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VIBROMYOGRAPHY AS A QUANTITATIVE MEASURE OF MUSCLE FORCE PRODUCTION

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ABSTRACT. This study was undertaken to investigate the use of vibromyography (VMG) as a tool for quantifying skeletal muscle force production. Fourteen healthy volunteers were pretested using a Cybex isokinetic dynamometer to determine their isometric quadricep maximum voluntary contraction (MVC) values. On the basis of these results, the subjects were separated into two groups: high-force ("HF" MVC $\bar{x}$ = 289 ft.lb., range 254–330) and low-force ("LF" MVC $\bar{x}$ = 154 ft.lb., range 101–198). A vibromyographic piezoelectric accelerometer (Dytran 3115A) and electromyographic (EMG) surface electrodes were affixed to the rectus femoris muscle and recordings were obtained at 20, 40, 60, 80, and 100% MVC. Root mean squares, median and mean values were computed from digitized data in the time domain while peak values were calculated from a fast Fourier transform for both the VMG and EMG data. A two-way repeated measures MANOVA using relative values and a linear regression model using absolute values were studied using BMDP and MiniTab software. Linear correlations were found between quadricept force and all EMG variables (R^2 range 0.71–0.90) except peak (R^2 = 0.39). The relationship between VMG and force was less linear (R^2 range 0.19–0.69) because VMG values reach a plateau or even drop at 80% and 100% MVC. The HF-LF group differences were significant ($p < 0.05$), for all VMG values with the exception of root mean squares, but were not significant ($p > 0.05$) for all four EMG values. This study shows that, while EMG can discriminate force production within a given subject, VMG is a better discriminator of absolute muscle force values between subjects, particularly up to 60% MVC.

Key words: Cybex, electromyography, force production, isokinetic, muscle sounds, skeletal muscle, vibromyography.

INTRODUCTION

Skeletal muscle force production is a direct indicator of both the energetic and mechanical properties of the muscle; its accurate measurement is vital for the assessment of muscular performance characteristics in conditions of disease and injury rehabilitation. It is therefore important that the methods employed to evaluate muscle strength provide objective, valid, reproducible and quantitative values. The two most common methods in use are dynamometry (isokinetic, isotonic, isometric) and electromyography (EMG). For example, the Cybex dynamometer is an isokinetic testing machine that uses an electric motor with a hydraulic pressure pad to apply resistance to a contracting muscle. It provides an absolute measurement of the force output of a muscle, and is both valid and reliable (11, 17, 20). By comparison, EMG measures the electrical activity generated as a result of sarcolemmal depolarization during a muscle contraction (13). This electrical activity correlates closely with the force of the muscle contraction. The signal is typically expressed as a percentage of the value recorded during a maximal contraction; thus, the EMG signal provides a relative index of the magnitude of force output (8).

The ideal device to measure muscular force production should meet the following conditions. It should: (i) permit the testing of individual muscles within a given group, (ii) be non-invasive, (iii) provide quantitative information, (iv) measure the absolute level of force production, (v) be inexpensive, and (vi) be portable and easy to use. Using these criteria, both the Cybex isokinetic dynamometer and EMG have limitations. The Cybex machine is large, costly, and not portable. In addition, measurements of muscle strength necessarily include the force output of all muscles that produce a given joint motion in a

specified plane. EMG is portable, less expensive, and capable of measuring the force output of the individual muscles acting on a given joint. However, with EMG, the electrical activity recorded is a value relative to the maximum, placing limits on its use as a technique for comparing absolute force production within patients (as is the case with monitoring rehabilitation) as well as between patients. There is therefore a need to find a method for measuring muscular force production that is quantitative, portable, inexpensive, and capable of testing individual muscles within a muscle group.

