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Relationships of the vibromyogram to the surface electromyogram of the human rectus femoris muscle during voluntary isometric contraction

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Abstract—The relationship between vibromyographic (VMG) and electromyographic (EMG) signals during isometric contraction of the human rectus femoris muscles was studied. The method of least squares was used to obtain the best-fitting linear regression model to the root mean squared (RMS) values of the VMG and the EMG. It is shown that for the rectus femoris of four subjects, a linear VMG versus EMG relationship exists during 20-80% of the maximum voluntary contraction (MVC) at 30°, 60°, and 90° of knee joint flexion angles. The relation between the VMG and the EMG may be explained by the order recruitment of motor units and by the "onion-skin" phenomenon of the firing rates of recruited motor units in the regulation of muscle force production as reported in electro-neurophysiologic studies.

Key words: *electromyography (EMG), EMG-VMG relation, vibromyography (VMG), voluntary contraction.*

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INTRODUCTION

The relationship between the surface electromyogram (EMG) of a contracting muscle and the mechanical state of the muscle has been an interesting research topic for several decades. A significant amount of work has been done in quantifying the relationship between the EMG and the mechanical state generated isometrically and isotonically by intact skeletal muscles (1). The form of the mechanical state can be different from one study to another, depending on the detection techniques used for the measurement of mechanical parameters, such as muscle force or muscle vibration (or muscle sounds). In most studies, force measurements have been used as indicators of the mechanical state of the contracting muscle. In studies using such a mechanical measure from intact limb muscles, the mechanical state of the muscle may be determined only indirectly by its effect on a limb segment. Also, the muscle under study generally acts synergistically with other muscles to produce the desired mechanical state. As a consequence, it is difficult to determine with absolute certainty how the mechanical output exerted by the limb segment on the measuring apparatus is related to the mechanical output generated by a single muscle of interest, and how the EMG detected by surface electrodes is related to the muscle's mechanical state. In addition, joint angle in the case of isometric contraction, angular velocity in the case of isotonic contraction, and the length of the limb segment in the above two types of contractions can

potentially complicate the measurements. An ideal system for quantifying relations between EMG and mechanical state of muscle would be one in which mechanical and myoelectrical measuring devices could be directly and noninvasively attached to the same muscle under study while the muscle is under voluntary control.

The use of muscle vibration measurement techniques, referred to as vibromyography (2), sometimes as muscle sounds (3,4), acoustic myogram (5), soundmyogram (6), or phonomyogram (7), together with the EMG measurement fulfills some of the requirements of such an ideal system. The mechanical measurements of the vibromyography (VMG) are not synonymous with the mechanical measurement of force. The arrangement of sensors on the same active muscle for VMG and EMG measurements may, at least, avoid the complication caused by joint angles and limb segments in intact muscle force measurements.

Both VMG (4,8–11) and EMG signals (12–20) are expected to indicate the level of muscle activation, but the two methods utilize different physical principles and detect different aspects of muscle activity: one mechanical and the other electrical. The mechanical state detected by the VMG measures muscle vibration associated with muscle contractions. This mechanical state of muscle is not the same as the mechanical state producing muscle force, although they are both mechanical. The fact that a contracting muscle generates VMG signals or sounds was noted about 300 years ago (21). However, it was neglected as a possible measure (either direct or indirect) of muscle mechanical output. Instead, most studies concentrated on the potential use of the EMG to quantify muscle force production and contractile properties. Only in recent years has interest in the study of VMG been renewed, partly due to the development of new instrumentation, measurement, and signal processing techniques (2,9,22–28).

Studies dealing with the relationship between EMG and force and VMG and force of different muscles have been conducted by a few investigators (2,5,7,11,25). Barry et al. (5), working with the biceps brachii muscle, found a quadratic relationship between the acoustic signal's root mean squared (RMS) value and the weight applied to the hand. Orizio et al. (3), Stokes and Dalton (25), and Zwarts and Keidel (11) showed that relationships between force and EMG and force and VMG were linear in the muscles that they tested, the biceps muscle (3,11) and the quadriceps muscles (25). In previous work, we performed a comparative analysis of the VMG with the EMG recorded simultaneously on the rectus femoris muscle, and determined their relative association with levels of contraction (2). Most of these studies described how the processed EMG and VMG related to muscle force. In order to obtain the relation between the myoelectric activity (EMG) and the vibratory or acoustic activities (VMG) of a muscle, a third variable, namely force, has to be used. However, direct and noninvasive muscle force measurement is complicated, if not impossible.

