Review

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Mechanomyography Sensors for Muscle Assessment: a Brief Review

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Abstract. [Purpose] There are three mechanomyography terminologies that are commonly used: acoustic myography, vibromyography, and phonomyography. There is no clear evidence concerning the sensors used among these terminologies. Thus the purpose of this review is to identify these three terminologies in terms of the implemented sensors, frequency ranges, and muscle assessment applications. [Methods] Thus, we first performed a systematic search of all the articles published up to April 15, 2012 in the IEEE, Elsevier, PubMed, SpringerLink, and Wiley Online Library databases using various combinations of the focused keywords. We then read the articles found in the search and selected papers related to these three technologies. After analysis, 32 articles were extracted to meet our objective. [Results] In turn, we determined that 100% and 54% of the studies of phonomyography and acoustic myography, respectively, utilized a microphone as the sensory device, whereas 91% of the articles on vibromyography detected the signal through an accelerometer. The remaining 46% of the acoustic myography studies recorded the signal through different types of sensors. In addition, acoustic myography was mostly applied to the study of muscle fatigue and the control of externally powered prostheses. Similarly, vibromyography was implemented in the monitoring of muscle fatigue, balance, contraction force, and effort. Phonomyography, however, was generally performed to study neuromuscular blockade in a clinical environment. Furthermore, no specific and distinct frequency ranges were found for the sensors associated with the terminologies. [Conclusion] Hence, the findings of this review may prove useful in the selection of suitable sensors for assessing different muscles.

Key words: Mechanomyography, Muscle-assessment and sensor

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INTRODUCTION

AMG is the recording of the sounds produced during muscle contraction, which become louder as the contraction force increases[15)]. Researchers have also found that the RMS value of the acoustic signal increases with increasing contraction force. In addition, the amplitude of the AMG signal decays with fatigue. Moreover, AMG signals have been used in a number of clinical applications, including the monitoring of paraspinal muscle function[16)] and muscle fatigue[17, 18)] and prosthesis control[19)].

PMG, which consists of recording of the low-frequency sounds created during muscle contraction, has been presented as a novel method to assess neuromuscular blockade (NMB) with high sensitivity and easy applicability. In addition, it can be used for the assessment of a number of different muscles, including the adductor laryngeal, adductor pollicis, and the corrugator supercilii[20–23)] muscles. Moreover, Hemmerling et al. (2004)[24)] reported that air-filled balloon mechanomyography assisted pressure measurements were very sensitive to artifacts in the PMG signal from the corrugator supercilii muscles. In addition, Hemmerling et al. (2002)[23)] determined the acoustic signal characteristics and best recording site of PMG at the corrugator' supercilii muscles and compared PMG with acceleromyography. They drew the conclusion[23)] that PMG intended to measure a longer onset with more pronounced maximum effect and shorter recovery at NMB. However, Guillaume et al. (2002)[25)] and Hemmerling et al. (2004)[26)] investigated two microphones for external laryngeal monitoring and comparison of neuromuscular blockade at the adducting and abducting laryngeal muscles. They also suggested[25)] that times to reach a train-of-four ratio of 0.8 (recover time) were significantly longer at the external laryngeal monitoring site and abductor laryngeal muscle than at the adducting laryngeal muscles, without being different between the posterior and external monitoring sites.

VMG signals are the vibrations associated with muscle contraction and can be detected with a contact sensor or a microphone mounted on the skin surface over an active muscle[27)]. Researchers that have studied the mechanical activity from the quadriceps muscle concluded that VMG can be used as an alternative to EMG (electromyography) in the assessment of muscle activities. In addition, Cole et al. (2006)[28)] investigated the capability of VMG in accurately representing the voluntary forearm muscle contractile force during attempted isometric contraction of the brachioradialis. These researchers also showed that VMG recordings are capable of providing a monotonic relationship between the VMG signal and the muscle force. Furthermore, Sonostics Inc. (2010 and 2011)[29, 30] recently investigated knee balance and muscular fatigue using VMG and used it as a rehabilitation tool in the reconstruction of quadriceps-hamstring activity following anterior cruciate ligament (ACL) injury. In addition, Kenneth et al. (2012) reported that VMG analysis may be capable of providing muscle balance in knee osteoarthritis[31]. Furthermore, Goddard et al. (2005) suggested use of VMG[32] to study the skeletal muscle pump response to the progressive pooling of blood and interstitial fluid that occurs during upright stance.