Vibromyography (VMG) makes use of a piezoelectric encased crystal accelerometer to measure the low frequency vibration signals generated by a muscle contraction (38). This technique uses a small transducer ($< 2\,cm^3$) affixed to the skin and connected to a chart recorder and a microcomputer. It is non-invasive, inexpensive and portable. Currently, it is thought that the vibrations or sounds recorded from contracting muscle reflect the muscle's mechanical properties, and arise from myosin cross-bridge movement during contraction of the myofibril (1, 3, 10, 14, 23, 26, 27, 30). There is some evidence to suggest that the intensity of the sounds produced are related to the force generated by the muscle (2, 4, 5, 23, 24). Both linear and non-linear relationships between the magnitude of the muscle sound generated and the force production of that muscle have been recorded in experimental studies (6, 24, 26, 29, 30, 31). Since the VMG signal is thought to arise from mechanical changes in the muscle in response to contraction, our hypothesis is that VMG is an absolute measure of force production in skeletal muscle, at least at contraction intensities below fused twitch summation (tetany).

The specific aims of this research were: (i) to determine the relationships between dynamometry, EMG and VMG recordings during muscular contractions of varying intensities, (ii) to determine if the VMG signal is an absolute measure of force output, and (iii) to determine the EMG/VMG test-retest-force relationship. In order to answer these questions, we simultaneously compared EMG, VMG, and Cybex recordings during five intensities of isometric quadriceps muscle contractions, in two groups of subjects; a high force (HF) and a low force (LF) group.

MATERIALS AND METHODS

Subjects

Healthy subjects between the ages of 18 and 42 volunteered for the study. They gave written consent and the study was approved by the University of Calgary Human Ethics Committee, in accordance with ethical standards laid down by the Declaration of Helsinki. None of the subjects had a history of lower limb musculoskeletal problems. In an initial pilot test the subjects were asked to perform three maximal voluntary isometric contractions (MVC) of their dominant side quadriceps muscle and the force produced was recorded on a computerized Cybex isokinetic dynamometer. The highest of the three values was used as the MVC. The results of the strength tests on all the subjects were rank ordered and, of the 32 subjects tested, subjects with the 7 lowest and 7 highest MVC values were selected. The high-force group had a mean age of 24.6 years (range 22–29) and a mean maximal quadriceps force value of 288.9 ft.lb. (range 254–330). The low-force group had a mean age of 31.4 years (range 21–42) and a mean maximal quadriceps force value of 153.6 ft.lb. (range 101–198).

Experimental protocol

The 14 subjects were asked to perform three maximal isometric voluntary contractions of their dominant quadriceps muscle against resistance provided by the Cybex machine. The contractions were held for 3 seconds. The highest value was recorded as the subject's MVC. Using the MVC, submaximal force levels of 20%, 40%, 60%, and 80% were calculated for each subject. Allowing 3 minutes rest between each test, the subjects then performed three 3-second isometric contractions of their dominant quadriceps muscle at 20%, 40%, 60%, 80%, and 100% MVC using the visual feedback on the torque display of the Cybex machine. Simultaneous VMG and EMG recordings were obtained. The order of the tests was 100% MVC → 20% MVC. The subjects were tested again two days later in order to establish test-retest reliability.

Cybex texts

The maximum voluntary isometric contraction force of the quadriceps muscle was recorded using a Cybex isokinetic dynamometer (Cybex 340, Cybex Division of Lumex Inc., Ronkonkoma, N.Y.). The subjects were seated in the Cybex chair with their hip flexed to 90° and their knee flexed to 60° in order to provide peak isometric knee extension force (35). The subject's pelvis and working leg were secured with separate velcro straps, the resting leg was braced behind a stabilizing bar, and the subjects were requested to hold the hand grips. The rotational axis of the knee joint was aligned to the rotational axis of the dynamometer, and the resistance pad was positioned over the distal one-third of the leg, avoiding any restriction of ankle dorsiflexion.

