Journal of Electromyography and Kinesiology 22 (2012) 51–59

Contents lists available at SciVerse ScienceDirect

Journal of Electromyography and Kinesiology

journal homepage: www.elsevier.com/locate/jelekin

Propagation direction of natural mechanical oscillations in the biceps brachii muscle during voluntary contraction

Akibi A. Archer [a,*], Perry Atangcho [b], Karim G. Sabra [a], Minoru Shinohara [c,1]

[a] Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA
[b] School of Biomedical Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA
[c] School of Applied Physiology, Georgia Institute of Technology, Atlanta, GA 30332, USA

ARTICLE INFO

Article history:
Received 14 June 2011
Received in revised form 9 September 2011
Accepted 22 September 2011

Keywords:
Mechanomyogram
Coherence
Biceps brachii
Vibration

ABSTRACT

The aim of the study was to determine the directionality of the coupling of mechanical vibrations across the biceps brachii muscle at different frequencies of interest during voluntary contraction. The vibrations that are naturally generated by skeletal muscles were recorded by a two-dimensional array of skin mounted accelerometers over the biceps brachii muscle (surface mechanomyogram, S-MMG) during voluntary isometric contractions in ten healthy young men. As a measure of the similarity of vibration between a given pair of accelerometers, the spatial coherence of S-MMG at low ($f < 25$ Hz) and high ($f > 25$ Hz) frequency bands were investigated to determine if the coupling of the natural mechanical vibrations were due to the different physiological muscle activity at low and high frequencies. In both frequency bands, spatial coherence values for sensor pairs aligned longitudinally along the proximal to distal ends of the biceps were significantly higher compared with those for the sensor pairs oriented perpendicular to the muscle fibers. This difference was more evident at the higher frequency band. The findings indicated that coherent mechanical oscillations mainly propagated along the longitudinal direction of the biceps brachii muscle fibers at high frequencies ($f > 25$ Hz).

Published by Elsevier Ltd.

1. Introduction

Continuous surface mechanical oscillations are naturally generated by skeletal muscle during voluntary contraction. These natural muscle vibrations result from the dimensional changes in muscle fibers and muscle-tendon geometry (Beck et al., 2005; Orizio, 1993). Independent of the type of sensors used, recordings of muscle mechanical oscillations with these sensors are called surface mechanomyograms (S-MMGs) (Orizio, 1993).

The physiological origin and time-frequency characteristics of S-MMGs depend on muscle structure, mechanical state, and the electromechanical coupling efficiency in muscles (Barry and Cole, 1990; Oster and Jaffe, 1980; Shinohara and Søgaard, 2006). S-MMGs have typically been used to monitor the mechanical activity of a contracting muscle. In contrast, S-MMGs have rarely been used to estimate the mechanical properties (*e.g.* viscoelasticity) of skeletal muscles (Cole and Barry, 1994). Indeed, since the S-MMGs correspond physically to propagating vibrations along the muscle, Sabra and his colleagues Sabra et al. (2007) and Sabra and Archer (2009) have been exploring the use of S-MMGs as a potential tool for non-invasive examination of muscle viscoelastic properties, such as muscle stiffness.

Despite the large body of literature on S-MMGs, the spatial variations of S-MMGs over a muscle remain unclear, specifically the frequency dependency of the spatial variation of S-MMGs. Most studies have used only a single sensor, and the influence of the sensor location over the muscle of interest was investigated only recently from various perspectives (Ouamer et al., 1999; Cescon et al., 2004, 2007, 2008; Madeleine et al., 2006, 2007; Farina et al., 2008). In particular, studies using a two dimensional array of accelerometers have shown that the S-MMGs' amplitude and frequency content is strongly influenced by the sensor location over the studied muscles (Sabra and Archer, 2009; Madeleine et al., 2007; Farina et al., 2008; Cescon et al., 2008). In these studies, the S-MMG analysis was predominantly on low-frequency content (i.e., mainly $f < 25$ Hz) that appeared to be mostly influenced by global synchronized activity of muscle fibers due to tremor activity or electrical stimulation. In preliminary studies using a single subject, high-frequency S-MMGs (i.e., filtered > 25 Hz) of the biceps brachii and vastus lateralis muscles mainly propagated longitudinally along the muscle fiber orientation during sustained voluntary contractions (Sabra et al., 2007; Sabra and Archer, 2009). Indeed these high-frequency S-MMGs were likely generated by asynchronous muscle fiber activity for these superficial muscles and were likely not significantly influenced by synchronized tre-

