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Muscle shear elastic modulus measured using supersonic shear imaging is highly related to muscle activity level

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Nordez A, Hug F. Muscle shear elastic modulus measured using supersonic shear imaging is highly related to muscle activity level. *J Appl Physiol* 108: 1389–1394, 2010. First published February 18, 2010; doi:10.1152/japplphysiol.01323.2009.—This pilot study was designed to determine whether the shear elastic modulus measured using supersonic shear imaging can be used to accurately estimate muscle activity level. Using direct visual feedback of torque, six healthy subjects were asked to perform two incremental isometric elbow flexions, consisting of linear torque ramps of 30 s from 0 to 40% of maximal voluntary contraction. Both electromyographic (EMG) activity and shear elastic modulus were continuously measured in the biceps brachii during the two ramps. There was significant linear regression ($P < 0.001$) between shear elastic modulus and EMG activity level for both ramps of all six subjects ($R^2 = 0.94 \pm 0.05$, ranging from 0.82 to 0.98). Good repeatability was found for shear elastic modulus estimated at both 3% (*trial 1*: 21.7 ± 6.7 kPa; *trial 2*: 23.2 ± 7.2 kPa, intraclass correlation coefficient = 0.89, standard error in measurement = 2.3 kPa, coefficient of variation = 12.7%) and 7% (*trial 1*: 42.6 ± 14.1 kPa; *trial 2*: 44.8 ± 15.8 kPa, intraclass correlation coefficient = 0.94, standard error in measurement = 3.7 kPa, coefficient of variation = 7.1%) of maximal EMG activity. The shear elastic modulus estimated at both 3 and 7% of maximal EMG activity was not significantly different ($P > 0.05$) between the two trials. These results confirm our hypothesis that the use of supersonic shear imaging greatly improves the correlation between muscle shear elastic modulus and EMG activity level. Due to the nonlinearity of muscle mechanical properties, the muscle elasticity should be linked to the muscle stress. Therefore, the present study represents a first step in attempting to show that supersonic shear imaging can be used to indirectly estimate muscle stress.

electromyography; biceps brachii; elastography; ultrasound; muscle elasticity

EXPERIMENTAL TECHNIQUES CLASSICALLY used to study the mechanical behavior of muscle in vivo (e.g., quick release or sinusoidal perturbations) assess global mechanical properties of the musculo-articular complex without any differentiation of the various structures (i.e., muscle, tendon, joint) and muscles involved in the task. More localized techniques, such as elastographic methods, have recently been implemented to quantify local muscle mechanical properties by measuring the propagation velocity of shear waves using imaging techniques. For example, using magnetic resonance elastography, some studies have proposed that muscle shear elastic modulus can be linked to myoelectrical activity level or muscle force (13, 16). However, since this technique implies performing static experiments with an acquisition time of ~1 min, it cannot be used to follow rapid changes of shear elasticity during muscle contraction in vivo. In contrast, transient elastography allows shear elastic modulus to be measured in 30 ms and can be proposed as a suitable method to follow changes in muscle elasticity during a contraction. In this way, some studies have shown that the transverse shear elastic modulus measured using transient elastography is related to myoelectrical activity level (12) and passive muscle tension (18). However, the coefficients of determination reported by Gennisson et al. (12) ($R^2 = 0.55$) and the repeatability reported by Nordez et al. (18) were low and indicate the limitations of this one-dimensional technique to accurately estimate muscle activity from the elastic modulus. Two main hypotheses have been proposed to explain these results. *1*) Skeletal muscle is a heterogeneous tissue. Since muscle fibers move under the skin during contraction, elasticity measurements are not always performed in the same region using this one-dimensional technique. *2*) In transient elastography, a mechanical vibrator is used to induce the generation of shear waves. However, this external mechanical vibration is difficult to standardize for in vivo experiments, and it probably influences shear wave velocity measurements.

With the new transient elastography technique, designated supersonic shear imaging (SSI) (1), these problems can be addressed. Indeed, two-dimensional measurements are performed. Therefore, it is possible to obtain mean values that are more representative of muscle properties. In addition, because SSI uses ultrasonic focused beams to generate mechanical vibration sources inside tissues without any external mechanical vibration (1), the measurement should be independent of any pressure between the probe and the skin.