Electromyography (EMG)

A pair of Ag-Ag Cl surface EMG electrodes, aligned longitudinally 3 cm apart over the middle of the rectus femoris muscle belly, was affixed to the skin with tape. The ground electrode was placed over the middle third of the ipsilateral adductor muscle. Data were obtained using computer software written by the authors that permitted integrated EMG readings on a six-channel recorder. Signals were conditioned with bandpass filters with bandwidths between 10 Hz and 1 KHz, and were digitized with a sampling rate of 2 KHz. Power spectra EMG signals were obtained using a fast Fourier transform (FFT) algorithm, and then averaged

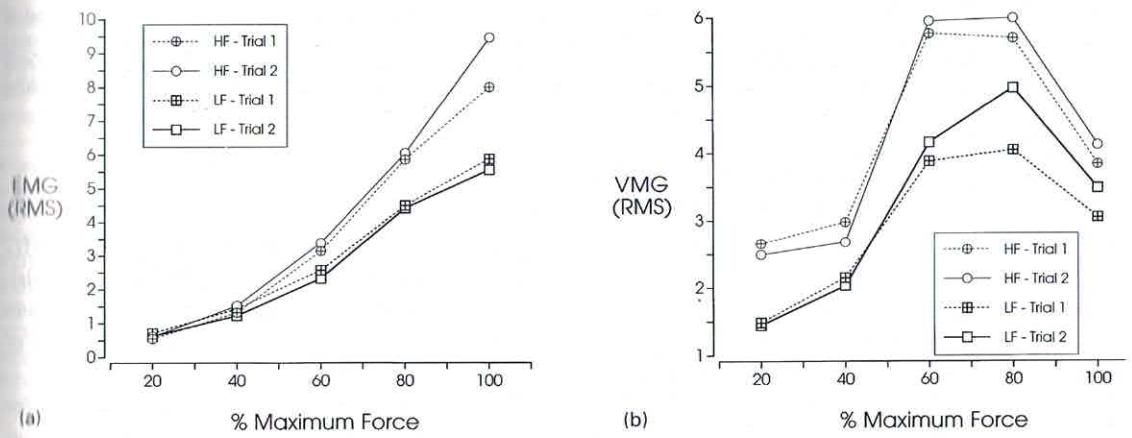

Fig. 1. EMG (1a) and VMG (1b) test–retest reliability data. VMG-rms and EMG-rms (root mean squares) values for low- (LF) and high-force (HF) groups were obtained on two separate test days (trials) over the five quadriceps force values.

over six consecutive segments to reduce the variance of estimation. Signals were stored on a computer. The root mean squares (RMS) values of the EMG signals were computed from the digitized data in the time domain. The average mean, median and peak frequency values were computed from the FFT spectra for the EMG at each contraction level.

Vibromyography (VMG)

VMG recordings were obtained simultaneously with the Cybex and EMG recordings. A miniature piezoelectric accelerometer (Dytran 3115A) was placed in-between the two EMG electrodes over the middle of the rectus femoris muscle, and held in place with double-sided tape. Signals

