



Applications of Mechanomyography for Examining Muscle Function, 2010, 69-93
Editor: Travis W. Beck ISBN : 978-81-7895-449-3

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Mechanomyographic responses during dynamic muscle actions

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Abstract

Surface mechanomyographic (MMG) signals have been detected during various types of dynamic muscle actions, including dynamic constant external resistance (DCER) muscle actions, concentric and eccentric isokinetic muscle actions, as well as incremental and constant power output cycle ergometry. Although the MMG amplitude and center frequency [mean power frequency (MPF) or median frequency] responses may differ slightly for different muscles and types of muscle actions, a particularly interesting relationship is that between MMG amplitude and muscle power output. Specifically, many

studies have shown that MMG amplitude is closely related to power output during cycle ergometry and maximal concentric and eccentric isokinetic muscle actions. These findings are important from a practical standpoint, because many training programs are designed to improve muscle power output, rather than just maximal torque. Thus, MMG could potentially be used to examine training-induced changes in the power output of individual muscles, which is useful since most joints are crossed by more than one muscle.

Introduction

Although most previous studies have examined the mechanomyographic (MMG) amplitude and/or frequency responses during isometric muscle actions, there are several investigations that have used MMG to study muscle function during dynamic muscle actions. Important factors that must be considered when recording MMG signals during dynamic muscle actions include changes in torque production, muscle length, and the thickness of the tissue between the muscle and MMG sensor. Each of these factors can affect both the amplitude and frequency contents of the MMG signal detected during a dynamic muscle action, thereby affecting the validity of these parameters. There are, however, several pieces of evidence that indicate that the MMG signal is generated by muscle vibrations during a dynamic muscle action. First, MMG amplitude increases with torque production during both concentric and eccentric muscle actions, as well as with increases in power output during cycle ergometry. Furthermore, for a given torque level, MMG amplitude is lower during an eccentric muscle action than a concentric muscle action, thereby reflecting a reduced level of muscle activity. Perhaps the most convincing evidence, however, that muscle activity generates the MMG signal during a dynamic muscle action is that MMG amplitude decreases to levels that are similar to those at rest when the pedals on a cycle ergometer are driven by the investigator, rather than the subject. As soon as the subject begins driving the pedals, MMG amplitude increases. Thus, the majority of MMG research during dynamic muscle actions has been focused on determining whether or not the MMG signal can be used to evaluate differences in muscle between various types of dynamic muscle actions.

Evetovich et al. (1997) were the first to examine the MMG amplitude responses with increases in velocity during isokinetic muscle actions. Specifically, MMG amplitude for the vastus lateralis increased with increases in velocity from $60\text{-}360^{\circ}\cdot\text{s}^{-1}$ during maximal concentric isokinetic leg extensions, even though isokinetic peak torque decreased. Thus, it was hypothesized that decreases in muscle stiffness at high velocities may have

allowed for greater muscle fiber oscillations and an MMG signal with greater amplitude. Theoretically, the velocity-related decrease in muscle stiffness could have been due to the fact that at high velocities, slow-twitch muscle fibers become unloaded, because they are unable to keep up with the speed of the movement, thereby resulting in less muscle stiffness and torque production. Another interesting finding from the Evetovich et al. (1997) study was that the MMG amplitude values were highly reliable, with intraclass correlation coefficients (ICCs) ranging from $R = 0.90-0.99$, and no significant mean differences between the test and retest values at any velocity (Evetovich et al. 1997). Smith et al. (1998) also reported a velocity-related increase in MMG amplitude during maximal concentric isokinetic muscle actions, but the muscle examined was the biceps brachii, and the velocities ranged from $30-150^{\circ}\cdot\text{s}^{-1}$. Similar results were also reported for the biceps brachii during maximal eccentric isokinetic muscle actions of the forearm flexors (Smith et al. 1998). Evetovich et al. (1998) then performed a second study that compared men and women for the velocity-related changes in MMG amplitude for the vastus lateralis during maximal concentric and eccentric isokinetic muscle actions. The results showed that there were greater velocity-related increases in MMG amplitude for the men than the women, and the mean MMG amplitude values were greater for the men at all velocities. Interestingly, the velocity-related decreases in concentric isokinetic peak torque were greater for the women (33.3% decline) than the men (28.5% decline). Thus, it was suggested that the gender differences in the MMG amplitude responses may have been due to discrepancies in fiber type composition, muscle mass, and/or the thickness of the subcutaneous adipose tissue over the vastus lateralis. Interestingly, the velocity-related increases in MMG amplitude during the eccentric isokinetic muscle actions were the same for the men and women, but, like the concentric isokinetic muscle actions, the mean MMG amplitude values were higher at all velocities for the men than the women. Thus, it was concluded that MMG amplitude is related to velocity during maximal concentric and eccentric isokinetic muscle actions, and may be useful for differentiating between muscle function in men and women (Evetovich et al. 1998).