This pilot study was designed to determine whether the shear elastic modulus measured using supersonic shear imaging can be used to accurately estimate muscle activity level.

MATERIALS AND METHODS

Subjects

Six healthy subjects participated in the study (5 men, 1 woman; aged 32.3 ± 8.9 yr, height 177.5 ± 8.4 cm, weight 73.2 ± 12.5 kg). They were informed in detail of the purpose of the study and methods used and gave written consent. This study was conducted according to the Helsinki statement (last modified in 2004) and has been approved by the local ethics committee.

Instrumentation

Ergometer. A Biodex system 3 research (Biodex medical, Shirley, NY) isokinetic dynamometer was used to measure elbow angle and torque. The position of the subjects was similar to the position previously described (12). Briefly, subjects sat on the dynamometer with their right upper arm and forearm placed in a 90° flexion position, and wrist in supine position.

Elastography. An AixPlorer ultrasonic scanner (Supersonic Imagine, Aix en Provence, France), coupled with a linear transducer array

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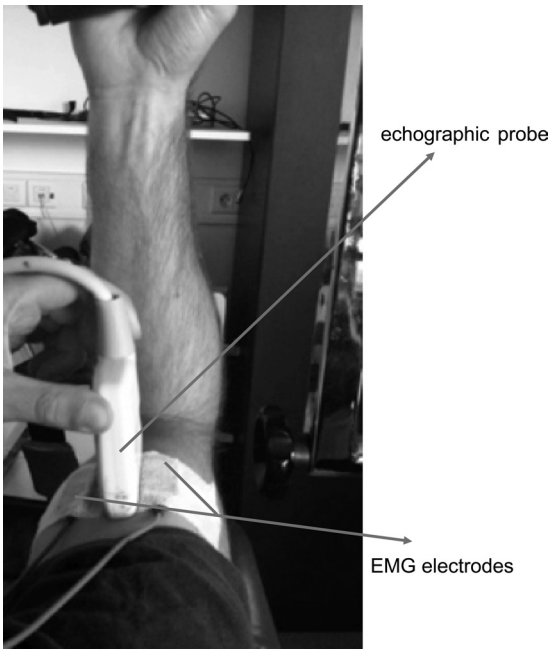

Fig. 1. Placement of the electromyographic (EMG) electrodes with respect to the ultrasound transducer. To obtain a representative EMG activity level, one pair of electrodes was placed on both sides of the echographic probe.

(4–15 MHz, SuperLinear 15–4, Vermon, Tours, France) was used in the present study. The scanner was set at the SSI mode that has previously been described in detail (1, 19). Briefly, it generates a remote radiation force through focused ultrasonic beams that induce the propagation of transient shear waves. An ultrafast echographic imaging sequence is then performed to acquire successive raw radio-frequency data at a very high frame rate. One-dimensional cross-correlation of successive radio-frequency signals is used to calculate muscle displacements due to shear wave along the ultrasonic beam axis, and shear wave velocity is determined along the principal axis of the probe using a time-of-flight estimation. The echographic probe was placed on the Biceps brachii belly (Fig. 1) and carefully aligned with the shortening direction of the muscle. Since the biceps is fusiform, the shear wave propagation was measured in the fiber direction ($V_s^{\|}$)(11, 12). Thus, considering a linear elastic transverse isotropic material, the longitudinal shear elastic modulus (c_{44}) was then calculated as follows (11, 12):

$$c_{44} = \rho V_s^{\|2} \qquad (1)$$

where ρ is the muscle mass density (1,000 kg/m^3).

First, considering muscle architecture of the biceps brachii muscle, the hypothesis of a transverse isotropic material seems the most reasonable (11, 12). Second, the hypothesis of linear material is classic in muscle elastographic studies, using both echographic (1, 3, 4, 11, 12, 18, 19) and magnetic resonance imaging (6, 13, 16, 20). In fact, the shear wave amplitude is very small, and nonlinear effects are negligible. Finally, *Eq. 1* considers a purely elastic material and implicitly neglects viscous effects. The influence of viscosity on shear wave velocity measurements has been previously studied (3, 4). Deffieux et al. (4) have shown that, when measured longitudinally using SSI, the shear wave velocity is almost independent of the frequency of the mechanical shock, indicating no significant viscous effects. This result is in accordance with those of Catheline et al. (3) using the one-dimensional transient elastography technique. Therefore, the shear elastic modulus measured in the present study is little affected by viscous effects; hence they are negligible.