We found two studies that commonly referred to these techniques as MMG[15, 18]. However, Matta et al. (2005)[33] mentioned that VMG and acceleromyography are the same, another article by Petitjean et al. (1992)[34] discussed the fact that AMG records signals as micro-vibrations in muscle contraction, and Zagar and Krizaj (2005)[35] referred to micro-vibrations from muscle contractions as either VMG or acceleromyography. In addition, Bellemare et al. (2000)[36] initially referred to PMG as AMG, and Hemmerling et al. (2004)[20, 21] interchangeably use PMG and MMG.

To our knowledge, no study has discussed the sensor dependency of AMG, VMG, and PMG for muscle assessment. Therefore, the purpose of this review is to clearly classify the sensors associated with AMG, PMG, and VMG and identify their applications for muscle measurement. We hypothesized that there would be some differences in the frequency spectra and sensors among the three techniques.

SUBJECTS AND METHODS

We performed a comprehensive literature search of articles up to April 2012 in the Elsevier, PubMed, IEEE, SpringerLink, Google Scholar, and Wiley Online Library databases. Our search terms and strategies are detailed in Table 1. In addition, we studied the reference lists of all the important articles that were retrieved in the search.

The inclusion criterion was mainly limited to the terms AMG, PMG, and VMG, which are used for neuromuscular assessment and muscle characterization. We then examined the abstracts of all the articles identified; those that were clearly not relevant based on their key words and those that did not evaluate the terms of interest were excluded. We also eliminated two papers that were written in a language other than English. The remaining articles were divided into three groups by the neuromuscular application described and the sensor devices used: i) AMG, ii) VMG, and iii) PMG. To maintain the quality of the articles, we mostly confined our search to ISI listed journals and conferences although we did add some important clinical papers.

RESULTS

After application of the inclusion and exclusion criteria, we selected to study 57 papers to study that fulfilled the eligibility criteria. Out of these papers, only 32 potential studies were analyzed for systematic evaluation. We only found 11, 11, and 10 articles that clearly described and analyzed the sensors associated with AMG, VMG, and PMG, respectively as shown in Table 2.

Table 2 shows the details of the sensor devices that are used according to terminology. As shown, AMG detects signals through different types of sensors; of these, the microphone is used most often (54%). Conversely, PMG signals were only measured using a microphone (100%), whereas VMG measurements almost always (91%) employed an accelerometer as the sensor.

We hypothesized that there would be a clear differentiation in the frequency spectrum used for each sensor used according to terminologies. However, there was no clear frequency range distinction that we could use to rigidly classify the sensors associated with AMG, PMG, and VMG. A number of articles used a frequency range of up to 100 Hz, and others used frequencies up to 1000 Hz for each of the three sensors. Therefore, there is significant overlap in the frequency ranges used by the three different sensors.

As shown in Table 3, we can claim that AMG, which utilizes a microphone, an accelerometer, or a piezoelectric contact sensor (PIZ), is used mostly for the monitoring of muscle fatigue or as an externally powered controlled prosthetic device. In addition, it can be used to study muscles in both the upper and lower limbs. Conversely, researchers mostly deploy PMG to monitor NMB in diverse muscles to assess the onset and recovery time in a clinical environment. All studies placed a microphone (MIC) as a sensory device for PMG measurement. We found strong evidence for the use of an accelerometer (ACC) sensor in case of VMG assessment in the measurement of motion, joint angle, balance, fiber structure, and contraction force of different muscles. Table 3 focuses mainly on the classification among the three groups in terms of sensor, frequency range, and muscle types, although it also includes some additional features, including potential applications and some comments of the authors.

DISCUSSION

The current review analyzed the sensors used according to the different terminologies for MMG. The literature clearly demonstrates that AMG utilizes different sensors, such as an ACC, MIC, and PIZ, with different frequency ranges for the assessment of muscles, particularly to determine the level of fatigue and to externally power and control prosthetic devices. PMG, however, always uses a microphone as the sensory device and it is especially suitable for monitoring the onset and recovery time of NMB in a clinical environment. VMG utilizes an accelerometer with diverse frequency ranges to assess a variety of muscle activities, particularly balance, motion, knee joint, fiber composition, and force or effort. However, we could not classify the groups solely in terms of the frequency spectrum that the sensors use.