Ebersole et al. (2001) examined the MMG amplitude responses for the vastus lateralis with increases in velocity during maximal concentric isokinetic and passive leg extension muscle actions to determine if changes in MMG amplitude were a function of movement velocity, independent of muscle activation. During both the active and passive leg extension muscle actions, MMG amplitude for the vastus lateralis increased with velocity, but during the passive muscle actions, the vastus lateralis was inactive because the EMG amplitude values from the muscle were very small and did not change with

increases in velocity. Thus, it was suggested that the velocity-related increases in MMG amplitude may have been due to greater turbulence of the intracellular and extracellular fluid mediums and/or cross-talk from the hamstring muscles (Ebersole et al. 2001). Ebersole et al. (2001) also performed the first study to examine the MMG center frequency responses with increases in velocity during maximal concentric isokinetic muscle actions. The results showed that with an increase in velocity from 60 to $300^{\circ}\cdot\text{s}^{-1}$, there was a significant decrease in leg extension peak torque and an increase in MMG amplitude for the vastus lateralis. There was, however, no change in the mean MMG MPF values for the vastus lateralis with increases in velocity. Thus, it was hypothesized that the tendonous iliotibial band that covers the vastus lateralis could have interfered with the muscle fiber oscillations that generate the MMG signal (Ebersole et al. 2000).

Cramer et al. (2000a) examined the relationship between MMG amplitude and power output during maximal concentric isokinetic leg extensions. The experimental protocol required the subjects to perform maximal concentric isokinetic muscle actions of the leg extensors at velocities of 60, 120, 180, 240, 300, 360, 420, and $480^{\circ}\cdot\text{s}^{-1}$. During each muscle action, MMG signals were detected from the vastus lateralis, rectus femoris, and vastus medialis. The results showed that with increases in velocity, isokinetic peak torque decreased, but mean power output increased up to approximately $180^{\circ}\cdot\text{s}^{-1}$, plateaued from 180 to $300^{\circ}\cdot\text{s}^{-1}$, and then decreased from 300 to $480^{\circ}\cdot\text{s}^{-1}$. Interestingly, the patterns of responses for MMG amplitude were nearly identical to those for mean power output (Figure 1).

Thus, it was concluded that MMG amplitude may be more related to muscle power output than peak torque during maximal isokinetic muscle actions, and, therefore, could be useful for monitoring training-induced changes in power output (Cramer et al. 2000a). Cramer et al. (2000b) also examined muscle-specific differences in the MMG amplitude responses with increases in velocity during maximal concentric isokinetic muscle actions. All subjects were required to perform maximal concentric isokinetic leg extensions at velocities ranging from 60 to $300^{\circ}\cdot\text{s}^{-1}$, and MMG signals were detected from the vastus lateralis, rectus femoris, and vastus medialis. The results showed that MMG amplitude for each muscle increased from 60 to $180^{\circ}\cdot\text{s}^{-1}$. At velocities greater than $180^{\circ}\cdot\text{s}^{-1}$, however, MMG amplitude increased to $240^{\circ}\cdot\text{s}^{-1}$, and then plateaued from 240 to $300^{\circ}\cdot\text{s}^{-1}$ for the vastus lateralis, plateaued from 180 to $300^{\circ}\cdot\text{s}^{-1}$ for the rectus femoris, and increased from 180 to $300^{\circ}\cdot\text{s}^{-1}$ for the vastus medialis. Thus, it was concluded that the muscle-specific differences in the MMG amplitude responses could have been due to differences in fiber type composition and/or muscle architecture (Cramer et al. 2000b)