Maps of the shear elastic modulus (Fig. 2) were calculated at 1 Hz (i.e., the maximal sampling rate of SSI measurements of the current version of the ultrasonic scanner) with a spatial resolution of 1 × 1 mm.

Electromyography. Surface electromyographic (EMG) activity was measured with dry-surface electrodes (Delsys DE 2.1, Delsys; 1-cm interelectrode distance) placed on the biceps brachii, longitudinally with respect to the underlying muscle fiber arrangement, distal to the motor point. A reference electrode was placed at the wrist level. To obtain a representative EMG activity, one pair of electrodes was placed on both sides of the echographic probe (Fig. 1). EMG signals were amplified (×1,000) and digitized (bandwidth of 6–400 Hz). Torque and EMG signals were collected synchronously at 1 kHz with an analog/digital converter (Bagnoli 16, Delsys).

Protocol

First, subjects performed three 3-s maximal isometric voluntary elbow flexions (1-min rest between flexions) to determine both maximal voluntary contraction (MVC) and maximal EMG activity. Then subjects were asked to realize two incremental isometric tasks (2-min rest between tasks), consisting of smooth linear torque ramps of 30 s from 0 to 40% of MVC performed using direct visual feedback of the torque signal. Before each trial, subjects were asked to be completely relaxed during a 5-s period to measure the shear elastic modulus at rest.

Data Analysis

For each incremental isometric task, 30 root mean square (RMS) values were calculated from the raw EMG data in a 1-s window. EMG RMS values were normalized with the maximal level reached during the maximal isometric contractions (calculated over a 500-ms interval centered on the maximal torque), and the values obtained in the two

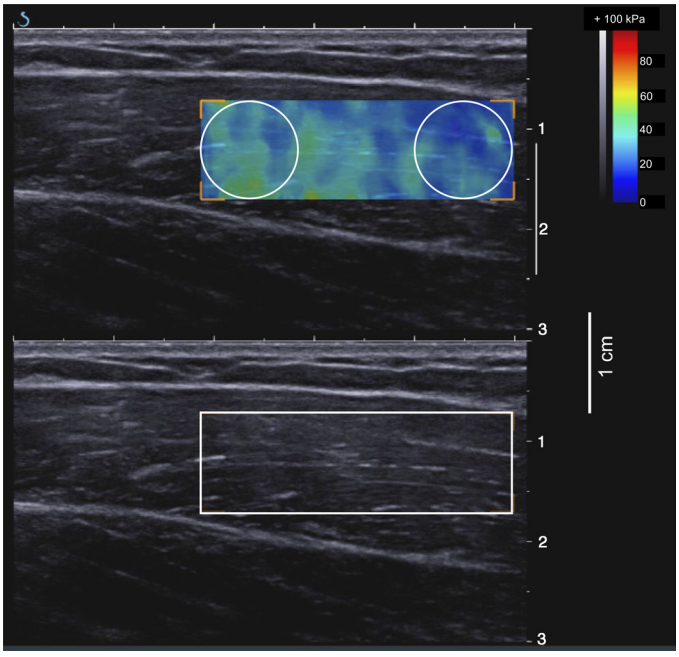

Fig. 2. Typical example of shear elastic modulus measurement. The region of interest (colored region) was chosen in the biceps brachii muscle using an echographic image. For the sake of clarity, the echographic image without the color map is depicted at the *bottom* of the figure. The colored region represents the shear elasticity map with the scale to the *right* of the figure. The software allowed us to measure the mean shear elasticity value over two circular regions. The mean values obtained in these two circular regions were then averaged to determine a more representative measure.

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recording sites were averaged. Figure 2 depicts a typical example of one of the 30 shear elastic maps of the biceps brachii obtained during an incremental task. The software of the ultrasound scanner allowed us to measure 30 mean shear elasticity values obtained in two circular regions (from 0.8 to 1 cm in diameter, depending on muscle thickness) placed on the biceps brachii. Due to a technical limitation of the ultrasonic scanner, the measurements saturated at 100 kPa, limiting the range of analysis for most of the subjects. If one value in the circular region reached 100 kPa, the mean data of this region was discarded from further analysis. The five shear elastic measurements performed at rest before each incremental contraction were averaged to obtain a resting value.