Based on the evidence that we found, we can claim that PMG only utilizes microphones as sensors because 100% of the PMG articles used a microphone in their measurements. However, AMG uses different types of sensors, including

Table 1. Literature search: keywords and strategies

(Acousticmyography OR Vibromyography OR Phonomyography NOT Acceleromyography) AND Sensor AND Muscle assessment
Frequency spectrum AND (Acousticmyography OR Vibromyography OR Phonomyography NOT Acceleromyography) AND Sensor
(Accelerometer OR Microphone OR piezoelectric contact sensor) AND (Acoustic myography OR Vibromyography OR Phonomyography NOT Acceleromyography) AND Muscle assessment AND Frequency spectrum
(Acoustic myography AND Vibromyography) OR (Phonomyography AND Acoustic myography) OR (Vibromyography AND Phonomyography)
Classify AND (Acoustic myography AND Vibromyography AND Phonomyography)

Table 2. Details of sensors used according to each terminology

Terminologies	Sensors types				Total
	Accelerometer	Microphone	Piezoelectric contact	Others	
AMG	2	6	1	2	11
VMG	10	0	1	0	11
PMG	0	10	0	0	10
Total	12	16	2	2	32

MICs[15, 37–42], ACCs[17, 43], PIZs[44, 45], hydrophones[46], and strain sensors[47]; in essence, the evidence shows that a MIC was used in 54% of the articles on AMG to perform measurements and that the other 46% of the articles used an ACC (18%), PIZ (9%), hydrophone (9.5%), or strain sensor (9.5%). Moreover, almost 100% of the articles on VMG used ACCs, although one used a PIZ[48]. Oster and Jaffe (1980)[49] mentioned that vibrations can be measured by either an ACC or a MIC. Furthermore, although Zhang et al. (1992)[27] mentioned that a VMG signal can be recorded using either a piezoelectric contact or a microphone, we found no evidence of the use of a microphone in the recording of a VMG signal and thus concluded that an accelerometer records the VMG signal.

We found insufficient evidence to define a distinct frequency range for ACC, MIC, and PIZ sensors according to the terminology for muscle assessment. However, Oster and Jaffe (1980)[49] mentioned that the typical frequency range is 5–100 Hz, although the bandwidth may vary from person to person. Moreover, Orizio (1993)[50] reported that most of the power of the MMG signal falls within the 0–30 Hz bandwidth and that no significant frequency components beyond 100 Hz have been reported in the assessment of arm muscles. Furthermore, Hemmerling et al. (2004)[20] was the only group to report that most of the PMG signal had a frequency of less than 20 Hz. However, we hypothesized that each of these techniques (AMG, PMG, and VMG) would operate at a clear frequency range. Because the acoustic signal frequency range is clearly defined as 20 Hz–20 KHz, the frequency range of the vibration signal is outside the range of the acoustic signal. However, we found 12, 6, 5, and 1 articles that used frequencies up to 100, 500, 1000, and 2000 Hz, respectively; the remaining 8 articles did not clearly state the frequency range used in their measurements. These widespread frequency ranges are also mentioned in different review articles that we analyzed. Consequently, it is clear that we cannot absolutely classify AMG, PMG, and VMG in terms of the frequency spectrum of their sensors.

As expected, there is a large amount of evidence concerning the three techniques of MMG. We found that AMG has mostly been used to study the fatigue of different muscles, although there is some evidence that AMG can be used to measure prosthesis control[38], bite force in jaw muscles[40, 42] and muscle tension[46]. Alternatively, VMG can be used for supervising muscle fatigue[30], muscle balance[51], joint angle[29], functional motion[52], and muscle force[28, 53, 54]. Furthermore, PMG is suitable for monitoring NMB in clinical environments, and some proof has been found that PMG and MMG have been used interchangeably in the evaluation of NMB[20, 21]. In addition, some evidence shows that PMG can be used to study muscle tension[34], muscle force[55], and diaphragm fatigue[56, 57].