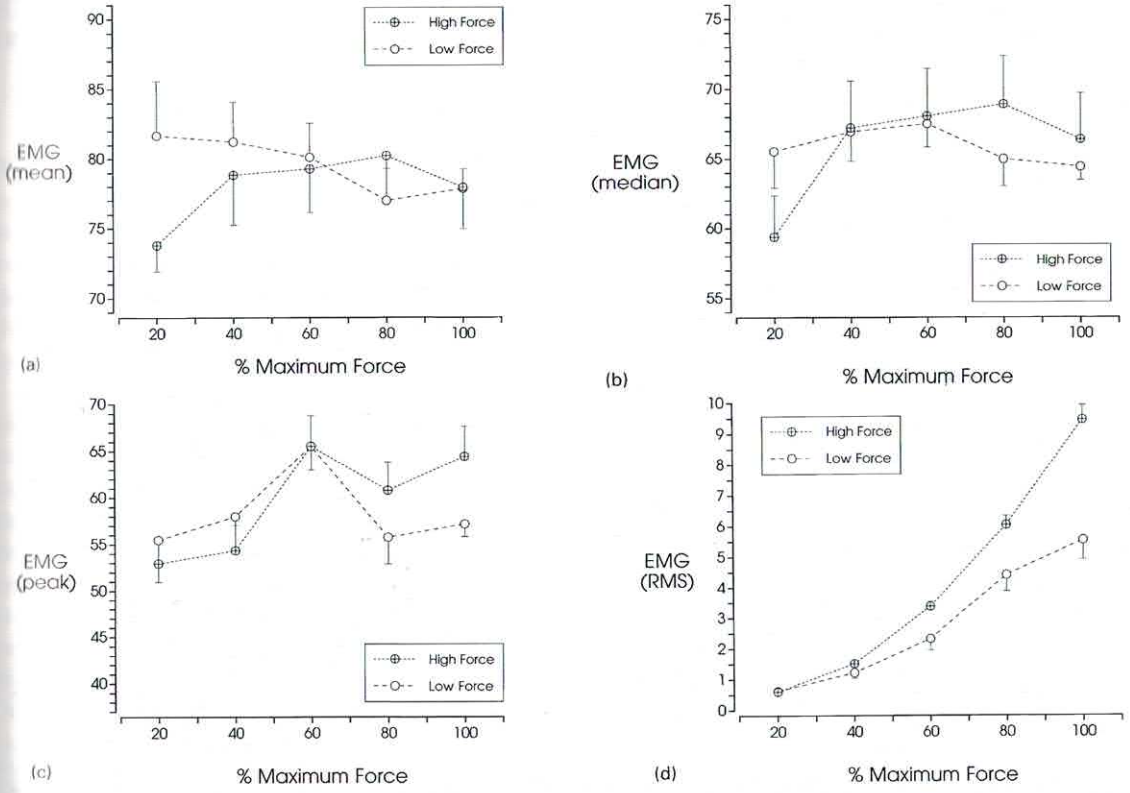

Fig. 2. EMG values for the low- and high-force groups. No significant differences were found between the two groups for mean, $p = 0.175$ (2a); median, $p = 0.957$ (2b); peak, $p = 0.662$ (2c); and root mean squares (rms), $p = 0.119$ (2d) EMG values.

were conditioned with bandpass filters with bandwidths between 3 and 100 Hz and were digitized with a sampling rate of 2 KHz. Power spectra VMG signals were obtained using an FFT algorithm, and then averaged over six consecutive segments to reduce the variance of estimation. Signals were stored in a computer. The RMS values of the VMG signals were computed from the digitized data in the time domain. The average mean, median and peak frequency values were computed from the FFT spectra for the VMG at each contraction level.

Data analysis

Recordings from the EMG, VMG and Cybex were viewed on a computer monitor. A 2.5 second segment was extracted from the raw data for each of the three recordings. The segment chosen for extraction was determined by marking the drop-off point on the torque recording (coincidental with the point of relaxation) and scrolling 2.5 seconds back. The tagged point on the Cybex recording was simultaneously marked on the EMG and VMG recordings.

Statistical analysis

Given the potential interdependence of the outcomes, a two-way repeated measures MANOVA (two groups—high and low force; five levels of force) was carried out using a total of four measures as dependent variables (root mean squares, peak, median, and mean values). In order to determine whether absolute force is a significant predictor of the outcomes, due to the repeated measures design, subject effects were included with the absolute force in our regression models. Both MiniTab and BMDP software were used.

RESULTS

Figure 1 shows the test–retest reliability of the EMG and VMG data collected on two separate days (trials). With the exception of the percentage MVC 80 data in the low force group (trial, 1, Fig. 1a), the two sets of data are very similar.

Figure 2 shows the differences in EMG values for the high- and low-force groups. All four dependent EMG variables failed to discriminate between the two groups over the range of muscle forces tested.