For each incremental isometric task, linear regressions between the shear elastic modulus and EMG RMS values were performed, and coefficients of determination (R^2) were calculated (Origin 8, OriginLab). To assess the repeatability of the measurements, shear elastic moduli were estimated with regression coefficients at 3 and 7% of maximal EMG RMS activity (common range for all subjects). The intraclass correlation coefficient (ICC), standard error in measurement (SEM) and coefficient of variation (CV) were calculated (15) for these two estimated shear elastic moduli.

To compare the shear elastic modulus between the two incremental isometric contractions, 2 (incremental isometric contraction) $\times$ 2 (contraction intensity at 3 and 7% of the maximal EMG RMS activity) repeated-measures analysis of variances (ANOVA) were performed (Origin 8, OriginLab). The critical level of significance in the present study was set at $P < 0.05$.

RESULTS

Changes in the shear elastic modulus during the first incremental isometric tasks in the two circular regions are shown in Fig. 3. Although different starting values were obtained for some subjects in these two regions, very similar patterns were obtained. Therefore, to be more representative of the muscle belly, all of the following results represent averages on these two circular regions.

The shear elastic modulus measured at rest was 11.3 $\pm$ 3.8 kPa (ranged from 5.6 to 15.2 kPa) and 10.7 $\pm$ 4.5 kPa (ranged from 6.7 to 18.3 kPa) for the first and the second ramp, respectively.

Figure 4 depicts two typical changes in both shear elastic modulus and EMG activity level during the incremental isometric task. It shows very good agreement between EMG and echographic measurements. It is confirmed by data shown in

