which VFS can be used to train swallowing maneuvers, without increasing harm to patients and without substantial increases in cost or decreases in clinical productivity. We also need to further investigate swallowing treatments or maneuvers for which ssEMG is best suited. This study is limited by the small patient sample and single etiology, so future studies are necessary to investigate a larger cohort of patients with dysphagia. Furthermore, we investigated ssEMG methods that were typical for clinicians who train this maneuver in a clinical setting. It is possible that more complex ssEMG analyses that are meant to infer complex characteristics of muscle contraction might yield different outcomes when compared to videofluoroscopic hyo-laryngeal kinematics. Outcomes from these future studies may lead to important changes in the

way that dysphagia rehabilitation techniques are learned by patients and hopefully improve training target behaviors of specific therapeutic techniques.

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Table 1

1kHz	ssEMG vs dMHE			ssEMG vs dLVC			dMHE vs dLVC			Means(SD) (sec)		
Comparisons	**R^2**	**p-value**	**CI**	**R^2**	**p-value**	**CI**	**R^2**	**p-value**	**CI**	**ssEMG**	**dMHE**	**dLVC**
1. Full LVC MM trials												
All subjects:	0.118	0.01	.083-.586	0.114	0.007*	.99-.590	0.996	<0.001*	.964-.997	8.6(8.4)	14.7(8.7)	14.8(8.9)
Interpretation:					Very weak, positive			Very strong, positive				
Partial LVC MM trials												
All subjects:	0.056	0.278	(-.197- .652)	0.065	0.239	(-.281-1.0)	0.010	0.647	(-.558-.879)	12.7(10.4)	17.3(10.8)	9.9(6.8)
Interpretation:												
2. Full LVC MM trials												
Healthy:	0.260	0.306	(-.158- .492)	0.033	0.247	(-.134-.505)	0.996	<0.001*	.991-1.0	10.4(8.7)	17.1(8.3)	17.3(8.5)
Interpretation:								Very strong, positive				
Stroke:	0.358	0.040	0.21- .724	0.330	0.051	(-.002-.656)	0.910	<0.001*	.679-1	2(.87)	6.1(1.4)	5.9(1.5)
Interpretation:								Very strong, positive				
Partial LVC MM trials												
Healthy:	0.001	0.875	(-.470- .547)	0.011	0.666	(-.602-.920)	0.022	0.537	(-.957-.516)	11(6.6)	19.4(10)	14.4(10.3)
Interpretation:												

Correlations for 1kHz data for each comparison including the linear regression correlation (R^2), p-value (* indicates statistical significance), 95% confidence interval (CI) of R^2, and means (seconds) and standard deviations for ssEMG, dMHE, and dLVC. The interpretation of the significant relationships is also shown.

Table 2

10kHz	ssEMG vs. dMHE			ssEMG vs. dLVC			dMHE vs. dLVC			Means(SD) (sec)		
Comparisons	R^2	p-value	CI	R^2	p-value	CI	R^2	p-value	CI	ssEMG	dMHE	dLVC
1. Full LVC MM trials												
All subjects:	0.428	<.001*	.250-.603	0.432	<0.001*	.258-.618	0.994	<0.001*	.991-1.035	5.7(5.3)	4.7(5.3)	4.6(5.2)
Interpretation:		Moderate, positive			Moderate,positive			Very strong, positive				
Partial LVC MM trials												
All subjects:	0.473	0.051	(-.102-.963)	0.548	0.026	(-.011-1.629)	0.349	0.121	(-.442-1.574)	6.2(6.6)	7.8(7.3)	2.2(4.5)
Interpretation:												
2. Full LVC MM trials												
Healthy:	0.423	<0.001*	.204-.624	0.43	<0.001*	.215-.641	0.998	<0.001*	1.002-1.032	6.4(5.8)	5.7(6.0)	5.6(5.9)
Interpretation:		Moderate,positive			Moderate, positive			Very strong, positive				
Stroke:	0.14	0.226	(-.39-.853)	0.118	0.264	(-.439-.837)	0.903	<0.001*	.758-1.093	4.2(3.4)	2.4(2.1)	2.3(2.02)
Interpretation:								Very strong, positive				
Partial LVC MM trials												
Healthy:	0.452	0.111	(-.31-1.13)	0.579	0.051	(-.209-1.825)	0.344	0.182	(-.762-1.820)	7.1(7.6)	9.3(8.3)	2.3(5.4)
Interpretation:												