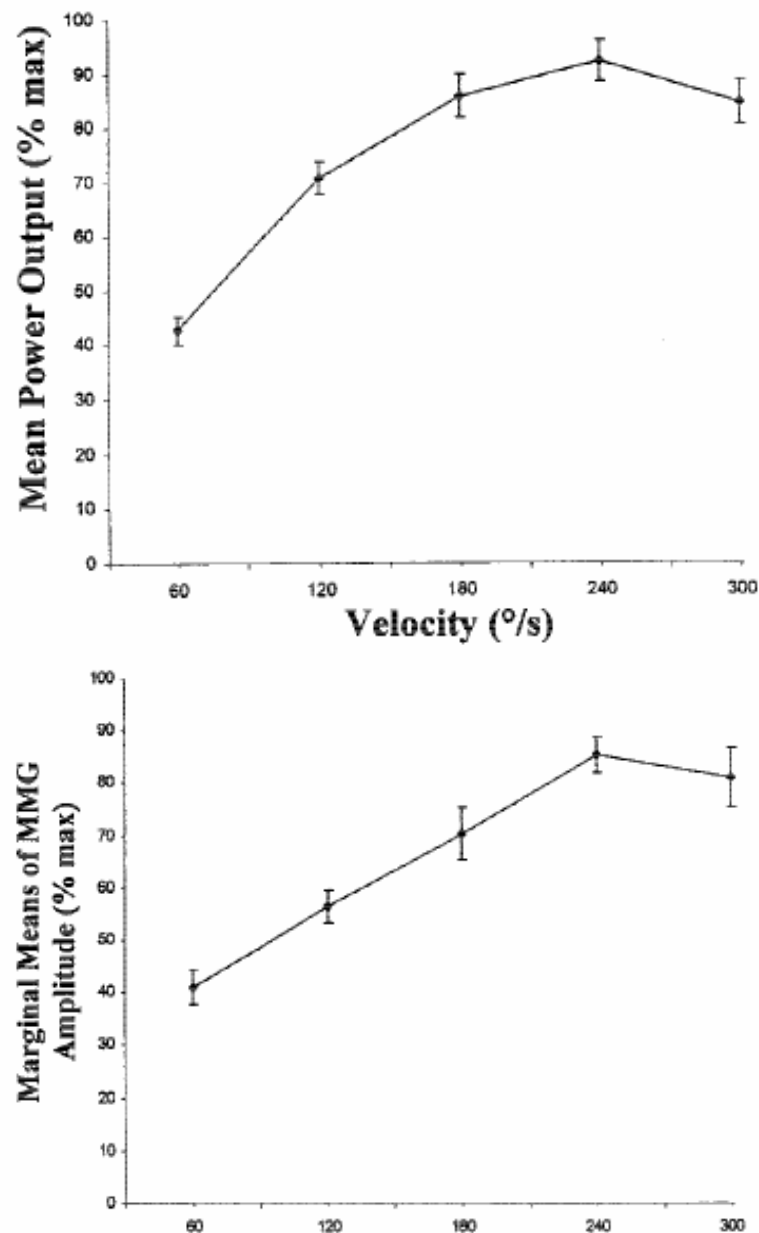


Figure 1. The top graph shows changes in mean power output with increases in velocity during maximal concentric isokinetic muscle actions of the leg extensors. The bottom graph demonstrates the corresponding changes in mechanomyographic (MMG) amplitude for the superficial quadriceps femoris muscles (data are collapsed across muscles). Notice that the patterns for mean power output and MMG amplitude were very similar. *Reprinted with permission from Cramer et al. (2000a).