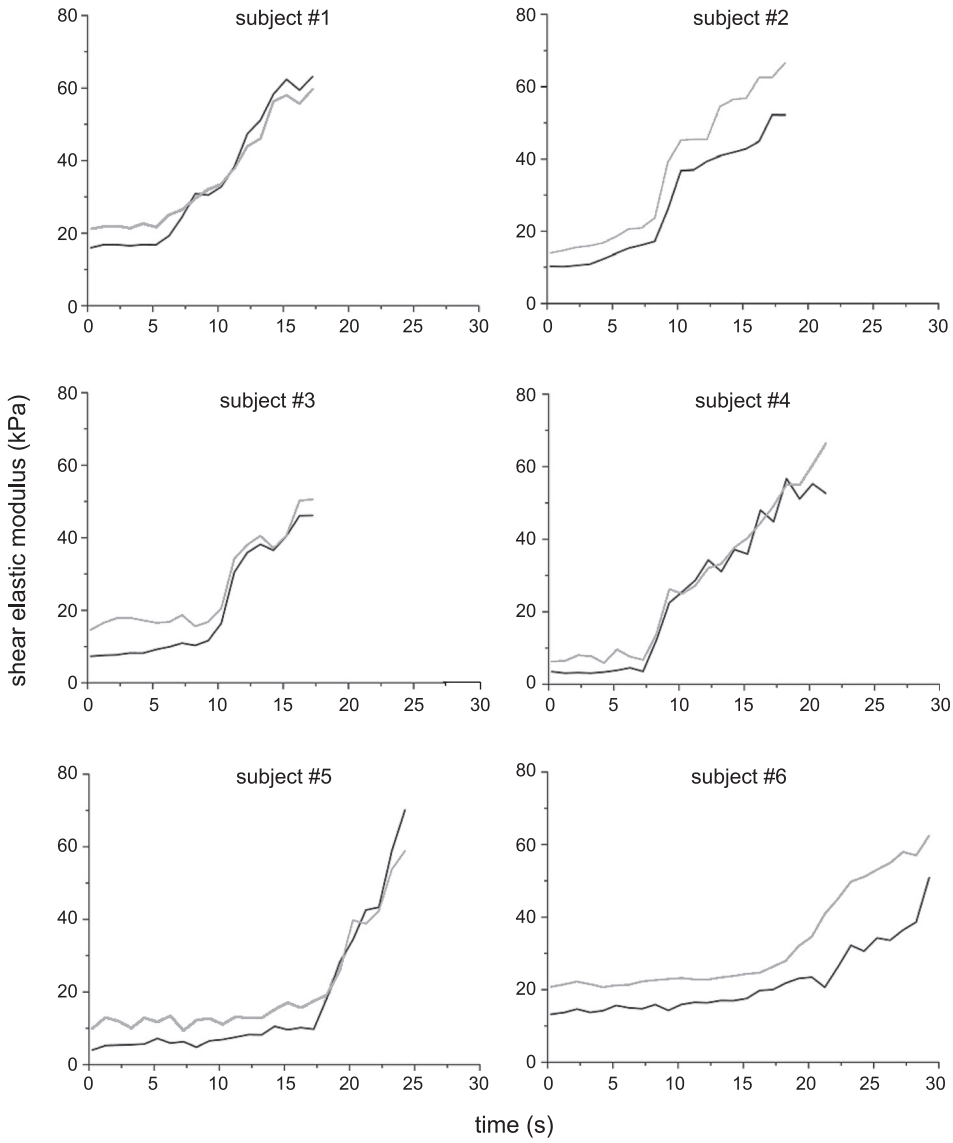

Fig. 3. Changes in shear elastic modulus during the first incremental isometric tasks in the two circular regions. Although different starting values were obtained for some subjects in the two circular regions, very similar patterns were obtained. Dark gray and light gray lines correspond to the distal and the proximal positions, respectively.

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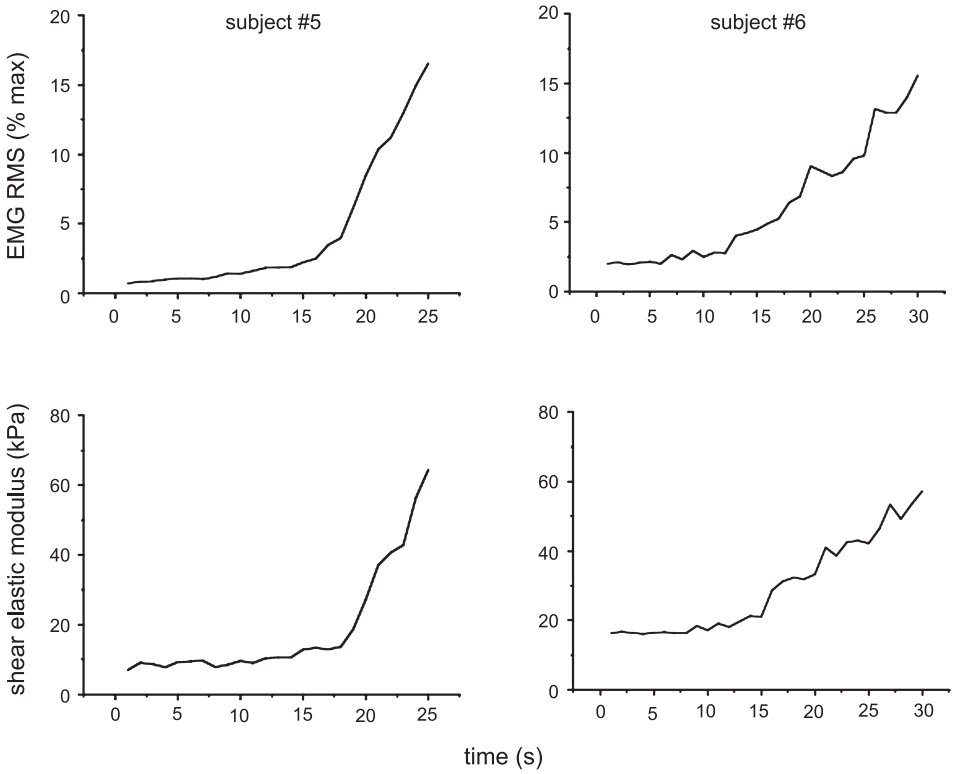

Fig. 4. Two individual examples of changes with time (and hence with torque) in the normalized root mean square (RMS) of EMG signals and shear elastic modulus. These demonstrate very good agreement between both EMG and shear elastic modulus measurements. Both EMG activity level and the shear elastic modulus of the biceps brachii increase moderately during the first half (i.e., from ~0 to 20% of maximal voluntary contraction) of the exercise, suggesting a higher implication of other elbow flexor muscles (e.g., brachial, brachioradialis).