Recently, Maton et al. (7) made a comparison between simultaneous recordings of the phonomyogram (PMG) and monopolar EMG from the isometrically contracting biceps brachii muscle. They found that the PMG RMS value was proportional to the EMG RMS value, and that both showed a quadratic relationship to muscle force. They further recommended that more research needs to be conducted in order to study such relationships for other muscles and to apply PMG or VMG to the fields of clinical medicine and rehabilitation (7). Stokes et al. (24), who compared acoustic and electrical signals from erector spinae muscles, also made a similar comment that there is a need for more research to gain further understanding of the phenomenon of sounds or vibrations from contracting muscles.

The experiments presented in this paper were performed on the human rectus femoris muscle to determine the relationship between time-averaged features of the EMG and the VMG obtained simultaneously during isometric, voluntary contractions. Compared with biceps brachii the rectus femoris is larger, and compared with the erector spinae muscles, it is better defined. As a single two-joint muscle, the rectus femoris can perform two movements—flexion of the hip and extension of the knee joint. In the present study, we establish a mathematical model for the relationship between VMG and EMG signals based on experimental data from the rectus femoris during extension of the knee joint. In particular, the method of least squares is used to obtain the best-fitting linear regression model to the RMS values of the VMG and the EMG obtained simultaneously from the rectus femoris during isometric contraction.

METHODS

Subjects

Our study population consisted of four nondisabled, adult, male volunteers ranging in age from 22

years to 40 years, with body weights ranging from 40 kg to 79 kg. In order to qualify for this study, the subjects were required to be free of abnormalities of the neuromuscular system and lower limbs. The right limb was tested for each subject, regardless of the dominant or nondominant side. Subjects were seated in a chair on a Cybex II isokinetic dynamometer, and were asked to perform contractions against a resistance arm on the dynamometer (2).

Testing Procedure

The technique for recording VMG signals is briefly summarized here: 1) An initial adjustment period permitted the subjects to practice performing isometric contractions with different specified levels of contraction using visual feedback of the torque display on the Cybex II dynamometer. Each contraction duration was approximately 6 seconds. Between the practice period and data collection, subjects rested for 2–5 minutes to avoid the development of muscle fatigue. 2) Each subject was asked to perform extension of the knee against the resistance arm on the dynamometer at the maximum level. The corresponding torque was noted to calculate the percentage of other levels of muscle contraction required. 3) Four levels of contraction from 20 to 80 percent of the maximum voluntary contraction (MVC) level were performed with a knee joint angle of 90°. Each level of contraction was performed once and held for 6–7 seconds. Between each contraction the subjects had an approximately 2-minute rest period to avoid muscle fatigue. 4) The four contraction levels in step 2 were repeated at knee joint angles of 60° and 30°. Since the rectus femoris is a two-joint muscle connected to the hip and the knee joint, flexion of the hip is closely associated with extension of the knee. In this study, the hip joint angle thus was stabilized with a strap fixed on the chair of the Cybex machine and maintained at 90° while the knee joint angle was changed, to prevent any potential variation being induced by flexion of the hip.

Simultaneous VMG and EMG Measurements

Figure 1 shows sensor placements for the experiment. In this setup, VMG signals were obtained using a miniature accelerometer (Dytran 3115a) placed on the skin over the rectus femoris muscle using two-sided adhesive tape. Some previous studies have used acoustic or phonocardiographic devices for VMG measurements (3,4,6,29). An important guideline for the choice of the VMG sensor concerns the ratio between the mass of the sensor and that of the muscle under study. For acceptable frequency response and sensitivity, a sensor with a small mass is preferable to reduce possible distortion in the VMG measurement.

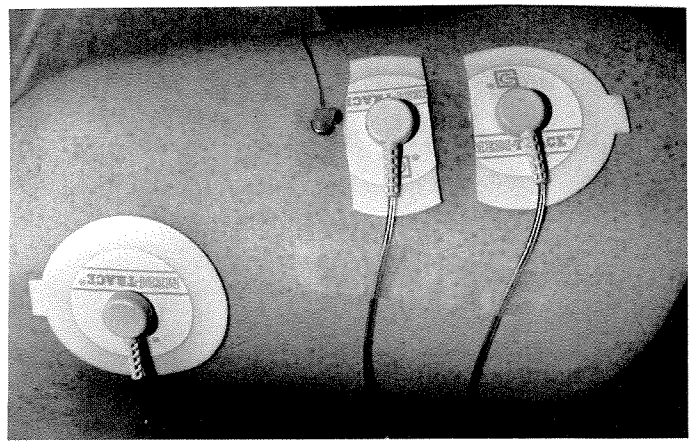

Figure 1.
Sensor placement on the skin surface over the rectus femoris for measuring the VMG and the EMG.