Figure 3 shows the differences in VMG values for the high- and low-force groups over the five quadriceps force values tested. These data have two distinct characteristics. The VMG signal in the high-force group is significantly ($p < 0.05$) higher than that for

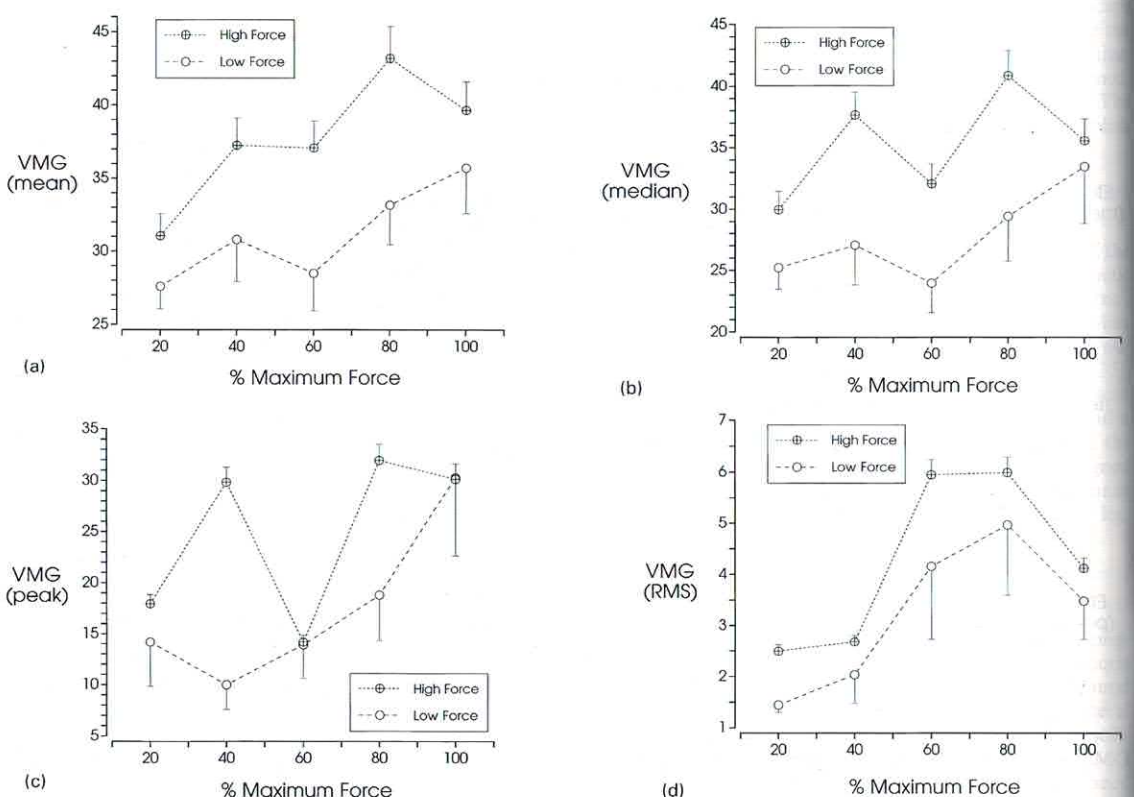

Fig. 3. VMG values for the low- and high-force groups. Significant differences between the two groups were found for mean, $p = 0.037$ (3a); median, $p = 0.008$ (3b); and peak $p = 0.050$ (3c) VMG values. VMG root mean square values were not significantly different between the two groups, $p = 0.126$ (3d).

Table I. *Results of regression analysis comparing absolute values of force production to root mean square (RMS), mean, median, and peak values for vibromyography (VMG) and electromyography (EMG)*

Correlation	Coefficient	R^2	p
FORCE-VMG RMS	0.009	0.521	0.009
FORCE-VMG mean	0.047	0.700	0.000
FORCE-VMG median	0.041	0.521	0.006
FORCE-VMG peak	0.057	0.194	0.140
FORCE-EMG RMS	0.033	0.900	0.000
FORCE-EMG mean	0.021	0.734	0.027
FORCE-EMG median	0.041	0.710	0.001
FORCE-EMG peak	0.061	0.393	0.024

the low-force group in all of the VMG dependent variables except for root mean squares. Second, the VMG signal decreases at 60% MVC in the mean, median and peak variables, and plateaux at 80% MVC in the RMS variable.