Fig. 5, demonstrating significant linear regressions ($P < 0.001$) between shear elastic modulus and EMG activity level for both trials of the six subjects ($R^2 = 0.94 \pm 0.05$, ranging from 0.82 to 0.98).

Similar relationships were found for both trials (Fig. 5). Good repeatability was found for the shear elastic modulus estimated at both 3% (*trial 1*: 21.7 ± 6.7 kPa; *trial 2*: 23.2 ± 7.2 kPa, ICC = 0.89, SEM = 2.3 kPa, CV = 12.7%) and 7% (*trial 1*: 42.6 ± 14.1 kPa; *trial 2*: 44.8 ± 15.8 kPa, ICC = 0.94, SEM = 3.7 kPa, CV = 7.1%) of maximal EMG activity. Concerning the comparisons of the shear elastic modulus between the two incremental isometric contractions at the two intensities, a significant main effect of contraction intensity ($P < 0.01$) was found, indicating that the shear elastic modulus was higher at 7 vs. 3% of the maximal EMG RMS activity. In contrast, the main effect of the incremental isometric contraction and the interaction (incremental isometric contraction × contraction intensity) were not significant ($P > 0.05$), indicating that the shear elastic modulus was not significantly different between the two incremental isometric contractions.

DISCUSSION

The present study shows that SSI greatly improves linear regression (i.e., better R^2 and excellent repeatability) between the shear elastic modulus and EMG activity level compared with one-dimensional measurements performed in previous studies (12, 18).

Due to saturation at 100 kPa, the incremental isometric tasks were analyzed only until 28 ± 7% of MVC corresponding to 11 ± 4% of the maximal EMG RMS. Thus these preliminary results cannot be extrapolated to higher contraction levels. However, since accurate and repeatable results were found for these low ranges of muscle activity levels (e.g., CV = 7% for predicting a shear elastic modulus at an EMG activity of 7%), it demonstrates the high sensitivity of SSI to quantify muscle activity level. A technical improvement of the ultrasound scanner should allow us to measure higher shear elastic modulus values (>100 kPa) and thus to investigate a higher range of muscle activity levels. These results have interesting implications, particularly for the assessment of deep muscle activity.

As previously indicated, although different starting values were obtained for some subjects in the two circular regions (Fig. 3), very similar patterns were obtained, justifying the averaging to be more representative of the muscle belly. However, as shown in Fig. 2, the local spatial variability in each region is much higher. The spatial variability of the shear elastic modulus measurement would be very interesting to analyze in further study, for instance with a comparison to the previously described spatial variability of EMG measurements measured by electrode arrays (9, 14).

Since the contraction intensities are not the same, the comparison of shear elastic modulus values obtained during contraction with the literature can be quite complicated. The comparison with resting shear elastic modulus is easier to perform. For instance, using magnetic resonance elastography for the biceps brachii, previous studies reported a shear elastic modulus of 12.3 ± 0.5 kPa (16), 27 kPa (ranged from 14.1 and 39.2 kPa) (6), and 17.9 ± 5.5 kPa (20). These results are completely in accordance with the results of the present study. All of these shear elastic modulus values assessed using both magnetic resonance elastography and SSI are in the same range as modulus reported on resting isolated muscle using a stress-strain relationship (~10 kPa) (17).

The estimation of the force exerted by a muscle is of high relevance, in both biomechanical studies and clinical applications (2, 5, 7). However, it cannot be directly measured in vivo.

