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# Frequency features of mechanomyographic signals of human soleus muscle during quiet standing

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ABSTRACT

The purpose of the present study was to determine whether the frequency features of the MMG signals during quiet standing reflect body sway as well as recurring muscle activity. Twenty healthy men maintained quiet standing in a barefoot position with their eyes open or closed. During quiet standing, MMG detected using uniaxial piezoresistive accelerometer and surface electromyogram (EMG) signals were recorded from the soleus (SOL) muscle, and the center of mass (CoM) displacement (CoMdis) in the anteroposterior direction was measured by a high-resolution laser displacement sensor. In addition, CoMdis was time-differentiated to yield CoM velocity (CoMvel). Cross-spectral analysis revealed that significant coherency spectra from MMG to CoMdis and from MMG to rectified EMG of SOL were observed below 2 Hz and 8–12 Hz frequency band, respectively. Furthermore, we revealed that the trajectories of MMG and the calculated d$MMG/dt$ were significantly correlated to CoMdis and CoMvel, respectively. These results suggest that kinematic and physiological parameters of postural control during quiet standing can be quantified by frequency features of the MMG.



## 1. Introduction

Mechanomyogram (MMG) involves recording and quantifying the low-frequency oscillations produced by activated skeletal muscles (Barry, 1987; Frangioni et al., 1987). Studies using evoked contractions by electrical stimulation of isolated motor units in rat (Bichler and Celichowski, 2001a,b), cat (Orizio et al., 1999, 2000) and human (Yoshitake et al., 2002) gastrocnemius muscles provided evidence that MMG signals are dependent on the contractile properties of the activated motor units. In voluntary contractions in humans, many researchers have succeeded in investigating the amplitude and frequency responses of MMG signals during anisometric as well as isometric contractions under well-controlled conditions (reviewed by Beck et al. (2005) and Orizio (1993)). In addition, fatigue-related changes in the activation strategies and contractile properties of motor units have been assessed by means of MMG (reviewed by Shinohara and Søgaard (2006)). Although the fundamental findings of the MMG characteristics have been reported by many researchers, there are only a few research groups that have examined the functional performance of daily activities in relation to MMG; furthermore, the task investigated in these studies is limited to a bicycle exercise (Housh et al., 2000; Perry et al., 2001; Shinohara et al., 1997).

Upright standing is one of the most basic daily human activities, and postural stability during quiet standing deteriorates with age (Maki et al., 1990; Panzer et al., 1995) or inactivity (Kouzaki et al., 2007). The deterioration of equilibrium control is associated with an increased risk of falls in elderly persons (Gehelsen and Whaley, 1990), and, therefore, postural control during upright standing has strong functional significance in daily living. Based on the dynamics of the human quiet stance, it has been observed that the plantar flexor muscles play a significant role in stabilizing the body during quiet standing (Masani et al., 2003; Morasso and Schieppati, 1999). Additionally, the activities of the plantar flexors have been found to be coherent with both spontaneous body sway (Gatev et al., 1999; Masani et al., 2003) and mechanically induced body sway (Fitzpatrick et al., 1996). From these previous findings, therefore, in order to examine the human postural control mechanism revealed by MMG, a technique is needed that can detect and quantify not only the activities of the plantar flexor muscles but also the kinematic parameters of postural control.

The MMG signals include the displacement of moving parts of the body, not only the changes in the muscle itself (Watakabe et al., 2001). Up to now, the signals related to body or limb movements

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have been regarded as artifacts, and therefore most studies have used a filter with a 5 Hz high pass cutoff frequency to attenuate movement artifacts in MMG signals (Beck et al., 2005). According to the model of a single joint inverted pendulum rotating around the ankle joint (Masani et al., 2003; Morasso and Schieppati, 1999), the low-frequency component of the MMG signal without a high pass cutoff filter is likely to represent the displacement of body sway during quiet standing.

In addition to the dynamics of the bipedal quiet stance as a postural control mechanism, an upright posture is partially stabilized by recurring muscle activity of the soleus (SOL) muscle. Mori (1973, 1975) reported that there is a motor unit synchronization recurring at around 10 Hz in the SOL during quiet standing in healthy subjects. Mochizuki et al. (2005) also observed evidence that different motor units were synchronized within the SOL during quiet standing. The recurring muscle activity around 10 Hz produced by motor unit synchronization appears as physical oscillations of the body surface on the activated muscle fibers (Lippold, 1970). These oscillations are referred to as physiological tremor (McAuley and Marsden, 2000). It has been reported that during sustained contraction of even low intensity, the involvement of the physiological tremor has a large influence on the MMG signals (Goldenberg et al., 1991; Orizio, 1993). Thus, the recurring muscle activity during quiet standing can be extracted by frequency-domain analysis of the MMG signals.

The literature indicating the frequency features of the MMG signals leads us to hypothesize that the MMG signals make it possible to evaluate kinematic and physiological parameters related to postural control mechanisms. To this end, in the present study, the frequency characteristics of the MMG were compared with body swaying and recurring muscle activity during quiet standing.