In contradistinction to previous studies, the work reported here employed a miniature accelerometer with light weight (1.5 g), good frequency response (1 Hz to 20 kHz), and a reasonable sensitivity (10 mv/g or approximately 1 mv/m/s2) for VMG measurements. This sensor, which is almost 90 times lighter than contact sensors such as the Hewlett Packard HP 21050A, may avoid external sensor loading of the muscle during experimentation. Furthermore, the small size of the VMG sensor permits easy attachment using double-sided adhesive tape, avoiding problems caused by straps needed to attach large sensors. A pair of Ag-AgCl electrodes was placed over the same muscle next to the accelerometer, and was used for simultaneous EMG measurement. The inter-electrode distance was 5 cm, and the sensors were all aligned longitudinally along the muscle. The signals were conditioned with bandpass filters with bandwidths of 3 Hz–100 Hz for the VMG and 10 Hz–300 Hz for the EMG, recorded on an HP 3968 FM tape recorder, and digitized with a sampling rate of 250 Hz for the VMG and 1 kHz for the EMG (12 bits per sample). Segments of VMG and EMG data were selected from the mid-portions of the collected signals for digitization and analysis to avoid possible transition effects caused by contractions and the FM recorder. The appropriate units were obtained by accounting for the gain factor used and for the sensitivity of the accelerometer for VMG measurements. The RMS

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values of the VMG and EMG signals were computed from the digitized data in the time domain over a period of 5 seconds. In order to find a model for the relationship between the VMG RMS values and the EMG RMS values, least squares regression analysis was performed on the experimental data.

Although the EMG and VMG signals were mainly measured over the rectus femoris muscle and the signals are referred to as rectus femoris signals in the rest of the text, the possibility exists that some of the signals are also emitting from the three other quadriceps muscles. Since the sensors for the measurement of VMG and EMG were placed over the same active muscle, we believe that the complication caused by joint angles and limb segments in intact muscle force measurements is minimized by the experimental design.

Regression Model

The EMG RMS values were used to predict the RMS values of the VMG according to the following linear transformation:

$$y = mx + b,$$

where y represents the VMG RMS value, x represents the EMG RMS value, and m and b are model constants (m is the regression coefficient expressing the change in y for a given change in x, and b is the y-intercept). The ordinary correlation coefficient was computed for evaluation of the quality of the fit.

RESULTS

A visual representation of a set of VMG and EMG signals obtained simultaneously for 40 percent MVC and 60 percent MVC at 60° knee joint angle in one representative subject is presented in **Figure 2.** The amplitudes of the VMG and EMG increase with an increase in the percentage of MVC. This phenomenon is typical for the range of levels of muscle contraction performed at the three joint angles across the four subjects.