In summary, this review found that PMG and VMG signals are recorded through the use of a microphone and an accelerometer respectively, whereas the AMG signal may be recorded by a microphone, piezoelectric contact sensor, or accelerometer. In addition, AMG can be applied to the study of muscle fatigue and the control of an externally powered prosthesis. Similarly, VMG can be used in the monitoring of muscle fatigue, balance, contraction force, and effort. PMG, however, is mostly used in the assessment of neuromuscular blockade. Unfortunately, there is no significant evidence that can be used to identify distinct frequency ranges between the three sensors used according to the terminologies. This review might be useful in selection of appropriate sensors for different muscle types. Because we did not find any recent work on AMG in the databases, further study on AMG is recommended due to the advancement of sensory technology. In addition, to avoid technological conflicts, different frequency ranges should be clearly identified and

Table 3. An overview of the sensors and frequency ranges used and the muscles studied in AMG, VMG, and PMG

Author	Myography	Sensor	Frequency range	Muscle	Study	Application
Kenneth et al. (2012)[31]	VMG	Developed sensor	(30–250) Hz	VL, VM, BF, and sartorius	Muscle balance	To assess muscle balance in knee osteoarthritis
Comment: VMG analysis may be capable of providing muscle balance in knee osteoarthritis.						
Sonostics Inc. (2011)[30]	VMG	ACC	NF	VL and BF	ACL reformation	To track rehabilitation progress
Comment: VMG provides a convenient means for assessing rehabilitation progress following sports injuries such as ACL tears.						
Sonostics Inc. (2011)[29]	VMG	ACC	(20–200) Hz	QDR and HAM	Knee balance and fatigue	Muscle fatigue and balance assessment
Comment: VMG analysis provides a simple and reproducible means for assessing absolute muscle effort.						
Sonostics Inc. (2010)[52]	VMG	ACC	NF	BR, BA, and BB	Functional motion	To assess muscle fatigue
Comment: Three muscles exhibit almost the same muscular effort with time in pronated and supinated modes. This can be used to assist in optimizing functional motions so as to reduce fatigue.						
Sonostics Inc. (2010)[51]	VMG	ACC	NF	TB	Rehabilitation	As a therapy tool
Comment: VMG provides a highly accurate means for evaluating isometric muscle effort in groups either before and after rehabilitation or before and after a sports training regimen.						
Cole et al. (2006)[28]	VMG	ACC	(10–150) Hz	BR	Contractile Force	As a therapy tool
Comment: VMG appears to be capable of reporting absolute force levels.						
Goddard et al. (2005)[32]	VMG	ACC	(0–500) Hz	Soleus	Pumping activity	NF
Comment: VMG examines the skeletal muscle pump response to the progressive pooling of blood and interstitial fluid that occurs during upright stance.						
Sarver and Selikta (2000)[53]	VMG	ACC	(0–160) Hz	TB	Muscle effort to assess fatigue	To assess fatigue
Comment: VMG is able to discriminate between the 75% and 100% effort levels better than EMG.						
Matheson et al. (1997)[54]	VMG	ACC	NF	QDR	Muscle force production	NF
Comment: VMG is a better discriminator of absolute muscle force values between subjects, particularly up to 60% MVC.						
Mealing et al. (1996)[48]	VMG	PIZ	(0–400) Hz	BB and soleus	Muscle fiber composition	NF
Comment: VMG in frequency domain analysis of this signal may provide a noninvasive measure of muscle fibre composition.						
Zhang et al. (1992)[27]	VMG	ACC	(3–100) Hz	QDR	Muscle contraction	To study mechanical behavior
Comment: VMG can be used as an alternative to EMG for studying muscle activity.						
Hemmerling et al. (2004)[26]	PMG	MIC	(0.5–1000) Hz	AdL and AbL	NMB	For monitoring NMB
Comment: Onset, peak effect, and start of recovery of NMB are similar between the two muscles.						
Hemmerling et al. (2004)[20]	PMG	MIC	(0.5–1000) Hz	AP	NMB	For monitoring NMB
Comment: PMG measurements of onset and maximum effect of NMB are not significantly different from MMG.						
Hemmerling (2004)[24]	PMG	MIC	(0.5–1000) Hz	CS	NMB	For monitoring NMB
Comment: PMG at the CS muscle shows good agreement with this modified version of MMG.						
Hemmerling et al. (2003)[22]	PMG	MIC	(0.5–1000) Hz	AdL	NMB	For monitoring NMB
Comment: PMG allows measurement of laryngeal blockade with an endotracheal tube in the normal position.						
Guillaume (2002)[25]	PMG	MIC	NF	CS and larynx	NMB	For monitoring NMB
Comment: Onset time and peak effect determined at the CS or the larynx cannot be used interchangeably and are not correlated.						
Hemmerling (2002)[23]	PMG	MIC	Below 40 Hz	CS	NMB	For monitoring NMB
Comment: PMG can be used to determine NMB for the corrugator supercilli muscles.						

Petitjean et al. (1997)[56]	PMG	MIC	(0.5–250) Hz	Eighth intercostal spaces	Fatigue of diaphragm	To assess fatigue of diaphragm
Comment: PMG indicates that all diaphragmatic motor units can be affected by fatigue.						
Petitjean (1995)[57]	PMG	MIC	(10–60) Hz	Anconeus	Single motor unit activity	NF
Comment: PMG represents the activity of individual motor units during voluntary isometric contractions, rather than the overall muscle properties.						
Petitjean et al. (1992)[34]	PMG	MIC	(10–60) Hz	BB and BR	Muscle tension	As a tool to assess voluntary dynamic contraction
Comment: PMG allows convenient evaluation of muscle tension during human dynamic contraction.						
Maton et al. (1990)[55]	PMG	MIC	(15–60) Hz	BB	Muscle force	As a rehabilitation tool
Comment: Despite a slightly higher variability, PMG appears to be a valid index of muscular isometric force.						
Barry (2004)[38]	AMG	MIC	(10–50) Hz	DI	Fatigue	As a prosthesis control and fatigue assessment
Comment: As AMG and force amplitudes decline simultaneously with fatigue, this can be a valuable parameter in distinguishing motor unit fatigue from lack of effort.						
Rigamonti et al. (2001)[39]	AMG	MIC	NF	FDI, DIA, and GG	NMB	At clinic for NMB assessment
Comment: AMG can be used to study the muscular relaxation at the DIA and the GG. These two muscles show a very similar time course of relaxation and both differ from the FDI.						
Mamaghani et al. (2001)[17]	AMG	ACC	(0–100) Hz	BB and BR	Fatigue	To study muscle fatigue noninvasively
Comment: The RMS of AMG has a good and clear correlation with elbow angle at a low level of contraction.						
Ouamer et al. (1999)[47]	AMG	Strain sensors	(3.2–100) Hz	BB	Propagation vibration	NF
Comment: Coherence functions reveal a common vibration frequency band between 17 and 28 Hz.						
Tortopidis et al. (1998)[40]	AMG	MIC	(2–160) Hz	Masseter	Bite force	For monitoring fatigue
Comment: AMG may be used as a monitoring tool of force production from the masseter muscle.						
Smith and Stokes (1993)[45]	AMG	PIZ	NF	RF	Contact pressure effect	NF
Comment: Contact pressure can influence the degree of AMG activity if the pressure is high enough.						
Dalton et al. (1992)[41]	AMG	MIC	(8–160) Hz	RF	Fatiguing activity	Noninvasive monitor of force during early fatiguing activity
Comment: AMG appears to be more accurate than EMG as an indicator of fatigue during the early phase of intermittent fatiguing activity.						
Cole and Barry (1991)[46]	AMG	Hydrophone	NF	Semitendinosus muscles	Muscle tension	To assess muscle tension
Comment: Muscle tension can be monitored acoustically during contraction.						
Stiles and Pham (1991)[42]	AMG	MIC	(10–100) Hz	Anterior temporalis and masseter	Bite force	To monitor bite force activity
Comment: The AMG tension relation for a muscle may depend upon the ratio of recruitment to firing rate control of tension.						
Barry and Cole(1991)[43]	AMG	ACC	(2–2000) Hz	DI	Fatigue	Monitoring muscle fatigue
Comment: The reduction in muscle vibration accompanies muscle fatigue						
Barry et al. (1985)[15]	AMG	MIC	(25–100) Hz	BB	Muscle fatigue	Monitoring muscle fatigue
Comment: AMG represents a new modality for analyzing muscular activity to assess fatigue.						

Abbreviations: ACC= accelerometer, ACL= anterior cruciate ligament, AbL= abducting laryngeal, AdL= adductor laryngeal, AP= adductor pollicis, BA= brachialis, BB= biceps brachii, BF= biceps femoris, BR= brachioradialis, CS= corrugators supercilii, DI= dorsal interrosseus, DIA= diaphragm, FDI= first DI, GG=genioglossus, HAM=hamstring, MIC= microphone, NMB= neuromuscular blockade, NF= not found, PIZ= piezoelectric contact sensor, QDR= quadriceps, RF= rectus femoris, TB= triceps brachii, VL= vastus lateralis, VM= vastus medialis.

used for each of the sensors.

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