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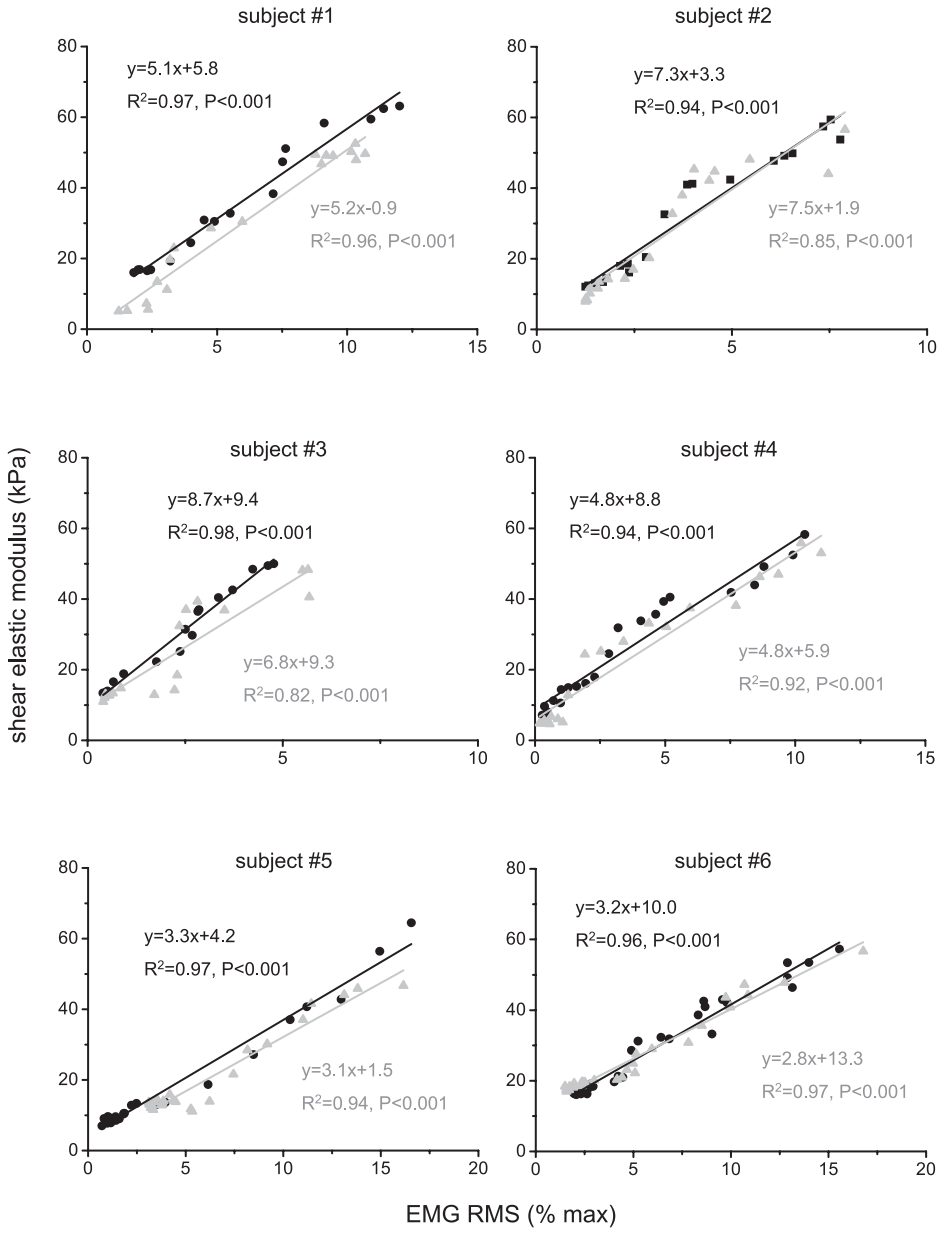

Fig. 5. Linear regressions between normalized RMS of EMG signals and shear elastic modulus for the two incremental isometric tests of the six subjects. Solid and light gray lines correspond to the first and the second ramp, respectively.

Numerous models based on mechanical and EMG measurements have been developed (2, 5, 7). However, various physiological/nonphysiological factors are known to affect the EMG signal during exercise (8). In addition, due to the lack of experimental methods, these models cannot be fully validated. Because of the nonlinearity of the mechanical properties of biological tissues (10), the muscle stress is linked to its elastic modulus. Thus one would expect that shear wave modulus is related to muscle stress. Thus the present study is a first step in attempting to show that SSI can be used to indirectly estimate muscle stress, but the accuracy of such indirect estimation remains to be determined.

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DISCLOSURES

No conflicts of interest are declared by the author(s).