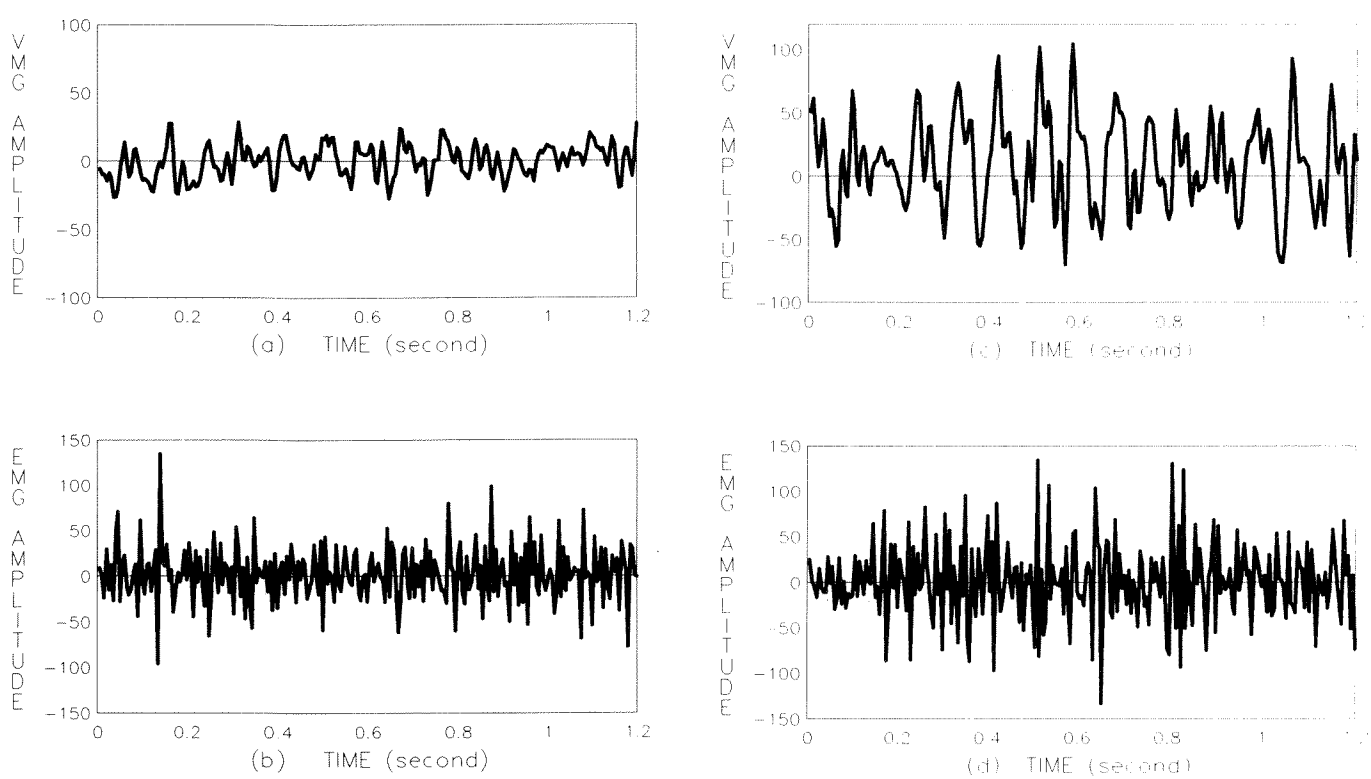

Figure 2.
A typical representation of VMG and EMG signals obtained simultaneously at 60° of knee joint angle from one subject. a) VMG at 40% MVC, b) EMG at 40%, c) VMG at 60% MVC, and d) EMG at 60% MVC.

Figures 3, 4, and **5** show plots of the RMS values of the VMG signals versus those of the EMG signals obtained during isometric contraction ranging from 20 percent to 80 percent MVC at knee joint angles of 30°, 60°, and 90° for the four subjects in the study. A datum point at 20 percent MVC from the subject with the lowest body weight was not used in **Figures 3, 4,** and **5** because of the uncertainty in filtering the noise and interference. The most obvious feature in these data is the consistent increase in the VMG RMS values as the EMG RMS values increase. The VMG-EMG model that provides the best fit to the data for each knee joint angle in the least-squares sense was found to be linear as described by the following equations:

For the knee joint angle of 30°:

$$y = 0.85x - 3.20, (R = 0.82), \quad (SE = 0.041, p < 0.001);$$

for the knee joint angle of 60°:

$$y = 0.91x + 0.67, (R = 0.92), \quad (SE = 0.028, p < 0.001);$$

and for the knee joint angle of 90°:

$$y = 0.78x + 2.74, R = 0.81, \quad (SE = 0.040, p < 0.001);$$

where *SE* represents the standard error, which describes the properties of the regression equation, and *R* is the ordinary correlation coefficient, the square of which gives the coefficient of determination. These RMS relationships between the VMG and the EMG are shown by the solid lines in **Figures 3, 4,** and **5.** These figures indicate that the VMG RMS values are linearly related, with positive regression coefficients in all cases, to the EMG RMS values obtained simultaneously for the same active muscle at the different knee joint angles. The correlation coefficients were, respectively, 0.82 at the knee joint angle of 30° (an outlier is obvious in **Figure 3,** and the removal of the outlier could give a higher correlation coefficient), 0.92 at the knee joint angle of 60°, and 0.81 at the knee joint angle of 90°. The correlation between the VMG and EMG RMS values at the three joint angles studied is statistically significant at the 0.001 level of significance. It should be noted that the value for the *y*-intercept in the equation for the knee joint angle of 30° is negative. The difference in the system noise between the EMG and VMG systems could possibly cause a change in the intercepts, but the direction of change should be the

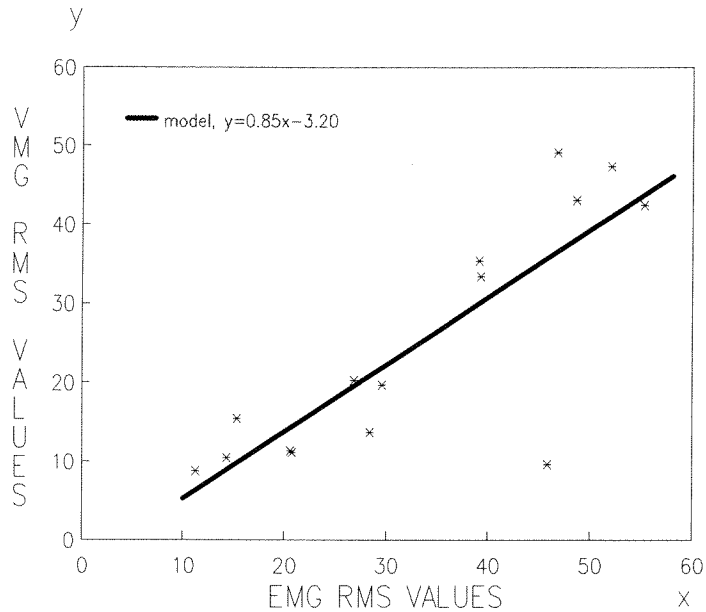

Figure 3.
The relationship between VMG and EMG RMS values (in arbitrary units) for isometric voluntary contractions (20%–80% of MVC) of the rectus femoris muscle at 30° of knee joint angle with four subjects.

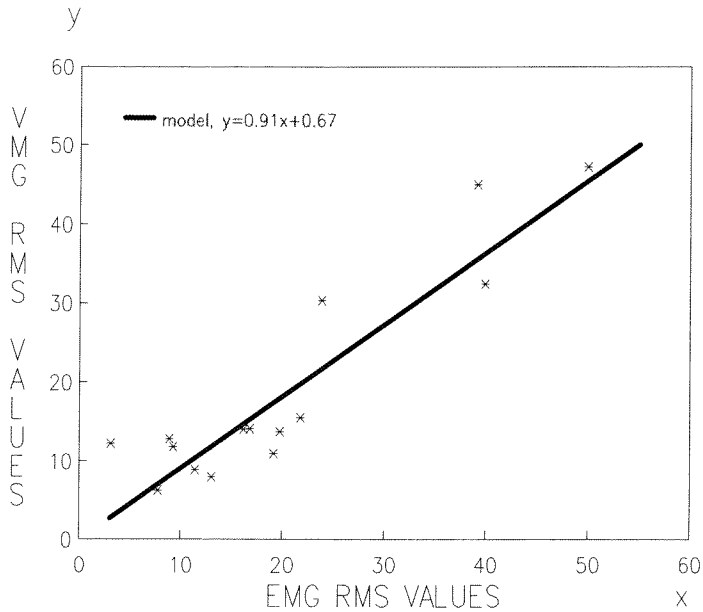

Figure 4.
The relationship between VMG and EMG RMS values (in arbitrary units) for isometric voluntary contractions (20%–80% of MVC) of the rectus femoris muscle at 60° of knee joint angle with four subjects.

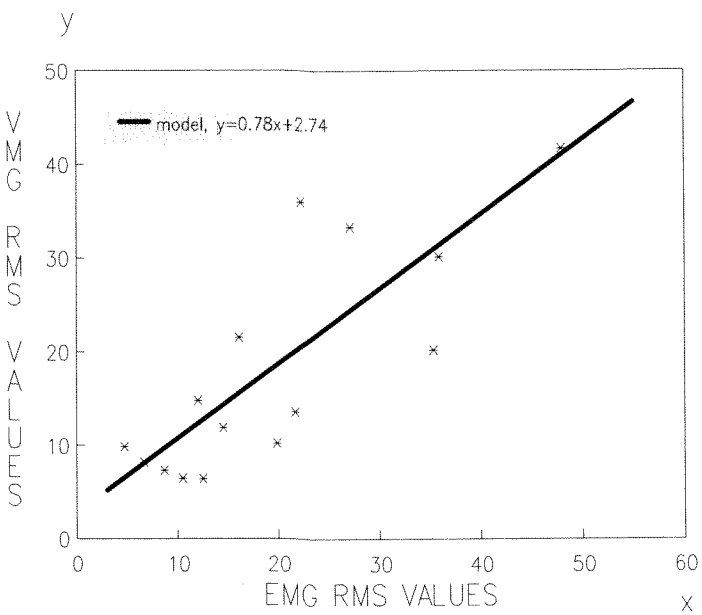

Figure 5.
The relationship between VMG and EMG RMS values (in arbitrary units) for isometric voluntary contractions (20%–80% of MVC) of the rectus femoris muscle at 90° of knee joint angle with four subjects.

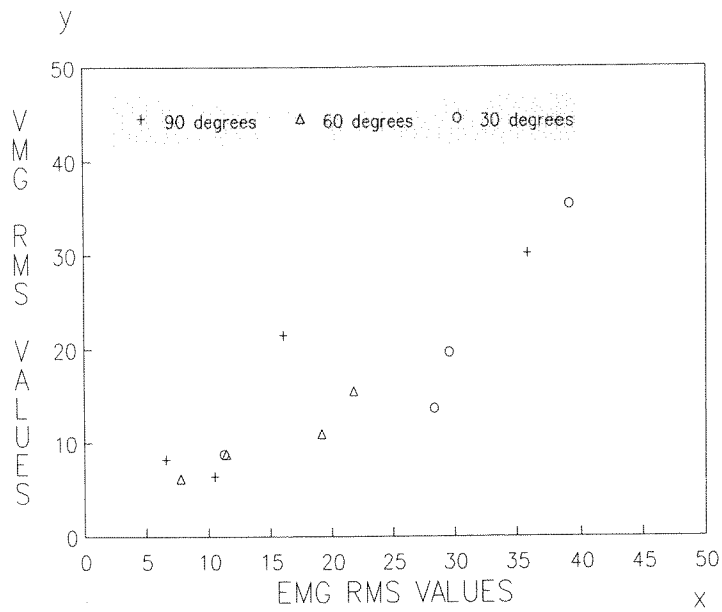

Figure 6.
A sample plot showing the dependence of the VMG on the EMG at three joint angles for a single subject.

same in the data across various knee joint angles. The negative value of the intercept may imply that the VMG-EMG relationship is nonlinear for contraction efforts below 20 percent MVC, which is beyond the range studied. Thus, the equations for the EMG-VMG relations are valid only over the range of the data corresponding to the contraction levels tested.

A sample plot showing the VMG-EMG relation for a single subject is given in **Figure 6** for three knee joint angles. In **Figure 7,** the average RMS values of VMG and EMG over four subjects are shown as a function of percent MVC at the knee joint angle of 60°. It is seen that an increase in isometric contraction level produces increasing VMG and EMG signal RMS values.

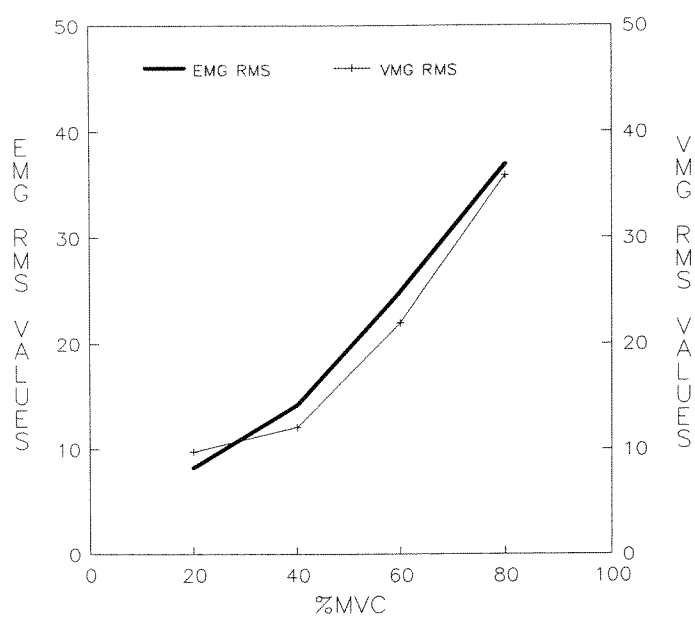

Figure 7.
The average RMS values of VMG and EMG signals for different muscle contraction levels at 60° of knee joint angle with four subjects.