A very important issue when recording MMG signals during dynamic muscle actions is cross-talk (i.e., contamination of the MMG signals from a muscle outside the muscle of interest). Cramer et al. (2003) quantified cross-talk among the superficial quadriceps femoris muscles during maximal

concentric and eccentric isokinetic muscle actions of the leg extensors at a velocity of $60^{\circ}\cdot\text{s}^{-1}$. The authors used the cross-correlation technique to quantify the cross-talk, and found that the common variance shared between the MMG signals from any two muscles ranged from 14-27%. Thus, it was concluded that the chances for cross-talk were fairly small during maximal isokinetic muscle actions, even for muscles that are close to each other and have a common innervation (Cramer et al. 2003). In addition, the results from a more recent study (Cramer et al. 2004) suggested that the MMG mean power frequency (MPF) responses to increases in velocity may be muscle-specific. In particular, during maximal concentric isokinetic leg extensions, there were velocity-related increases in MMG MPF for the rectus femoris and vastus lateralis muscles, but not for the vastus medialis (Cramer et al. 2004). Thus, it was difficult to identify the exact mechanisms underlying the MMG MPF responses during maximal isokinetic muscle actions. In addition, the patterns of responses for MMG amplitude and MPF with increases in velocity during concentric isokinetic muscle actions were not always the same as those for eccentric isokinetic muscle actions. For example, Smith et al. (1997) reported that during maximal eccentric isokinetic muscle actions of the leg extensors at velocities of 60, 90, 120, and $180^{\circ}\cdot\text{s}^{-1}$, there was no change in maximal eccentric peak torque with increases in velocity, but MMG amplitude for the vastus lateralis increased (Figure 2). Furthermore, the MMG amplitude values were highly reliable, with intra-class correlation coefficients ranging from $R = 0.97-0.98$ and no significant differences between the mean MMG amplitude values for test versus retest at any velocity. Thus, three potential hypotheses were proposed to explain the MMG amplitude responses. First, an increased rate of cross bridge activity during high speed eccentric muscle actions could have resulted in larger vibrations of the myosin heads, thereby increasing MMG amplitude. It is also possible, however, that derecruitment of low-threshold, slow-twitch motor units and selective activation of high-threshold, fast-twitch motor units during high velocity eccentric muscle actions could have resulted in greater MMG amplitude values. And finally, increases in MMG amplitude with velocity during eccentric muscle actions could have been due to faster movement of the limb and a subsequent greater overall disturbance of the intracellular and extracellular fluid mediums (Smith et al. 1997).

In addition, Evetovich et al. (1999) found that during maximal eccentric isokinetic muscle actions of the leg extensors at velocities of 60, 120, and $180^{\circ}\cdot\text{s}^{-1}$, MMG amplitude for the vastus lateralis increased with velocity, but there was no change in MMG MPF from 60 to $180^{\circ}\cdot\text{s}^{-1}$. Thus, it was hypothesized that the increase in MMG amplitude may have been due to factors