REFERENCES

1. **Bercoff J, Tanter M, Fink M.** Supersonic shear imaging: a new technique for soft tissue elasticity mapping. *IEEE Trans Ultrason Ferroelectr Freq Control* 51: 396–409, 2004.
2. **Buchanan TS, Lloyd DG, Manal K, Besier TF.** Neuromusculoskeletal modeling: estimation of muscle forces and joint moments and movements from measurements of neural command. *J Appl Biomech* 20: 367–395, 2004.
3. **Catheline S, Gennisson JL, Delon G, Fink M, Sinkus R, Abouelkaram S, Culioli J.** Measuring of viscoelastic properties of homogeneous soft solid using transient elastography: an inverse problem approach. *J Acoust Soc Am* 116: 3734–3741, 2004.
4. **Deffieux T, Montaldo G, Tanter M, Fink M.** Shear wave spectroscopy for in vivo quantification of human soft tissues visco-elasticity. *IEEE Trans Med Imaging* 28: 313–22, 2009.

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5. **Disselhorst-Klug C, Schmitz-Rode T, Rau G.** Surface electromyography and muscle force: limits in sEMG-force relationship and new approaches for applications. *Clin Biomech (Bristol, Avon)* 24: 225–235, 2009.
6. **Dresner MA, Rose GH, Rossman PJ, Muthupillai R, Manduca A, Ehman RL.** Magnetic resonance elastography of skeletal muscle. *J Magn Reson Imaging* 13: 269–276, 2001.
7. **Erdemir A, McLean S, Herzog W, van den Bogert AJ.** Model-based estimation of muscle forces exerted during movements. *Clin Biomech (Bristol, Avon)* 22: 131–154, 2007.
8. **Farina D, Merletti R, Enoka RM.** The extraction of neural strategies from the surface EMG. *J Appl Physiol* 96: 1486–1495, 2004.
9. **Farina D, Leclerc F, Arendt-Nielsen L, Buttelli O, Madeleine P.** The change in spatial distribution of upper trapezius muscle activity is correlated to contraction duration. *J Electromyogr Kinesiol* 18: 16–25, 2008.
10. **Fung YC.** *Mechanical Properties of Living Tissues.* New York: Springer-Verlag, 1983.
11. **Gennisson JL, Catheline S, Chaffaï S, Fink M.** Transient elastography in anisotropic medium: application to the measurement of slow and fast shear wave speeds in muscles. *J Acoust Soc Am* 114: 536–541, 2003.
12. **Gennisson JL, Cornu C, Catheline S, Fink M, Portero P.** Human muscle hardness assessment during incremental isometric contraction using transient elastography. *J Biomech* 38: 1543–1550, 2005.
13. **Heers G, Jenkyn T, Dresner MA, Klein MO, Basford JR, Kaufman KR, Ehman RL, An KN.** Measurement of muscle activity with magnetic resonance elastography. *Clin Biomech (Bristol, Avon)* 18: 537–542, 2003.
14. **Holtermann A, Roeleveld K, Karlsson JS.** Inhomogeneities in muscle activation reveal motor unit recruitment. *J Electromyogr Kinesiol* 15: 131–137, 2003.
15. **Hopkins WG.** Measures of reliability in sports medicine and science. *Sports Med* 30: 1–15, 2000.
16. **Jenkyn TR, Ehman RL, An KN.** Noninvasive muscle tension measurement using the novel technique of magnetic resonance elastography (MRE). *J Biomech* 36: 1917–1921, 2003.
17. **Lieber RL.** *Skeletal Muscle Structure, Function and Plasticity***.** Philadelphia, PA: Lippincott Willians & Wilkins, 2002.
18. **Nordez A, Gennisson JL, Casari P, Catheline S, Cornu C.** Characterization of muscle belly elastic properties during passive stretching using transient elastography. *J Biomech* 41: 2305–2311, 2008.
19. **Tanter M, Bercoff J, Athanasiou A, Deffieux T, Gennisson JL, Montaldo G, Muller M, Tardivon A, Fink M.** Quantitative assessment of breast lesion viscoelasticity: initial clinical results using supersonic shear imaging. *Ultrasound Med Biol* 34: 1373–1386, 2008.
20. **Uffmann K, Maderwald S, Ajaj W, Galban CG, Mateiescu S, Quick HH, Ladd ME.** In vivo elasticity measurements of extremity skeletal muscle with MR elastography. *NMR Biomedl* 17: 181–190, 2004.

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