Correlations for 10kHz data for each comparison including the linear regression correlation (R^2), p-value (* indicates statistical significance), 95% confidence interval (CI) of R^2, and means (seconds) and standard deviations for ssEMG, dMHE, and dLVC. The interpretation of the significant relationships is also shown.

Figure Captions

Figure 1. Raw and Rectified data (y-axis: volts; x-axis: seconds) are shown for 1kHz data (A = Raw, B = Rectified) and 10kHz (C = Raw, D = Rectified).

Figure 1
Raw and Rectified data (y-axis: volts; x-axis: seconds) are shown for 1kHz data (A = Raw, B = Rectified) and 10kHz (C = Raw, D = Rectified).

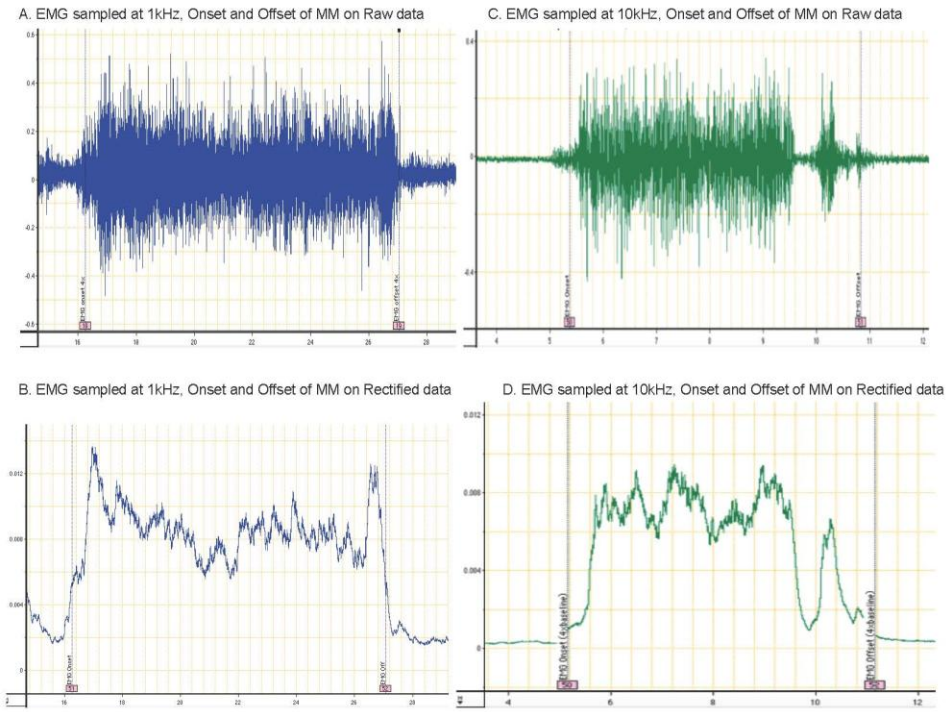
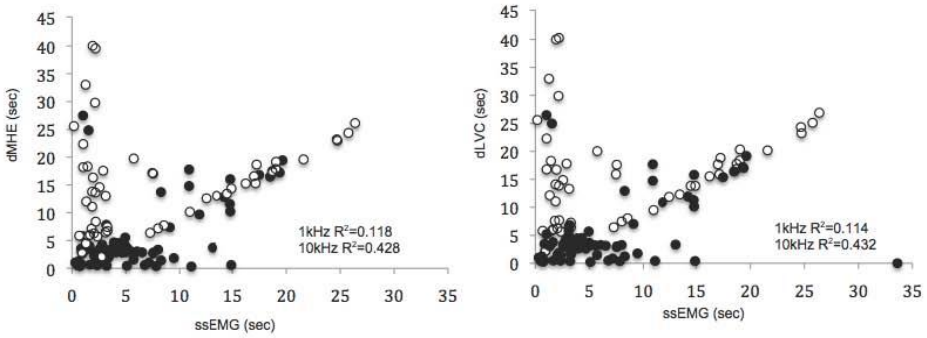