## 2. Methods

### 2.1. Subjects

Twenty young men (range: 23–35 years) volunteered for this experiment. They gave their written informed consent for the study after receiving a detailed explanation of the purposes, potential benefits, and risks associated with participation in the study. All subjects were healthy and had no history of any neurological disorders, and their vision was corrected to normal levels. All procedures used in this study were in accordance with the Declaration of Helsinki and were approved by the local ethical committee.

### 2.2. Experimental protocol and measurement

The basic procedure setup and measurement of postural sway during quiet standing has been described in our previous studies (Kouzaki et al., 2007; Masani et al., 2003, 2007). The subjects were required to maintain a quiet stance barefoot on a platform with their eyes open (EO) or closed (EC) and with a distance of 15 cm between their heels, for approximately 70 s. The subjects held their arms by their sides. Three trials were conducted for each eye condition, and sufficient resting time was allowed between trials. The order of the trials was pseudo-randomized.

A surface mechanomyogram (MMG) detected using an uniaxial piezoresistive accelerometer (ASV-2GA, Kyowa, Tokyo, Japan) was recorded from the muscle belly of the right soleus (SOL) muscle. We utilized the accelerometer and not a microphone to detect the body sway as well as muscle activity, because the accelerometer records the displacement of moving parts of the body better than the microphone (Watakabe et al., 2001). The accelerometer had a flat frequency response from DC to 150 Hz, and its physical dimensions were 22 mm times 22 mm for the base, 11 mm in height, and 13 g in mass. The MMG attached to the posterior part of the SOL so that it was as flat as possible within the SOL and so that the limb movement could be detected in the anteroposterior direction (Fig. 1). Furthermore, the accelerometer was secured over the muscle belly of the SOL with adhesive tape so that the polarization between positive and negative values represents the inward and outward directions from the surface, respectively. To minimize the influence of signals from the neighboring synergists (i.e., medial and lateral gastrocnemius) to SOL, the location of the accelerometer was determined using ultrasound B-mode images (SSD-900, Aloka, Tokyo, Japan), which can monitor visually the boundary between SOL and gastrocnemius muscles.

The surface electromyogram (EMG) of the right SOL located laterally near the MMG was recorded using bipolar Ag–AgCl electrodes with a diameter of 10 mm and an interelectrode distance of 20 mm. The electrodes were connected to a preamplifier and a differential amplifier (×1000) having a bandwidth of 20–500 Hz (SX203, Biometrics Ltd., Gwent, U.K.).

The reference electrode for the EMG was placed on the medial malleolus. To assess the trajectory of the center of mass (CoM) displacement (CoMdis), the horizontal position of a lumbar point at L3 was measured by a laser displacement sensor (1 μm resolution, LK-2500, Keyence, Osaka, Japan) (Masani et al., 2003) (Fig. 1). Laser displacement sensor makes it possible to detect the range of 30 to 40 cm from the source of luminescence. All electrical signals were stored with a sample frequency of 1 kHz by a 16-bit analog-to-digital converter (PowerLab/16SP, ADInstrument, Sydney, Australia) and stored on the hard disk of a personal computer for later analyses.

### 2.3. Data analysis

For all recorded signals, data for a 60 s period in the middle portion of the collected data (∼70 s) were selected for analysis of individual trials.

The auto-spectral analysis was performed for the CoMdis, the full-wave rectified EMG of the SOL, and the MMG of the SOL. For frequency characteristics of surface EMG, we adopted the rectified EMG because rectification of the surface EMG signal and its power spectrum is a strategy that has been used to reveal the temporal pattern of grouped motor unit discharges (Halliday et al., 1995; Myers et al., 2003), and the activation strategy of the muscles (Yoshitake et al., 2007). The cross-spectral analysis from MMG to EMG and CoM was performed to investigate the coherency and time shift between MMG signals and the muscle activity and body sway. These frequency domain analyses were executed according to Bloomfield (2000). The data for 60 s were divided into 13 subsets with a length of 8192 data points (8.192 s). Almost half of the segment overlapped with the adjacent segments. A 13-bit fast-Fourier transform algorithm was then applied to generate a periodogram for each subset. Consequently, the frequency resolution was 0.122 Hz. An ensemble-average auto-power spectral density was calculated across these segments.

The coherency spectrum [$\mathrm{Coh}^2(f)$] for the two time series ($x$ and $y$) was given as follows:

$$\mathrm{Coh}^2(f) = \frac{|S_{xy}(f)|^2}{S_x(f)S_y(f)}$$

where $f$ denotes frequency. $S_{xy}(f)$ is the cross-power spectrum function of $x$ and $y$, $S_x(f)$ and $S_y(f)$ are the auto-power spectrum functions of $x$ and $y$, respectively. The phase spectrum [$\theta_{xy}(f)$] was defined as: