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## The mechanomyographic amplitude and frequency versus isometric force relationships

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### Abstract

*The most common experimental design used in mechanomyographic (MMG) studies is to examine the patterns of responses for MMG amplitude and/or center frequency [mean power frequency (MPF) or median frequency] versus isometric force. The results from the studies that have used this approach have shown that these relationships can provide information regarding the motor control strategies (i.e., the relative contributions of motor unit recruitment and firing rate modulation) that are used by various muscles to increase isometric force*

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*production. It is important to point out, however, that other factors, such as the type of muscle action that is being performed (i.e., isometric ramp versus step) and the joint angle (which affects the muscle's length) can affect these patterns. Several investigations have also examined these relationships in patients that suffer from neuromuscular disorders, as well as in preadolescents and the elderly. Recent studies, however, have shown that the patterns of responses for MMG amplitude and center frequency versus isometric force differ on a subject-by-subject and muscle-by-muscle basis. This obviously reduces the validity of drawing any general conclusions from these patterns regarding motor control strategies. Future research is needed to identify the mechanisms that cause differences in the MMG amplitude and center frequency versus isometric force relationships.*

## **Introduction**

By far the most common experimental design used in mechanomyographic (MMG) studies is to record MMG signals at multiple isometric force levels, and then examine the patterns of responses for MMG amplitude and/or center frequency [mean power frequency (MPF) or median frequency] versus force. The first investigation to use this approach was performed by Lammert et al. (1976), who recorded MMG signals from the biceps brachii and rectus femoris during submaximal to maximal isometric muscle actions of the forearm flexors and leg extensors from 10% to 100% of the isometric maximum voluntary contraction (MVC). The authors (Lammert et al. 1976) reported that for the biceps brachii muscle, MMG amplitude increased linearly with force from 10% to 60% MVC, followed by a plateau from 60% to 80% MVC, and then another increase from 80% to 100% MVC. The patterns of responses for MMG amplitude from the rectus femoris muscle, however, were more complex. In particular, two of the subjects that had previously demonstrated high percentages (69.3% and 83.1%) of slow-twitch fibers showed almost no change in MMG amplitude from 10% to 50% MVC, followed by a linear increase from 50% to 100% MVC. Two other subjects with low percentages (28.6% and 35.8%) of slow-twitch fibers, however, demonstrated no change in MMG amplitude from 10% to 30% MVC, followed by a rapid increase from 30% to 50% MVC, and then a plateau from 50% to 100% MVC. In addition, five subjects with an unknown fiber type composition showed an almost linear increase in MMG amplitude from 10% to 100% MVC. Thus, it was suggested that the shape of the MMG amplitude versus isometric force relationship was affected not only by the muscle that was being investigated, but also by differences between subjects for fiber type composition. It was also hypothesized that increases in MMG amplitude with force likely reflected

recruitment of new motor units, while a plateau or decrease in MMG amplitude with increases in force is probably due to high motor unit firing rates and the subsequent fusion of twitches. This hypothesis became a popular explanation when describing the shapes of the MMG amplitude versus isometric force relationships in future studies. Specifically, as discussed in Chapter 1, firing of motor units at high rates increases fusion of twitches and reduces the lateral oscillations of the contracting muscle fibers. This results in decreases in MMG amplitude to the point where no muscle sound is present during fully fused tetanus.

An important issue when investigating the MMG amplitude and center frequency versus isometric force relationships is the experimental protocol that is used. The most common protocol is to have the subjects perform a separate muscle action (i.e., a step contraction) for each force level. The primary advantage of the step contraction methodology is that a relatively stable (i.e., stationary) MMG signal is generated for each force level. The main disadvantage is the time commitment required to perform all contractions, particularly when many force levels are being examined. The second most common protocol involves a continuous, linear (i.e., ramp) increase in isometric force throughout a given force range. The primary advantage of the ramp protocol is that the force range of interest can be examined with a single contraction that does not require a large time commitment from the subject. The biggest disadvantages are that the resulting MMG signal is not stationary, and most subjects need a few practice trials before they are capable of generating a sufficiently linear increase in isometric force. In addition, with some muscles, it is very difficult to achieve maximal force levels (i.e., near 100% MVC) during an isometric ramp, which limits the protocol to a submaximal force range.

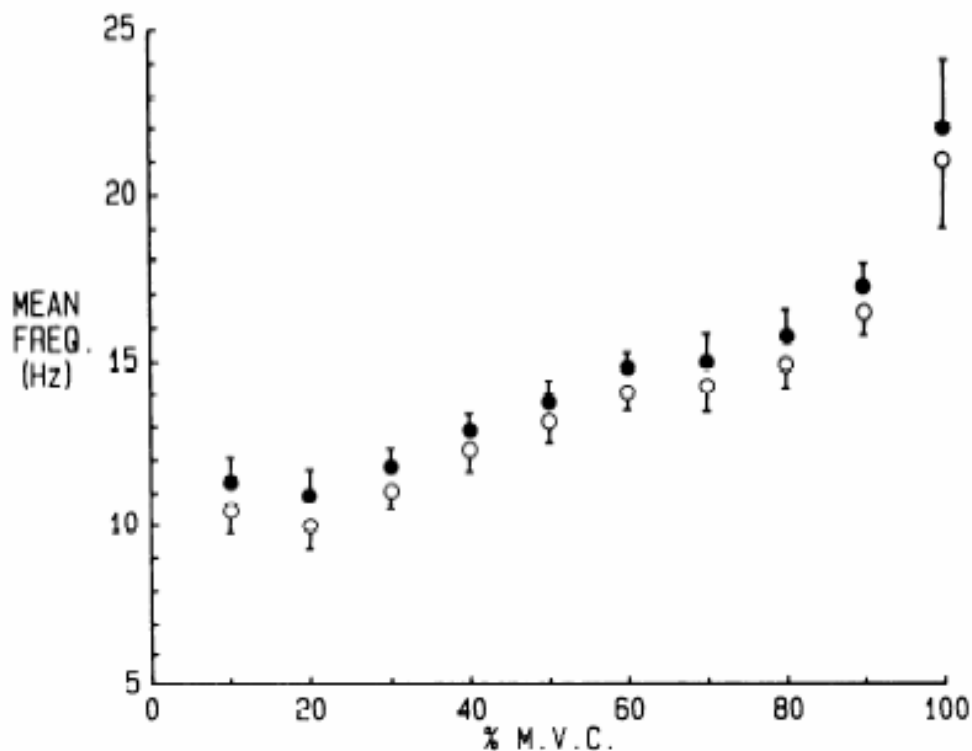
It is important to point out that the force range being examined is a major factor that can affect the MMG amplitude and center frequency responses. For example, Oster and Jaffe (1980) reported that MMG amplitude for the biceps brachii increased linearly with force when the forearm was flexed at 90° and progressively heavier weights were placed in the hand. The weights used, however, only ranged from approximately 0.25-9.0 kg, which resulted in submaximal efforts for all subjects. A similar approach was used by Barry et al. (1985), who recorded MMG signals from the biceps brachii during isometric muscle actions of the forearm flexors in which the forearm was at a 90° angle and weights of 0, 5, 10, 12.5, 15, and 20 pounds were placed in the hand. The authors (Barry et al. 1985) reported that MMG amplitude increased linearly with force between 5 and 15 pounds, with nonlinearities occurring at forces below 5 pounds and above 15 pounds. Like Oster and Jaffe (1980), however, the 0-20 pound force range was submaximal for all subjects. Thus, a

very important study was conducted by Orizio et al. (1989), who examined the MMG amplitude versus force relationship for the biceps brachii during isometric step muscle actions of the forearm flexors throughout the entire force range (0-100% MVC). The authors (Orizio et al. 1989) reported that MMG amplitude increased curvilinearly with force from 0% to 80% MVC, followed by a rapid decrease from 80% to 100% MVC. It was hypothesized (Orizio et al. 1989) that the increase in MMG amplitude from 0% to 80% MVC was probably due to motor unit recruitment, while the rapid decrease from 80% to 100% MVC likely reflected either high motor unit firing rates and subsequent fusion of motor unit twitches or high levels of muscle stiffness and/or intramuscular fluid pressure.

The study by Orizio et al. (1989) for MMG amplitude was followed up by a second investigation that used the same experimental protocol, but examined the MMG MPF versus force relationship for the biceps brachii (Orizio et al. 1990). The authors (Orizio et al. 1990) reported that MMG MPF remained relatively stable from 10% to 20% MVC, then increased in a linear fashion from 20% to 80% MVC, followed by a very rapid increase from 80% to 100% MVC. In addition, at force levels below 70% MVC, the MMG power spectrum was unimodal, with a single peak that shifted toward higher frequencies with increases in force. From 70% to 100% MVC, however, the MMG power spectrum became more bipolar, with a second peak that developed at higher frequencies. It was hypothesized that the rapid increases in MMG MPF and bimodal shape of the MMG power spectrum at force levels above 70% MVC was likely due to fusion of motor unit twitches, since the biceps brachii relies at least partially on firing rate changes to increase force production at high force levels (Orizio et al. 1990) (Figure 1).

This combination of studies that examined the MMG amplitude (Orizio et al. 1989) and MPF (Orizio et al. 1990) versus force relationships provided important evidence that the amplitude and frequency contents of the MMG signal are rich with information regarding motor control strategies.

The studies that followed the work of Orizio et al. (1989, 1990) began investigating the effects of biomechanical factors and various other influences on the MMG amplitude and center frequency versus force relationships. For example, Maton et al. (1990) examined the influence of both forearm position (pronated versus supinated) and MMG sensor location (proximal versus distal) on the patterns of responses for MMG amplitude and MPF versus isometric force for the biceps brachii. The results showed that for both forearm positions and sensor locations, MMG amplitude increased curvilinearly with force from 10% to 100% MVC. The slope of the MMG amplitude versus force relationship was greater, however, when the hand was supinated than when it was pronated. In addition, sensor location had very little effect on the shape



**Figure 1.** Mechanomyographic (MMG) mean power frequency (MPF) (indicated as MEAN FREQ. in this figure) for the biceps brachii muscle as a function of relative isometric forearm flexion force (i.e., %MVC). Values are mean  $\pm$  SEM. The open circles represent the values from the maximum entropy spectrum estimation method, and the solid circles reflect the values from the fast Fourier transform. Notice that the increases in MMG MPF with force were particularly rapid from 80% to 100% MVC. It was hypothesized that this pattern was due to high motor unit firing rates. \*Reprinted with permission from Orizio et al. (1990).