DISCUSSION

The purpose of this research was to study the relationship between VMG and EMG signals, in particular the relationship of a power-related parameter (RMS) for the rectus femoris muscle during isometric voluntary contraction. The possibility of a direct relationship between EMG and VMG has not been previously investigated in a systematic fashion, except for a few indirect observations (2,25).

Barry et al. (5) have noted that the RMS values of VMG and EMG signals increase with increasing load on the biceps brachii muscle. Orizio et al. (3), by observing their data from the same muscle as that used by Barry et al., commented that VMG signals can be thought to be the result of lateral vibrations induced by muscle

activation. Zwarts and Keidel (11) working also with the biceps brachii, showed that both integrated EMG and integrated VMG have a clear correlation with force. In our work, as shown in **Figures 3, 4,** and **5**, the VMG RMS values obtained from the rectus femoris at three knee joint angles (90°, 60°, and 30°) showed a fairly linear correlation with those of the EMG detected simultaneously over the same muscle. The plots in **Figure 7** show the dependence of the EMG and the VMG on percent MVC. Therefore, the conjecture made by Barry et al., Orizio et al., and Zwarts and Keidel that the VMG power may be dependent on contraction seems plausible. These findings support the observation reported by Stokes and Dalton (25) who used an electronic condenser microphone with quadriceps muscles to show that the relationships between force and integrated acoustic-myogram, and between force and integrated EMG, were linear in all subjects they studied. In contrast with all of the observations mentioned above, the results of the present current study are in better agreement with those of Maton et al. (7), who found a linear relationship between the RMS values of the PMG and those of the EMG in the biceps brachii muscle. This seems to indicate that whatever the muscle considered and sensors used, and regardless of whether the relationships between the VMG and force and the EMG and force are linear (2) or nonlinear (2,7), the relationship of the VMG RMS value to that of the EMG is fairly linear for isometric effort over a wide range. In spite of the argument in favor of a linear relationship, a slope difference exists in these studies. In the work of Maton et al., the slopes of the linear regression lines (R>0.99) were in the range of 0.94 to 1.20 for EMG and PMG RMS amplitudes at different positions (supine or prone) of the hand. The slopes found in the present study are lower, in the range of 0.78 to 0.91 (R>0.81) for different joint angles tested. The difference in slopes of VMG versus EMG RMS values may be due to the different fiber types in the muscles tested, the different sensors used, and the different biomechanical experimental conditions in the two independent studies. A variation in correlation coefficients was also noted in the present study between the three joint angles. This variation indicates that there may be a stronger linear relation between the EMG and VMG at one joint angle as compared with others. However, this finding has not been tested for statistical validity. Further research on the VMG is needed to affirm the relationship of the VMG RMS value to the EMG and direct muscle force for different muscle lengths and with muscles of known distribution of fiber types.

The VMG is believed to be the result of lateral vibration activity caused by muscle activation. However, the specific factor or structure responsible for VMG activity is not known. The results of the present work seem to indicate that, in nondisabled subjects, the activity of the muscle may be influenced directly by recruitment and firing properties of motor units. Based on existing information (2,3,8), one may speculate that the VMG might be related to vibration caused by muscle twitches, while the EMG is related to the electrical activity associated with such twitches. Since the RMS values used in this work correspond to the power produced during contraction, the correlation of the VMG RMS values with EMG RMS values does support the above speculation. The relatively high correlation of 0.81 (or larger) between the RMS values provides further evidence that the VMG-EMG model is reasonable for representing the electro-vibratory relationships for the rectus femoris muscle during voluntary isometric contractions. The linear RMS relationship between the simultaneous mechanical (VMG) and electrical (EMG) muscle signals during voluntary isometric contraction indicates that both signals can be used to describe basic muscle activation patterns. The linear relation between the VMG and the EMG does not simply indicate that one could be estimated from the other; more importantly, it implies that the muscle twitches of some motor units may not fuse at moderate contraction, and that VMG signals like EMG signals may be associated with the control scheme of motor units and the characteristics of muscle twitches.