Table I gives the results of regression analysis between absolute values of force (continuous, interdependent variable analysis), VMG, and EMG. EMG variables show a strong linear relationship (R^2 range 0.39–0.90) with force compared with VMG variables (R^2 range 0.19–0.69).

DISCUSSION

The data presented here indicate that EMG is unable to discriminate between subject groups that differ in their absolute force production by a factor of almost twofold. VMG signals, on the other hand, are able to discriminate the high- and low-force groups. These findings suggest that VMG may be a better measure of quantitative force production in skeletal muscle.

Acoustic myography, the study of low frequency vibration signals or sounds produced during muscle contraction, can be traced back to 1665 when Francesco Maria Grimaldi gave the first account of hearing muscle sounds (25). The exact mechanism for sound production when a muscle contracts is not yet fully understood. Huxley's sliding filament theory states that when muscle contracts, there is movement between the cross-bridges of the myofilaments and mechanical shortening of the sarcomere length (16). While some investigators believe that the sound is generated by myofilament movement itself (10, 26, 27), others believe the vibrations are generated by the lateral oscillation of muscle fibers (1, 14, 30) or the movement and expansion of the whole muscle (3).

Various recording devices and signal processing techniques have been used to investigate muscle sounds (2, 3, 5, 6, 12, 27, 38). In 1992, Barry (5), and Zhang et al. (38) investigated the use of an accelerometer, a piezoelectric encased crystal, to measure the low frequency vibration signals generated by a contracting muscle. The measurements obtained, in fundamental units of m/s^2 allowed for easy comparison of data, and eliminated the need to normalize the data (5).

Muscle sound measurement studies show an inconsistency with respect to whether the VMG-force relationship is linear or non-linear; both types of responses have been recorded (6, 24, 26, 29, 30, 31). Similar to EMG studies, the VMG-force relationship is thought to reflect the tested muscle fiber's spatial or temporal recruitment control strategy (24, 26). The intensity of the muscle sound generated is dependent on the number, type, and position of the muscle fibers present in the sampling volume (2, 4, 5, 24). The VMG signals in this study show a non-linear relationship with force (Fig. 3d). Explaining this phenomenon is beyond the scope of the measurements made in this study. However, we postulate that this observation is due to wave summation; the fusion of individual motor unit twitches and subsequent tetany which occurs between 60 and 80% MVC. Wave summation might produce a sound of lower intensity.

EMG measures the average voltage generated by ionic fluxes during depolarization of the motor endplate in a group of motor units (13). Since the motor unit is the basic functional unit of skeletal muscle (34), the number of spikes on the EMG recording represents the number of firing motor units. The magnitude of the force produced and the pattern of temporal recruitment are recorded in the EMG signal as the amplitude and rate of firing of motor units, respectively (19). The magnitude of the EMG potential from an active motor unit is related to the magnitude of the mechanical force output of that motor unit (15, 21). Small, low-threshold motor units produce a small force and are associated with small amplitude and relatively long duration EMG signals, while the converse is true for large force-producing units (32).

Although EMG can be used to monitor the degree of motor fiber recruitment, the signal remains relative to maximum (see Fig. 1a) and, in the present study, EMG was unable to discriminate between the high- and low-force groups (Fig. 2). Increasing the strength of a contraction through spatial recruitment, temporal

recruitment, or synchronization is similar in muscles of varying strength (36). Thus, although a positive EMG-force relationship exists (7–9, 18, 21, 22, 28, 32, 33, 37), it cannot be used quantitatively to measure muscular force production.

CONCLUSION

The results of this study indicate that VMG may be useful in quantifying absolute differences in muscle force production. We view the present study as preliminary. Further study will be required to substantiate these initial findings and is warranted given the potential utility of VMG as a bedside tool to measure skeletal muscle contractile properties and fatigue.

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