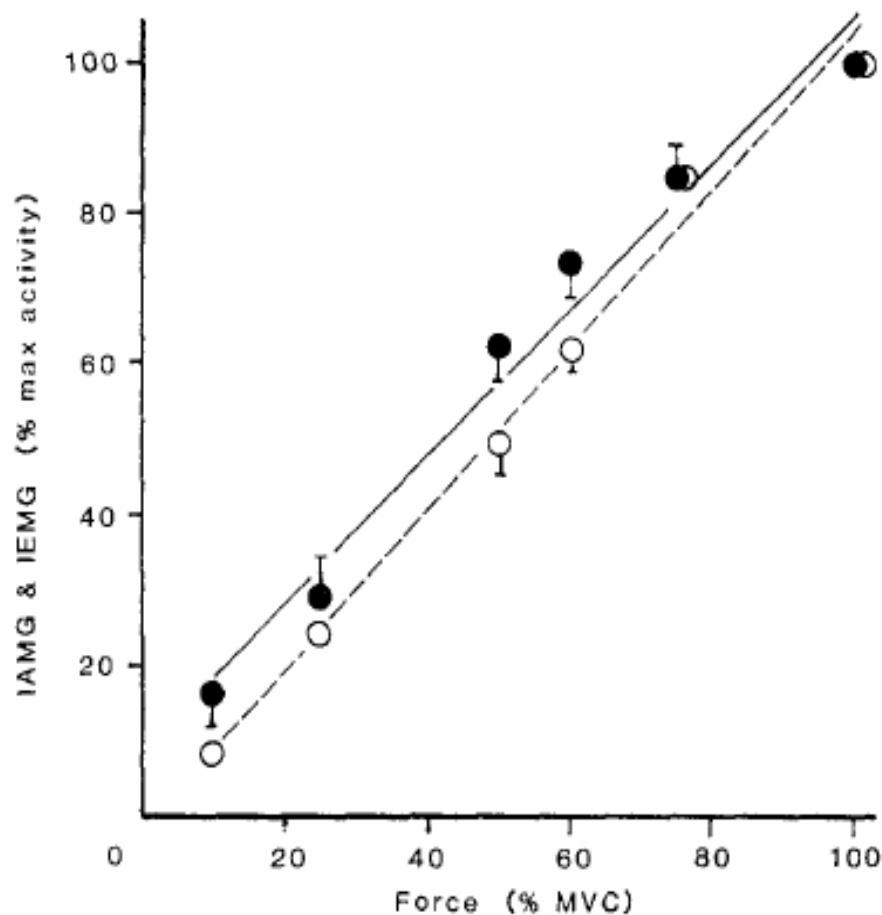
of the MMG amplitude versus force relationship. The MMG MPF versus force relationship was, however, affected by both sensor location and forearm position. When the sensor was in the proximal location and the hand was supinated, MMG MPF increased with force from 10% to 40% MVC and then plateaued from 40% to 100% MVC. In the pronated position, however, MMG MPF increased with force from 10% to approximately 80% MVC and then plateaued from 80% to 100% MVC. When the sensor was in the distal location and the hand was supinated or pronated, MMG MPF remained relatively stable from 10% MVC to approximately 60% MVC, followed by an increase from 60% to 100% MVC. Thus, it was concluded that both sensor location and forearm position are important factors that can affect the shapes of the MMG amplitude and MPF versus isometric force relationships for the biceps brachii muscle (Maton et al. 1990). Zwartz and Keidel (1991) also provided important information regarding inter-subject differences in the

MMG amplitude versus isometric force relationship. Specifically, the authors reported that for the biceps brachii muscle, some subjects demonstrated highly linear increases in MMG amplitude with force, while others showed an increase in MMG amplitude up to approximately 75% MVC, followed by a decrease from 75% to 100% MVC. This study made an important contribution because it was the first to suggest that the patterns of responses for MMG amplitude versus isometric force may be unique for each subject (Zwarts and Keidel 1991).

Up to this point, most studies had focused on the MMG amplitude and/or center frequency responses from large limb muscles such as the biceps brachii or rectus femoris, which rely primarily on motor unit recruitment for increasing isometric force. If, however, the MMG amplitude versus force relationship is influenced by motor control strategies, then it should have a unique shape for small hand and/or forearm muscles, which depend more heavily on firing rate modulation for increasing isometric force. Stokes and Cooper (1992) addressed this issue by examining the MMG amplitude versus isometric force relationship for the adductor pollicis muscle. The results showed that MMG amplitude increased curvilinearly with force from 10% to 100% MVC. Although this relationship differed from those in previous studies that reported linear patterns, it was similar to the results for the biceps brachii reported by Maton et al. (1990). Thus, it was still unclear if the patterns of responses for MMG amplitude and/or center frequency could be used to describe motor control strategies. An important consideration, however, is the potential for factors such as fiber type composition and/or muscle architecture to affect the MMG amplitude versus isometric force relationship. For example, Stiles and Pham (1991) examined the patterns of responses for MMG amplitude versus isometric force for the anterior temporalis and masseter muscles, both of which function in closing the jaw. The results indicated that MMG amplitude increased linearly with jaw closing force, or increased to a maximum value and then remained constant or decreased. In addition, for some subjects, the maximum MMG amplitude value occurred at a relatively low force level (5-10% MVC). An important consideration when discussing the results from this study is that the force range examined was only 0-30% MVC. The authors did, however, report that the peak frequency of the MMG power spectrum increased 2-4 Hz with increases in jaw closing force from 0-60% MVC. It was hypothesized (Stiles and Pham 1991) that motor unit recruitment may have been the primary mechanism underlying the increases in MMG amplitude, while increases in firing rate may have caused the decreases at higher force levels. In addition, Stokes et al. (1988) reported that during a 10-second isometric ramp muscle action of the back extensors, MMG amplitude for the erector spinae muscles increased curvilinearly from 0% to

100% MVC, while the electromyographic (EMG) amplitude versus force relationship was highly linear. In addition, the MMG amplitude versus isometric force relationship was slightly less reliable than the EMG amplitude versus isometric force relationship when repeated testing was performed on the same day. Thus, it was suggested (Stokes et al. 1988) that EMG may be a more reliable method than MMG for estimating muscle force production, but the information provided by the MMG signal is unique from that given by EMG. A second study (Stokes and Dalton 1991) reported that MMG amplitude for the rectus femoris increased linearly with isometric leg extension force from 10% to 100% MVC (Figure 2).

This pattern was obviously different from that reported for the biceps brachii (Orizio et al. 1989) and erector spinae (Stokes et al. 1988), so it was

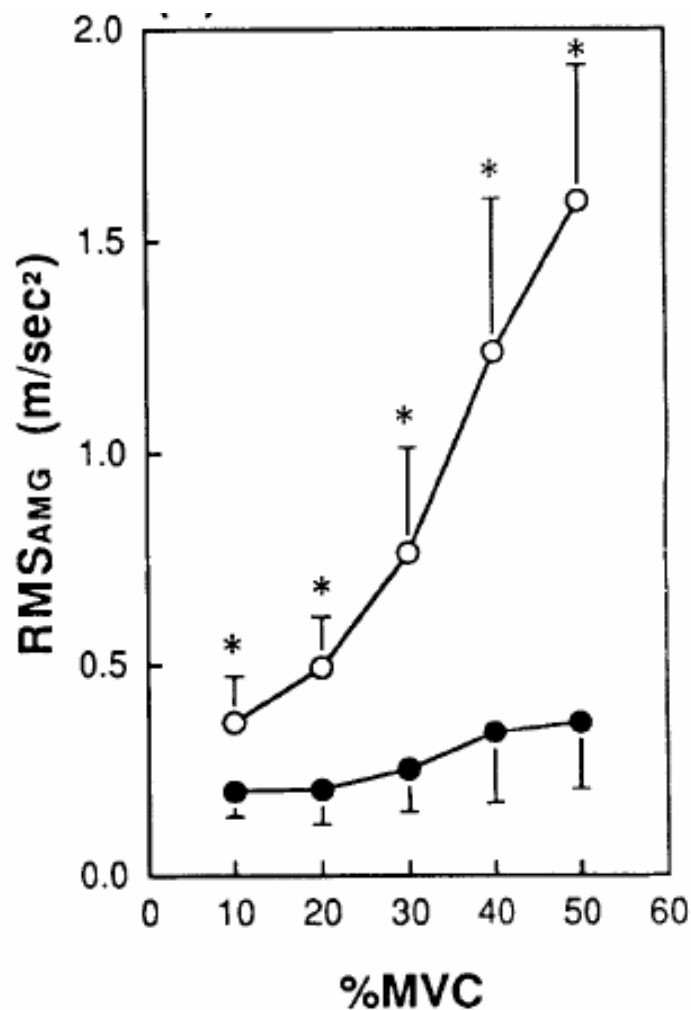


**Figure 2.** Linear relationships for mechanomyographic (MMG) amplitude (indicated as I AMG in this figure) and electromyographic (EMG) amplitude (indicated as I EMG in this figure) for the rectus femoris versus relative isometric leg extension force (%MVC). Values shown are mean  $\pm$  SEM. The closed symbols reflect the MMG data, and the open symbols represent the EMG data. Notice that both relationships are highly linear. \*Reprinted with permission from Stokes and Dalton (1991).

suggested (Stokes and Dalton 1991) that differences in muscle architecture and joint angle (which determines muscle length) could affect the patterns of responses for MMG amplitude versus isometric force. In addition, it was hypothesized that since the rectus femoris showed highly linear increases in MMG amplitude with isometric force, MMG could potentially be useful for estimating force production in situations where force cannot be measured directly, such as for examining subjective weakness in the quadriceps femoris muscles after knee joint surgery (Stokes and Dalton 1991). Similar results were also reported by these authors (Stokes and Dalton 1991) in a second study of the MMG amplitude versus isometric force relationship for the rectus femoris. Zhang et al. (1992) then examined the MMG amplitude and MPF versus isometric force relationships for the rectus femoris muscle at knee joint angles of 30°, 60°, and 90° (where 0° represents full leg extension). The authors found that MMG amplitude increased linearly with force at all three knee joint angles. In addition, the 60° and 90° knee joint angles showed linear increases in MMG MPF with force, but there was no change in MMG MPF with increases in force at the 30° knee joint angle. Thus, it was suggested that MMG amplitude may be useful for estimating muscle force production, and the frequency content of the MMG signal is affected by changes in joint angle (Zhang et al. 1992). This study (Zhang et al. 1992) was followed up by a second investigation (Zhang et al. 1996) that found that during submaximal isometric muscle actions of the leg extensors from 20% to 80% MVC, MMG amplitude for the rectus femoris increased curvilinearly with leg extension force. Thus, even though MMG amplitude for the rectus femoris increased linearly with isometric force in the first study (Zhang et al. 1992), a curvilinear pattern was reported in the second investigation (Zhang et al. 1996). These findings (Zhang et al. 1992, 1996) indicated that even when MMG signals are detected from the same muscle and in the same laboratory, the force-related patterns for MMG amplitude may differ for each subject.

Akataki et al. (1996) examined the potential clinical applications of the MMG amplitude versus isometric force relationship by comparing the patterns of responses for the biceps brachii from healthy subjects with those from patients that suffered from spastic cerebral palsy. Although the authors only examined submaximal force levels (i.e., 10-50% MVC), the mean MMG amplitude values for the patients with spastic cerebral palsy were less than those for the healthy subjects at all force levels (Figure 3).

In addition, the isometric forearm flexion MVC for the patients with spastic cerebral palsy was approximately one-half of the corresponding value for the healthy subjects. Thus, it was suggested that MMG may be a useful tool for studying the degradation in muscle function that occurs with spastic cerebral palsy, and, possibly, for other diseases that affect the neuromuscular



**Figure 3.** Mechanomyographic (MMG) amplitude (indicated as  $RMS_{SAMG}$  in this figure) for the biceps brachii as a function of relative isometric forearm flexion force (%MVC). The open symbols represent the values for normal, healthy subjects, and the closed symbols reflect the values for patients that suffer from spastic cerebral palsy. Notice that the values for the cerebral palsy patients are lower than those for the normal subjects at all force levels. \*Reprinted with permission from Akataki et al. (1996).

system (Akataki et al. 1996). Akataki et al. (1999) also conducted an interesting investigation of the factors that can cause the plateau or decrease in MMG amplitude at high isometric force levels. Specifically, the authors (Akataki et al. 1999) used a spectral decomposition procedure to remove the longitudinal muscle fiber vibrations from the MMG signal. Their hypothesis was that MMG signals from pennate muscles are affected by longitudinal and lateral muscle fiber vibrations, and the longitudinal vibrations could be estimated by placing an MMG sensor over the patella. The vibration signal from the patella would then be used in the spectral decomposition procedure to remove the longitudinal vibrations from the MMG signal. Interestingly, the

authors (Akataki et al. 1999) found that when the longitudinal vibrations were not removed from the MMG signal, 4 of the 12 subjects did not show a decrease in MMG amplitude at high force levels, while the remaining 8 subjects demonstrated a decrease in MMG amplitude for force levels above 70% MVC. When the spectral decomposition procedure was used to remove the longitudinal vibrations, however, all 12 subjects showed a decrease in MMG amplitude above 70% MVC. Thus, it was suggested that when subjects do not demonstrate a plateau or decrease in MMG amplitude at high force levels, the continued increases in MMG amplitude may be due to the influence of longitudinal vibrations on the MMG signal (Akataki et al. 1999).

In addition, Orizio et al. (1994) examined the effects of hypoxia on the MMG amplitude and MPF versus isometric force relationships for the biceps brachii muscle. Specifically, the authors (Orizio et al. 1994) recorded MMG signals from the biceps brachii muscle at 20%, 40%, 60%, 80%, and 100% MVC at 150 meters above sea level, as well as after 2, 15, and 40 days of exposure to an altitude of 5,050 meters above sea level (i.e., to induce hypoxia). The results showed that exposure to the high altitude condition had no effect on the patterns of responses for MMG amplitude and MPF versus force. Specifically, MMG amplitude increased with force from 20% to 60% MVC, followed by a decrease from 60% to 100% MVC. In addition, MMG MPF increased with force from 20% to 100% MVC. Thus, it was suggested (Orizio et al. 1994) that both acute and chronic exposure to high altitude did not affect the motor control strategy (as reflected in the patterns of responses for MMG amplitude and MPF) used by the biceps brachii to increase isometric force production. In addition, Esposito et al. (1996) used the MMG amplitude and MPF versus isometric force relationships to examine the influence of aging on the motor control strategy used by the biceps brachii to increase isometric force production. Specifically, the authors (Esposito et al. 1996) investigated the MMG amplitude and MPF versus isometric force relationships for the biceps brachii in young (age range = 20-34 years) and elderly (age range = 65-78 years) subjects. The results indicated that the young and elderly subjects showed similar patterns of responses for both MMG amplitude and MPF versus force. The mean MMG amplitude and MPF values for the elderly subjects were always lower, however, than those of the young subjects. Thus, it was hypothesized (Esposito et al. 1996) that the lower mean absolute MMG amplitude and MPF values for the elderly subjects may have been due to a loss of fast-twitch muscle fibers with aging. It was also suggested, however, that a thicker skinfold layer in the elderly subjects may have filtered the MMG signals to a greater extent than those for the young subjects (Esposito et al. 1996). Ebersole et al. (1999) also conducted a very interesting study that examined the influence of changes in knee joint angle on the patterns of

responses for MMG amplitude versus isometric torque for the vastus lateralis, rectus femoris, and vastus medialis muscles. The results showed that at 25° of leg flexion (where 0° represents full leg extension), MMG amplitude increased with torque from 25% to 100% MVC for both the vastus medialis and rectus femoris. The vastus lateralis, however, showed no change in MMG amplitude from 25% to 100% MVC. In addition, at 50° of leg flexion, MMG amplitude increased with isometric torque from 25% to 100% MVC for all three muscles. At 75° of leg flexion, however, MMG amplitude increased with isometric torque from 25% to 75% MVC, followed by a plateau from 75% to 100% MVC. Thus, it was suggested that the differences among the three knee joint angles for the patterns of responses for MMG amplitude versus isometric torque were probably due to differences in muscle stiffness, intramuscular fluid pressure, and/or the motor control strategies used to increase isometric torque (Ebersole et al. 1999). This was an important study from a practical standpoint because previous investigations had not always used a standardized joint angle. Thus, the different patterns of responses shown in previous studies could have been due at least partially to testing at different joint angles.

Nonaka et al. (2000) used the MMG amplitude versus isometric force relationship for the biceps brachii to examine potential differences in muscle function between pre-adolescent boys (age range = 9-11 years) and young men (age range = 21-23 years). The results showed that MMG amplitude increased with isometric force from 10% to 80% MVC for both the pre-adolescent boys and the young men. At 60% and 80% MVC, however, the mean MMG amplitude values for the young men were significantly greater than those for the pre-adolescent boys. Thus, it was suggested (Nonaka et al. 2000) that greater absolute force production by the young men than the pre-adolescent boys was the most likely cause for the greater mean absolute MMG amplitude values at 60% and 80% MVC. Up to this point, no studies had attempted a detailed description of the factors underlying the MMG amplitude and MPF versus isometric force relationships. Thus, a very important investigation was performed by Akataki et al. (2001) to examine the characteristics of the MMG amplitude versus force relationship for the biceps brachii during an isometric ramp muscle action of the forearm flexors. Specifically, the MMG amplitude and MPF versus force relationships were decomposed into five separate regions that were thought to reflect the dominant motor control strategy (i.e., recruitment versus firing rate modulation) being used. For example, from approximately 60% to 80% MVC, MMG amplitude decreased, while MMG MPF increased. Thus, it was suggested that above 60% MVC, force was increased primarily by increases in firing rates, rather than motor unit recruitment. From approximately 30% to 50% MVC, however, MMG amplitude increased rapidly, while MMG MPF increased slowly. These

changes were hypothesized to reflect rapid motor unit recruitment, with small increases in firing rates. Therefore, the findings from this study (Akataki et al. 2001) were important because they were the first to suggest that the patterns of responses for MMG amplitude and MPF could provide detailed information regarding motor control strategies.

Akataki et al. (2003) also published a second paper that compared the biceps brachii and first dorsal interosseous for the MMG amplitude and MPF versus force relationships. The results showed that for the first dorsal interosseous, MMG amplitude remained relatively stable from 5% to approximately 20% MVC, increased from 20% to approximately 40% MVC, and then decreased from 40% to 70% MVC. The pattern for MMG MPF, however, showed an almost linear increase from 5% to 70% MVC. In addition, MMG amplitude for the biceps brachii increased from 5% to approximately 60% MVC, and then decreased from 60% to 70% MVC. The results for MMG MPF showed an increase from 5% to roughly 50% MVC, a decrease from 50% to approximately 60% MVC, and an increase from 60% to 70% MVC. Thus, it was hypothesized that the differences between the biceps brachii and first dorsal interosseous for the patterns of responses for MMG amplitude and MPF were probably due to differences in the motor control strategies used to increase isometric force (Akataki et al. 2003). Yoshitake and Moritani (1999), however, reported that during submaximal isometric step muscle actions of the plantar flexors from 20% to 80% MVC, both MMG amplitude and MMG MPF increased linearly for the medial gastrocnemius. The soleus, however, showed an increase in MMG amplitude from 20% to 60% MVC, and then a decrease from 60% to 80% MVC, while MMG MPF increased linearly from 20% to 80% MVC. These findings were important because the medial gastrocnemius and soleus are both innervated by the tibial nerve. Thus, the differences between the two muscles for the patterns of responses for MMG amplitude versus isometric force were probably not due to differences in motor control strategies. Instead, a more likely explanation is that the differences were due to discrepancies in fiber type composition, with the soleus being dominated by slow-twitch fibers and the medial gastrocnemius containing mainly fast-twitch fibers (Yoshitake and Moritani 1999).

Orizio et al. (2003) also conducted a very interesting study that examined the MMG amplitude and MPF versus isometric force relationships for the biceps brachii muscle when it was in both a fatigued and non-fatigued state. The experimental protocol required the subjects to first perform a 6.75-second ramp from 15-85% MVC. The forearm flexors were then fatigued by having the subjects perform intermittent isometric muscle actions of the forearm flexors at 50% MVC until the required force could no longer be maintained. Immediately after this fatiguing protocol, the subjects performed another 6.75-

second ramp from 15-85% of their new MVC (which corresponded to 50% of their original MVC). The results showed that when the biceps brachii muscle was not fatigued, MMG amplitude increased from 15% to 65% MVC, and then decreased from 65% to 85% MVC, while MMG MPF increased from 15% to 85% MVC. In the fatigued state, however, MMG amplitude decreased from 15% to 85% MVC, while MMG MPF increased. Thus, it was concluded that MMG amplitude was the parameter most affected by fatigue, and its unique pattern of response with increases in force in the fatigued state was probably due to fatigue of fast-twitch muscle fibers. In addition, the MMG amplitude and MPF versus isometric force relationships are affected not only by motor control strategies, but also by the fatigue status of the muscle (Orizio et al. 2003).

Ebersole et al. (2002) conducted an interesting study that examined the influence of an 8-week strength training program on the MMG amplitude versus isometric force relationship for the biceps brachii muscle. The results showed that the strength training program elicited significant increases in both flexed arm circumference and isometric forearm flexion strength. There were no differences, however, between the patterns of responses for MMG amplitude versus force for the biceps brachii from the pre-training versus post-training tests. Thus, it was suggested (Ebersole et al. 2002) that the strength gains from the 8-week training program could have been due primarily to hypertrophic, rather than neural factors. In addition, increases in muscle stiffness with training may have counteracted the effects of hypertrophy on MMG amplitude, resulting in no changes in its patterns of response with force (Ebersole et al. 2002). Akataki et al. (2004) simultaneously examined the MMG and EMG amplitude and MPF versus force relationships for the biceps brachii to determine if MMG provided more information regarding motor control strategies than EMG. The results indicated that EMG amplitude increased curvilinearly with force from 5% to 80% MVC, whereas EMG MPF increased from 5% to 50% MVC and then plateaued from 50% to 80% MVC. In contrast, MMG amplitude increased curvilinearly with force from 5% to 60% MVC and then decreased from 60% to 80% MVC, while MMG MPF increased from 5% to 50% MVC, decreased from 50% to 60% MVC, and increased from 60% to 80% MVC. Thus, the authors (Akataki et al. 2004) hypothesized that the EMG MPF versus force relationship may be useful for determining when all motor units have been recruited, while the MMG amplitude versus force relationship showed when all the motor units had been recruited, as well as the beginning of fast-twitch motor unit recruitment. However, these hypotheses still needed to be tested directly.

Our laboratory has also examined some of the inter-individual factors that can affect the MMG amplitude and MPF versus torque or force relationships.

For example, Beck et al. (2008) investigated the patterns of responses for MMG amplitude versus isometric force for the vastus lateralis from resistance-trained (mean fast-twitch fiber type percentage = 59.1%), aerobically-trained (mean fast-twitch fiber type percentage = 27.4%), and sedentary subjects (mean fast-twitch fiber type percentage = 59.9%). At the beginning of the study, it was hypothesized that the subjects with a greater percentage of slow-twitch fibers may be more likely to demonstrate a plateau or decrease in MMG amplitude at high force levels than those with mostly fast-twitch fibers. The results indicated, however, that there was a large amount of variability between subjects for the patterns of responses for MMG amplitude versus force, and this variability was not related to the fiber type composition of the vastus lateralis (Beck et al. 2008). In addition, Beck et al. (2005) examined the influence of differences in gender on the MMG amplitude and MPF versus isometric torque relationships for the biceps brachii muscle. The authors (Beck et al. 2005) found that for young, college-aged men, MMG amplitude increased from 10% to 80% MVC and then plateaued from 80% to 100% MVC. The young college-aged women, however, showed a linear increase in MMG amplitude with force from 10% to 100% MVC. In addition, both the young men and young women showed linear increases in MMG MPF from 10% to 100% MVC. Thus, it was hypothesized that the differences between the men and women for the patterns of responses for MMG amplitude versus force were likely due to differences in absolute strength levels (since the mean forearm flexion strength value for the women was 43% that of the men), rather than differences in motor control strategies (Beck et al. 2005). Another study from our laboratory compared a piezoelectric crystal contact sensor with an accelerometer for the patterns of responses for MMG amplitude and MPF versus isometric torque for the biceps brachii (Beck et al. 2006). The results indicated that MMG amplitude increased linearly with isometric torque for both the piezoelectric crystal contact sensor and accelerometer. The patterns for MMG MPF, however, showed a linear decrease from 20% to 100% MVC for the accelerometer, but no change for the piezoelectric crystal contact sensor. Thus, it was concluded that the interpretation of the patterns of responses with regard to describing motor control strategies may be affected by the type of MMG sensor that is used to detect the signal (Beck et al. 2006).

Several recent studies have also compared isometric ramp versus step muscle actions for the MMG amplitude and MPF versus torque relationships. For example, Ryan et al. (2008) found that during isometric ramp and step muscle actions of the leg extensors, there was a substantial degree of inter-individual variability in the patterns of responses for MMG amplitude and MPF versus torque. These relationships were also different for each of the muscles that were investigated (the vastus lateralis and rectus femoris), as well

as for the step versus ramp muscle actions. Thus, it was concluded (Ryan et al. 2008) that the patterns for MMG amplitude and MPF versus torque should be interpreted with the understanding that they are mode (ramp versus step) and muscle-specific. In addition, the large degree of inter-individual variability suggested that these relationships may best be examined on a subject-by-subject basis (Ryan et al. 2008). Similar results were also reported in a previous study (Ryan et al. 2007) that compared the composite (i.e., mean) MMG amplitude and MPF versus isometric torque relationships for the vastus lateralis with the patterns of responses for individual subjects that were categorized into either a high strength or a low strength group. The results showed that for the composite patterns of responses, the MMG amplitude versus isometric torque relationship for the high strength group was best fit with a cubic model, while the corresponding relationship for the low strength group was best fit with a linear model. In addition, MMG MPF increased linearly with torque for both the high and low strength groups. Furthermore, only 66% and 33% of the subjects showed the same MMG amplitude versus force relationships as the composite patterns for the low strength and high strength groups, respectively. Only one of the twelve subjects showed the same linear increase in MMG MPF with isometric force that was seen for the composite patterns. Thus, it was concluded that differences in strength did not affect the patterns of responses for MMG amplitude or MPF versus isometric force. Instead, these relationships were different for each individual, which suggested that perhaps they should be investigated on a subject-by-subject basis (Ryan et al. 2007). An important question, however, is whether or not the patterns of responses for MMG amplitude and MPF demonstrate sufficient between-day reliability to be used for examining the effects of various interventions. Herda et al. (2008) recently examined this issue for the vastus lateralis during both isometric step and ramp muscle actions of the leg extensors. The results showed between-day reliability coefficients (intraclass correlation coefficients) ranging from 0.39-0.89 for MMG amplitude and 0.36-0.80 for MMG MPF. Thus, it was concluded that the reliability of the MMG signal was comparable to that of the EMG signal. It was also suggested, however, that future studies need to be done to determine if the patterns of responses (as opposed to the absolute values) for MMG amplitude and MPF demonstrate acceptable reliability (Herda et al. 2008).

Hwang (2007) investigated changes in the frequency contents of the MMG and EMG signals for the tibialis anterior during isometric load-varying contractions. Specifically, the subjects were required to perform two different tasks that included: (a) static isometric muscle actions of the dorsiflexors at four different force levels, and (b) load-varying isometric dorsiflexion where the subject was required to track a target sinusoidal force curve with three

different amplitudes. The results showed that during both the static and load-varying isometric muscle actions, the MPF of the MMG-EMG cross spectrum increased progressively with force, but the median frequency of the EMG signal remained constant. In addition, there was a positive, linear relationship between the MMG-EMG cross spectrum MPF and EMG amplitude, but the slope coefficient was significantly greater for the load-varying isometric muscle actions than for the static muscle actions. Thus, it was concluded that changes in motor unit firing rates for the tibialis anterior with increases in isometric force are dependent on the type of isometric muscle action that is being performed (i.e., static versus load-varying) (Hwang 2007). Ohta et al. (in press) investigated the potential relationship between changes in fascicle length and MMG amplitude during voluntary isometric muscle actions of the plantar flexors with a superimposed twitch. Specifically, the subjects were required to perform isometric muscle actions of the plantar flexors at 20%, 40%, 60%, 80%, and 100% MVC, and surface MMG signals were detected from the medial gastrocnemius muscle. During each muscle action, the plantar flexors were stimulated with a supramaximal stimulus that was sent through the posterior tibial nerve, and changes in fascicle length were measured with ultrasound. The results showed that MMG amplitude during the supramaximal stimulus and the change in fascicle length decreased curvilinearly from 20% to 80% MVC, but the superimposed twitch amplitude decreased linearly. In addition, there was a linear relationship between MMG amplitude and the change in fascicle length. Thus, it was concluded that MMG amplitude reflected changes in fascicle length better than the superimposed twitch amplitude. In addition, MMG amplitude may be useful for examining changes in muscle architecture (Ohta et al. in press).

Coburn et al. (2008) recently examined the MMG amplitude versus isometric torque relationships for the vastus lateralis, rectus femoris, and vastus medialis muscles. Specifically, the subjects performed submaximal to maximal isometric step muscle actions of the leg extensors, and the MMG amplitude responses were measured for the vastus lateralis, rectus femoris, and vastus medialis. The results showed that the composite (i.e., averaged across subjects) patterns for MMG amplitude were best fit with quadratic models for the vastus lateralis and vastus medialis, and a linear model for the rectus femoris. The individual responses, however, were very inconsistent, with some subjects showing linear patterns, others demonstrating a quadratic relationship, others showing cubic patterns, and for some subjects, there was no significant relationship between MMG amplitude and torque. Thus, it was concluded that when examining the patterns of responses for MMG amplitude versus isometric torque, the individual relationships should be considered, since they often differ from the composite patterns. In addition, caution should be used

when interpreting the patterns of responses for just one muscle, since these patterns often vary on a muscle-by-muscle basis (Coburn et al. 2008).

In summary, examination of the MMG amplitude and center frequency responses with increases in isometric force has played an important role in identifying the mechanisms that generate the signal and the information that it can provide. The results from the studies that have examined these responses clearly indicate that these relationships are rich with information. Future research in this area should examine the influence of factors such as changes in muscle stiffness, architecture, and intramuscular fluid pressure on these patterns. Although a great deal of research has been performed to identify the information that these patterns provide, there is still a lot that needs to be done to understand the factors that affect them.

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