Figure 2. (A) Full LVC MM trials of ssEMG and kinematics measure in all subjects (seconds) at 1kHz (white) and 10kHz (black) sampling frequency. (B) Full LVC MM trials of kinematic measures in all subjects (seconds).

Figure 2

A. Full LVC MM trials of ssEMG and kinematics measures in all subjects (seconds) at 1kHz (white) and 10kHz (black) sampling frequency.



B. Full LVC MM trials of kinematic measures in all subjects (seconds)

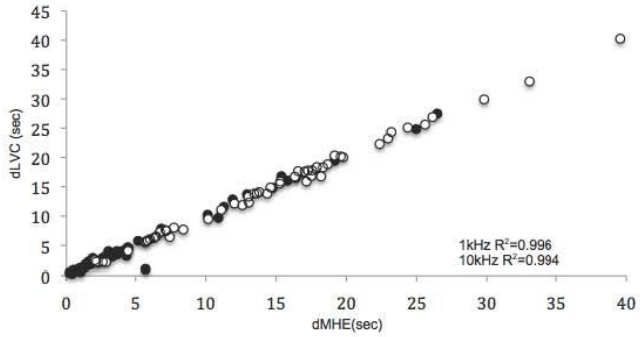
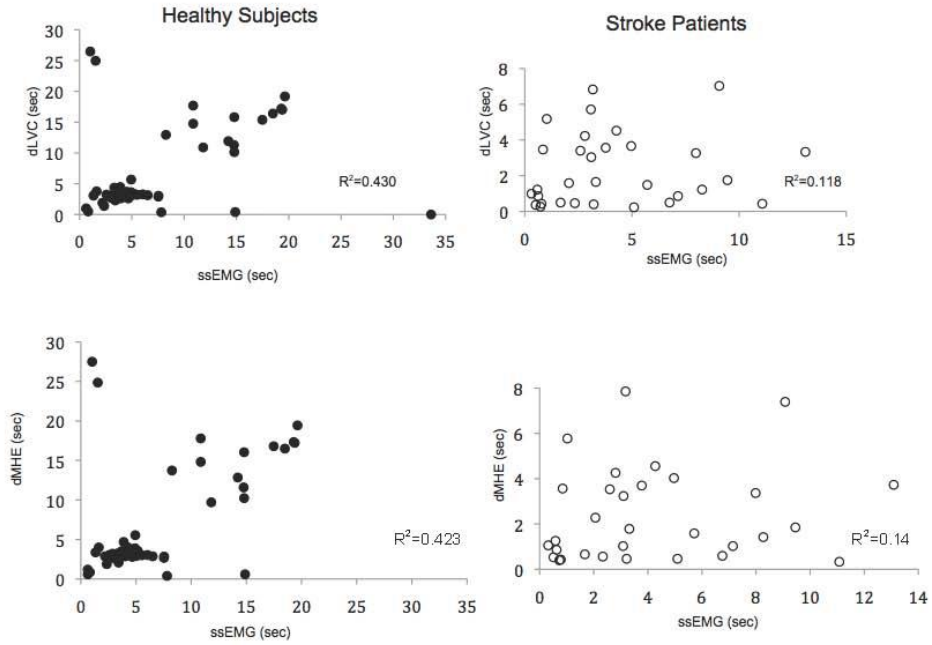


Figure 3. Full LVC MM trials of ssEMG and kinematic measures separated by healthy adults (black dots, left graphs) and stroke patients (white dots, right graphs).

Figure 3.



Full LVC MM trials of ssEMG and kinematic measures separated by healthy adults (black dots, left graphs) and stroke patients (white dots, right graphs)