* Corresponding author.
E-mail address: aarcher6@mail.gatech.edu (A.A. Archer).

[1] Minoru Shinohara is supported in part by VA MERIT Pilot Award (1 I01 RX000421-01).

1050-6411/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.jelekin.2011.09.011

mor activity that occurs at lower frequencies. No studies are found in the existing literature that systematically investigated directionality of the coupling of the measured S-MMG between low and high frequency bands.

For a given pair of vibration sensors (here skin-mounted accelerometers), the spatial coherence of the S-MMGs is a measure of the similarity of the S-MMGs measured at those two sensors (Gardner, 1992). For instance, the spatial coherence of mechanical vibrations increases when these vibrations propagate along a more homogeneous (or uniform) medium such that the relative phase of the propagating vibration signals remains relatively undisturbed. The main aim of this study was to systematically determine the directionality in different frequency bands of the spatial coherence of the S-MMGs from the biceps brachii muscle during submaximal isometric voluntary contractions using a two-dimensional array of skin-mounted accelerometers (see Fig. 1). Preliminary studies that investigated the directionality of natural muscle vibrations in one subject did not study the influence of the selected frequency band of the S-MMG (Sabra et al., 2007; Sabra and Archer, 2009). The spatial variation of S-MMG coherence across all sensor pairs at low ($f < 25$ Hz) and high ($f > 25$ Hz) frequency bands can then be used to infer how the S-MMG coherence varies with directionality (i.e., longitudinal vs. transverse) and sensor separation distance for various contraction levels.

In this work, the longitudinal direction corresponds to the main orientation of the biceps brachii muscle's fibers and is expected to be more homogeneous than the transverse directions (Fung, 1988). The high frequency mechanical oscillations ($f > 25$ Hz) are less influenced by synchronous tremor-like activity (Orizio, 2005). Therefore, the high frequency oscillations are more likely to propagate coherently along the muscle fiber orientation (i.e., longitudinal direction) similarly to elastic guided waves propagating along cable (or fiber) bundles (Romano et al., 2005). Consequently, it was hypothesized that the spatial coherence of high frequency S-MMG ($f > 25$ Hz) is overall higher in longitudinal directionality (i.e., along the muscle axis) than in transverse directionality (i.e., across muscle fibers).

2. Methods

2.1. Subjects

Ten healthy and right-handed men (age: 29 ± 5 years, height: 175 ± 9 cm, body mass: 71 ± 8 kg), with no overt sign of neuromuscular diseases, volunteered to participate in the present study and signed an informed consent form. This study was conducted according to the protocol approved by the Institutional Review Board of the Georgia Institute of Technology. For each subject, the thickness of the skin and fat layer overlaying the belly of the biceps brachii muscle was measured to be 2.7 ± 0.8 mm from conventional ultrasound B-mode images (GE LOGIQ P5, GE Healthcare, Waukesha, WI).

