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Review

Mechanomyography and muscle function assessment: A review of current state and prospects

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ABSTRACT

Previous studies have explored to saturation the efficacy of the conventional signal (such as electromyogram) for muscle function assessment and found its clinical impact limited. Increasing demand for reliable muscle function assessment modalities continues to prompt further investigation into other complementary alternatives. Application of mechanomyographic signal to quantify muscle performance has been proposed due to its inherent mechanical nature and ability to assess muscle function non-invasively while preserving muscular neurophysiologic information. Mechanomyogram is gaining accelerated applications in evaluating the properties of muscle under voluntary and evoked muscle contraction with prospects in clinical practices. As a complementary modality and the mechanical counterpart to electromyogram; mechanomyogram has gained significant acceptance in analysis of isometric and dynamic muscle actions. Substantial studies have also documented the effectiveness of mechanomyographic signal to assess muscle performance but none involved comprehensive appraisal of the state of the art applications with highlights on the future prospect and potential integration into the clinical practices. Motivated by the dearth of such critical review, we assessed the literature to investigate its principle of acquisition, current applications, challenges and future directions. Based on our findings, the importance of rigorous scientific and clinical validation of the signal is highlighted. It is also evident that as a robust complement to electromyogram, mechanomyographic signal may possess unprecedented potentials and further investigation will be enlightening.

1. Introduction

1.1. Historical background

The origin of muscle sound in relation to the muscle physiologic condition could be traced to 1665 by Grimaldi (1665), who referred to the sound as "motion of animal spirits", a formulation similar to other esoteric explanations of natural phenomena from that time (Rhatigan et al., 1986). In 1810, Wollaston was able to describe quantitatively with analogy the frequency of muscle sound within the range of 14–35 Hz (Wollaston, 1810). The characteristics of time and frequency domain analysis of the muscle sound during evoked and voluntary contraction was initiated by Oster and Jaffe (1980) and Oster (1984). They described the dominant frequency of muscle sound within 25 plus or minus 2.5 Hz. With the aid of stethoscope and microphone, the investigators verified that sound (a form of mechanomyogram (MMG)) is an intrinsic property of muscle contraction.

Rhatigan et al. (1986) and Orizio et al. (1990) in separate attempts to justify the mechanomyogram (MMG) relevance in muscle research, showed that the predominant power in MMG frequency spectrum of humans' biceps brachii under isometric contraction was within 10–22 Hz. Other investigators subsequently demonstrated that the lowest limit of frequency reported in human is approximately 2 Hz while the highest is 120 Hz (Beck et al., 2008). Consequently, MMG was validated as the complementary mechanical signal to the established electromyogram (EMG) to investigate neuromuscular activities (Stokes and Blythe, 2001) especially when noninvasive estimation of the muscle physiology underlying contraction and the fatigue phenomenon is sought (Esposito et al., 1998).

However, due to the emergence of sensitive, lightweight, inexpensive sensors, and advanced signal analysis techniques, acquisition of low frequency vibration of muscular activities in the form of MMG has been made feasible. The signal has been verified to be detectable at the skin surface during dimensional changes of active muscle fiber that generate pressure waves due to voluntary or evoked contraction and demonstrated to possess rich information of the underlying neuromuscular parameters leading to contraction and thus reliable in muscle function assessments (Orizio et al., 2003a). It has been suggested that

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the signal may reflect the three main physiological phenomena including the gross lateral movement of the contracting muscle at the initiation of contraction, smaller, subsequent vibrations at the resonance frequency of the muscle, and the dimensional changes in the active muscle fiber (Barry and Cole, 1990; Orizio et al., 2003a). In general, impetus from the classical work on muscle sound revealed that its properties i.e. vibration, acceleration and dimensional changes can be used to assess muscle contraction and performances.

Currently, electromyogram as the conventional signal modality to monitor skeletal muscle activities is unable to generate sufficient information regarding mechanical index of muscle contraction (Sasidhar et al., 2013) thus possessing limited information about the neural control of muscle function (Farina et al., 2004). The signal is also not sufficiently suitable to quantify muscle function during electrically evoked dynamic muscle action (Braz et al., 2009). The exploration of complementary paradigm that is sensitive to the muscle mechanical activities and devoid of inherent electrical noise, such as MMG, is therefore warranted. Inference from various scientific research verified that MMG signal can be used for the following: (i) muscle fiber typing (Herda et al., 2010); (ii) assessment of muscle force (Sarlabous et al., 2013); (iii) muscle fatigue (Hendrix et al., 2010); (iv) indication of resonance frequency of muscle (Barry and Cole, 1990); and (v) assessment of contractile properties (Gorelick and Brown, 2007). It has been observed that the mechanical nature of the muscle fiber activities that leads to contraction (Gerdle et al., 1999) could be better discerned and represented with signal response that is inherently mechanical.

With cognisance attention specifically to emerging area of applications of MMG due to its resistance to electrical interferences, and flexibility in its sensing technology, literature survey highlighted the robustness of MMG signal that is often underestimated. Aside from few isolated studies with variations, such as that of Herda and Cooper who demonstrated the inability of mechanomyographic amplitude–force relationship to distinguish differences in voluntary activation capacity between individuals (Herda and Cooper, 2013), it is apparent that the analysis of variables of MMG signal in time and frequency domains has been demonstrated to assess various aspects of neuromuscular functions (Malek and Coburn, 2012) and could be used to investigate motor unit activities (recruitments and firing rates) i.e. the force generation mechanism (Cè et al., 2013; Yoshitake et al., 2001) thus can be used to assess different conditions of skeletal muscle activities (Islam et al., 2013).

1.2. Basic principle of detection

The great surge of research activity noticed lately on the MMG application was due to the advancement in sensor technology and signal analysis techniques. Typically, MMG signal, characterized by frequency distribution below 100 Hz (Orizio, 1992), originates from the skeletal muscle contraction that leads to shortening of the muscle fiber length and increase in the fiber diameter (Farina et al., 2008). The vibration of muscle fibers and their dimensional changes during activation create pressure waves that could be detected on the skin surface; as an acceleration obtained by sensors such as accelerometer or as a skin displacement acquired by piezoelectric contact sensor (Watakabe et al., 1998), laser distance sensor (Orizio et al., 1999a), or condenser microphone (Orizio, 2004). Generally, the typical motor response of the muscle during contraction stage that is often accompanied by the transverse diameter changes to the muscle belly (Orizio et al., 2003b) could be readily obtained as MMG signals on the skin surface.

A recent interest in understanding the mechanism behind the MMG signal generation has led to an investigation of the relationship between the acceleration of motor unit and the surface spatial distribution. It has been inferred from the muscle anatomy and the theory of wave propagation that the muscle fiber contraction (fiber shortening and increase in the fiber diameter) (Farina et al., 2008) generates a time dependent spatial distribution of acceleration on the surface of the skin (Cescon et al., 2007). The spatial distribution of acceleration due to the activity of a single motor unit is termed motor unit acceleration map and it is dependent on the muscle morphology and architecture (Bichler, 2000). The limitation of using single channel MMG features for the assessment of the motor unit control strategies was highlighted by Madeleine and co-workers because of the substantial effect of the sensor's position on the relationship between force and MMG signal and they suggested that a two-dimensional array of accelerometers may contribute to a better understanding of the origin of MMG signal (Madeleine et al., 2006). However, the alteration of the acceleration of the skin by the weight of multiple sensors may have limited the observation to large muscles where such weight may only have an insignificant effect (Farina et al., 2008).

By implication, the weight of the sensor and the signal detection site are of vital importance for the MMG signal integrity. The sensor placement has been generally validated to have the strongest response near the muscle belly and increasingly weaker toward the tendon (Frangioni et al., 1987). Equally skin fold thickness may affect the MMG signal response because of the low pass filtering effect of the tissue between the target muscle and the detection sensor (Jaskólska et al., 2004). Therefore the response of the signal depends significantly on the consistency of sensor location between trials.

The technical characteristics of the signal have also been shown to be depended on the types and nature of the transducer adopted for acquisition (Beck et al., 2006). Investigators have continued to examine the signal characteristics of the differences in the variables indicated by MMG from different sensors. Fig. 1 shows the two major sinusoidal mechanical variables of the signal with different transducers.

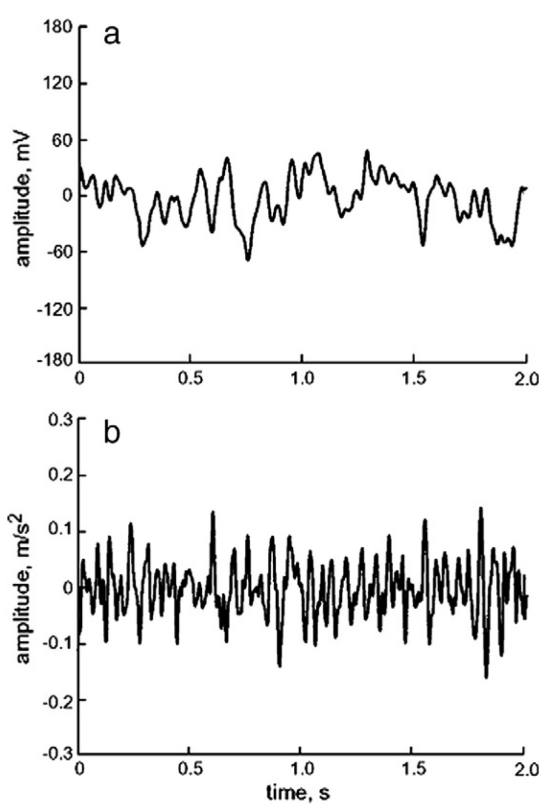

Fig. 1. Graphical representation of the key mechanical variables of MMG signals during voluntary contractions of the biceps brachii muscles where panel a represents the amplitude response of the condensed microphone transducer and panel b is the amplitude response of accelerometer transducer.
Reprinted with permission from Watakabe et al. (2001).