Recent research in motor control and electroneurophysiology has provided insight into the possible control scheme of motor units (30–32). In general, the production and regulation of muscle force is governed by recruitment of motor units and by modulation of the firing rates of recruited motor units. It has been reported that higher-threshold motor units that get recruited later in muscle contraction have force twitches that are shorter in duration and higher in amplitude compared with their counterparts that are lower-threshold and are recruited earlier. It has also been demonstrated (30) that the firing rates of motor units recruited earlier are greater than those of motor units recruited later. Furthermore, at each moment in time, as the contraction level increases, the earlier-recruited motor units maintain higher firing rates than the later-recruited ones. This recruitment (order firing behavior of motor units) has been termed an ''onion-skin'' phenomenon (30). Hence, as the level of muscle contraction increases and

progressively higher-threshold motor units get recruited, the lower-threshold motor units (or earlier-recruited motor units) may reach firing rates that cause their force twitches to fuse, but the twitches of the higher-threshold motor units will fuse to a lesser degree as both the firing rate and twitch duration factors decrease, thereby hindering fusing of the twitches. Hence, the increase of the VMG RMS with increasing contraction levels is expected. On the other hand, it is known that during isometric contraction, the EMG RMS value increases with increasing muscular force. Thus, the increase in the VMG amplitude with the increase in the EMG, as described by the regression model, is valid.

Specific physiologic data reported earlier further support the above explanation. Assuming the duration of motor unit vibration signals to be 60 ms, according to studies by electrical stimulation of isolated frog gastrocnemius muscles, multiphasic motor unit vibration signals have a duration of approximately 30–90 ms (8,9), the non-fusing firing rate would be less than 17 pulses per second (pps). In the rectus femoris muscle, the low-threshold motor units begin firing at 5 to 11 pps at low contraction levels and reach 18 to 21 pps at moderate contraction levels (19). Based on the onion-skin phenomenon or the recruitment (ordered firing behavior of motor units), one can assume that the higher-threshold motor units recruited later with increasing contraction begin firing at 10 to 14 pps. At low contraction levels (20 percent MVC to 40 percent MVC), the twitches of motor units do not fuse and, thus, an increase in the VMG RMS values with increasing EMG RMS values is expected. At moderate contraction levels (40 percent MVC to 60 percent MVC), the firing rates of 18 to 21 pps of low-threshold motor units, being greater than the non-fusing rate of 17 pps, cause the fusing of muscle twitches, while the firing rates of 10 to 14 pps of the high-threshold motor units with higher-amplitude and shorter-duration force twitches results in the fusion of twitches to a lesser degree. Therefore, the linear relationship between the VMG and EMG at moderate contraction levels can be explained using the physiological findings and the motor control scheme as reported previously (30–32).

A literature review also indicates that, as force further increases after about 60 percent MVC, the firing rate curve versus the percentage of force levels tends to converge to similar firing rates at the high-force levels of 80 percent MVC or above (30). No significant recruitment was observed in the higher-force region of 60 percent MVC and above. In this region, the firing rates of all recruited motor units increase continually even after the state of fusion-like contraction. In such a situation, each additional firing of motor units will add to the EMG RMS values, but add (to a lesser degree or almost nothing) to the VMG RMS. The similar rate of the increase in EMG and the VMG RMS values with increasing contractions in the high-force region (60 percent MVC to 80 percent MVC) may be attributed to other factors rather than the recruitment and firing properties of motor units. Evidence of the phenomenon of synchronization of motor units has been reported by several authors (33,34). Dietz et al. (33), using a cross-correlation analysis technique found that there was some synchronization in normal muscles. Libkind has suggested synchronization of motor units helps in the desired linearity between the EMG and muscular force (34). Milner-Brown et al. (35), reported that it might be possible to accentuate synchronization of motor units by exerting a large force for a short period of time. Thus, we speculate that synchronization of motor units and physiological tremor are uncertain factors that might contribute to an increase in the VMG RMS values at the high-force level contractions, in spite of the fact that the mechanisms of physiological tremor and synchronization of motor units are still poorly understood.

We view the present study as preliminary since only four subjects were studied and a single muscle was tested at only four discrete levels of muscle contractions for three joint angles. Further research along the same line with a larger database should be helpful in establishing the observations and the models suggested by the present study. Further studies on inter- and intra-subject variability over a larger range of muscle absolute forces will also be required to further understand VMG signals and their relationship to myoelectric activities and muscular force.

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