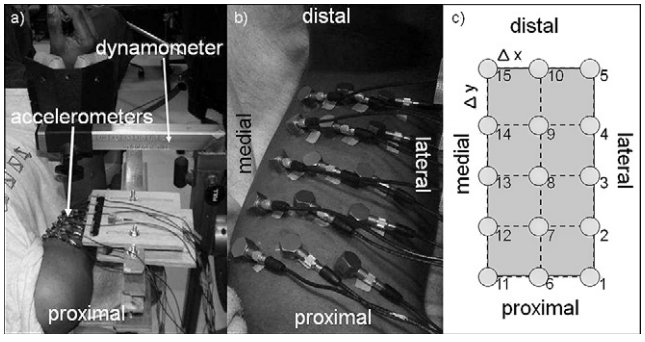

Fig. 1. (a) Experimental set-up for isometric elbow flexion tests, (b) top view of one subject's right arm with the 15 skin-mounted accelerometers, (c) schematic of the 15 accelerometers locations.

2.2. Experimental setup

Fifteen miniature single-axis accelerometers (A352C65, mass = 2 g, base diameter = 9.5 mm, measurement range = ±491 m/s^2 pk (50 g pk), sensitivity = 100 mV/g; PCB Piezotronics, Depew, NY) with thin flexible cables to reduce drag (<1 mm diameter) were used to record S-MMG over the biceps muscle (Fig. 1). The accelerometers were skin-mounted over the biceps brachii using double-sided medical tape to provide good contact while minimizing mounting artifacts and allowing the muscle to move freely without additional pressure interference. Previous studies have demonstrated that a mass up to 30 g on the skin does not significantly affect the S-MMGs' physical characteristics in large skeletal muscles (Cescon et al., 2002; Watakabe et al., 2003).

The accelerometers were arranged on a 3 × 5 grid (Fig. 1(b,c)). The biceps brachii length was determined based on anatomical landmarks for each subject as extending from the origin of the tendon of insertion (distally) to the coracoid process of the scapula (proximally) Graaff (2002). The sensor grid axis and thus imaging plane was approximately aligned with the longitudinal axis of the biceps brachii. This longitudinal axis corresponds to the muscle fiber orientation since the biceps muscle has a simple fusiform architecture (Pappas et al., 2002). The transverse sensor spacing along the medial-lateral direction (Δx) was set to 2 cm. This distance was the smallest achievable separation distance given the sensor diameter of ~9.5 mm. The longitudinal spacing distance along the proximal-distal direction between adjacent accelerometers (Δy) was determined as 8% of the estimated length of the biceps brachii long head muscle (26 cm < L_m < 34 cm), following a previous approach (Sabra and Archer, 2009; Pappas et al., 2002). In this study, Δy varied from 2.1 cm to 2.7 cm among subjects to ensure that the accelerometers were placed in anatomically comparable positions for each subject. Consequently for all subjects, the 3 × 5 sensor grid covered the region between 18% and 50% of L_m, where the coordinate origin was set at the distal end (0% of L_m) (Pappas et al., 2002).

2.3. Experimental protocol

For each subject, the S-MMGs were recorded during 10 s long voluntary isometric contractions with elbow flexors. A dynamometer (HUMAC, CSMi Medical Solutions, Stoughton, MA) was used as a platform for muscle contraction. Each subject was situated laying on his back with the right arm attached to the dynamometer at the wrist (Fig. 1(a)). The elbow was flexed at 90 degrees, and the wrist was oriented in the neutral position. The right upper arm was placed horizontally with its posterior part not touching the bed surface. A supporting stand for sensor cables was used to minimize motion/deformation artifacts during contractions. The rotation axis of the elbow joint was visually aligned with the rotation axis of the dynamometer. The force output of the biceps was recorded independently by a force transducer attached to the horizontal bar connected to the subject's wrist by a velcro strap. The cables of the five accelerometers located on each of the three longitudinal grid lines (e.g., lateral grid line sensors 1–5, see Fig. 1(c)) were firmly attached with an equal cable length to one of three plywood boards. The boards extended from a sturdy vertical platform that was separated and insulated from the potential vibrations generated by the dynamometer bench. The three plywood boards were stacked vertically to prevent the wires from contacting with each other (see Fig. 1(a)). Each stack board was extended horizontally