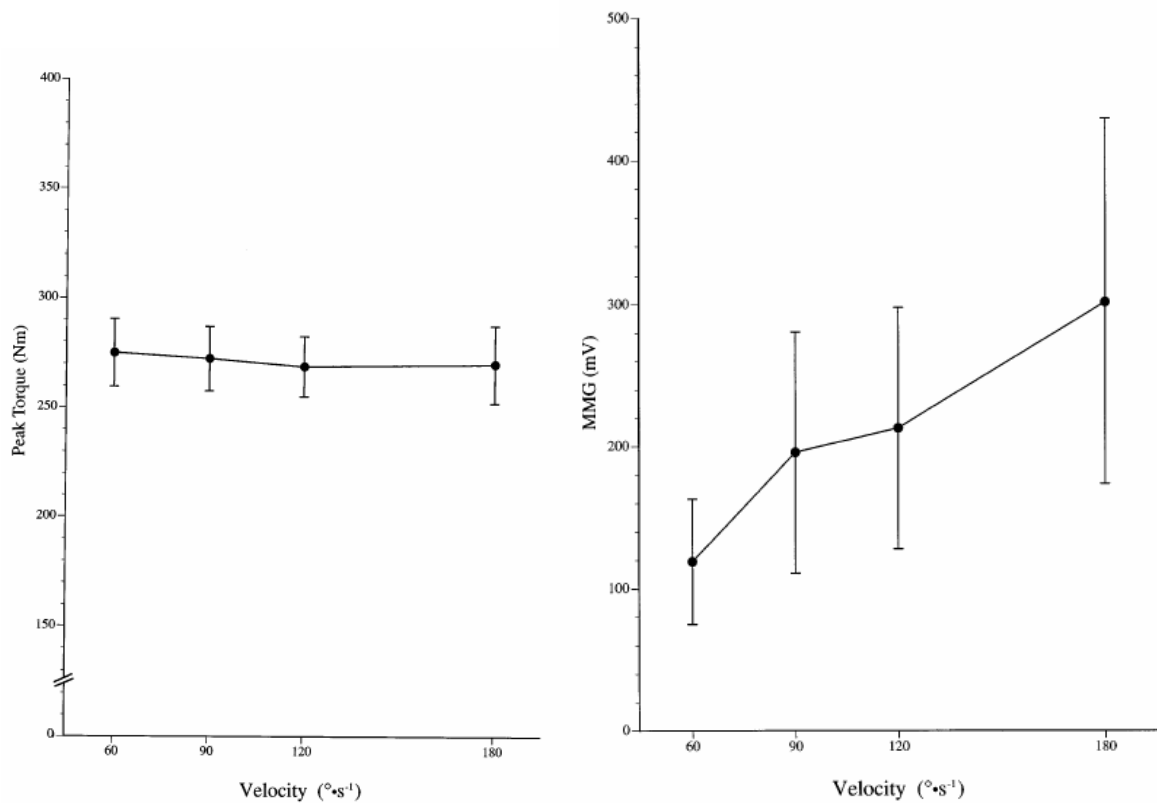


Figure 2. The top graph shows changes in leg extension peak torque with increases in velocity during maximal eccentric isokinetic muscle actions of the leg extensors. The bottom graph demonstrates the corresponding changes in mechanomyographic (MMG) amplitude for the vastus lateralis. Notice that eccentric peak torque changed very little with increases in velocity, but MMG amplitude increased. *Reprinted with permission from Smith et al. (1997).

other than a velocity-related shift in the contributions of slow- and fast-twitch muscle fibers to torque production (Evetovich et al. 1999).

Furthermore, Cramer et al. (2002) reported that during maximal eccentric isokinetic muscle actions of the leg extensors, MMG MPF for the vastus lateralis, rectus femoris, and vastus medialis decreased with an increase in velocity from 60-120°·s⁻¹, and then remained relatively stable from 120-180°·s⁻¹. In addition, Cramer et al. (2002) recently found that mean power output and MMG amplitude for the vastus lateralis increased with velocity during maximal eccentric isokinetic muscle actions of the leg extensors at velocities of 30, 90, and 150°·s⁻¹. These velocity-related increases in MMG amplitude were statistically equivalent for the men and women that participated in the study. Thus, it was suggested that like maximal concentric isokinetic muscle actions, MMG amplitude may be closely related to muscle power output during maximal eccentric isokinetic muscle actions (Cramer et al. 2002).

Although much of the dynamic MMG literature has used isokinetic muscle actions, several studies have also examined the MMG amplitude and center frequency responses during dynamic constant external resistance (DCER) muscle actions. For example, Dalton and Stokes (1991) reported that during concentric and eccentric DCER muscle actions of the forearm flexors in which the subjects lifted and lowered weights ranging from 0-8.5 kg, MMG amplitude for the biceps brachii increased linearly from 0-8.5 kg during both the concentric and eccentric muscle actions (Figure 3).

In addition, during a separate study that used the same experimental protocol, MMG MPF for the biceps brachii increased from 0 to approximately 5.5 kg, and then decreased from 5.5-8.5 kg during the concentric muscle actions (Dalton and Stokes 1993). During the eccentric muscle actions, however, MMG MPF remained relatively stable from 0-8.5 kg. Thus, it was concluded that during concentric muscle actions of the forearm flexors, torque production may be increased by recruiting more motor units in the biceps brachii, as well as increasing their firing rates. During eccentric muscle actions,

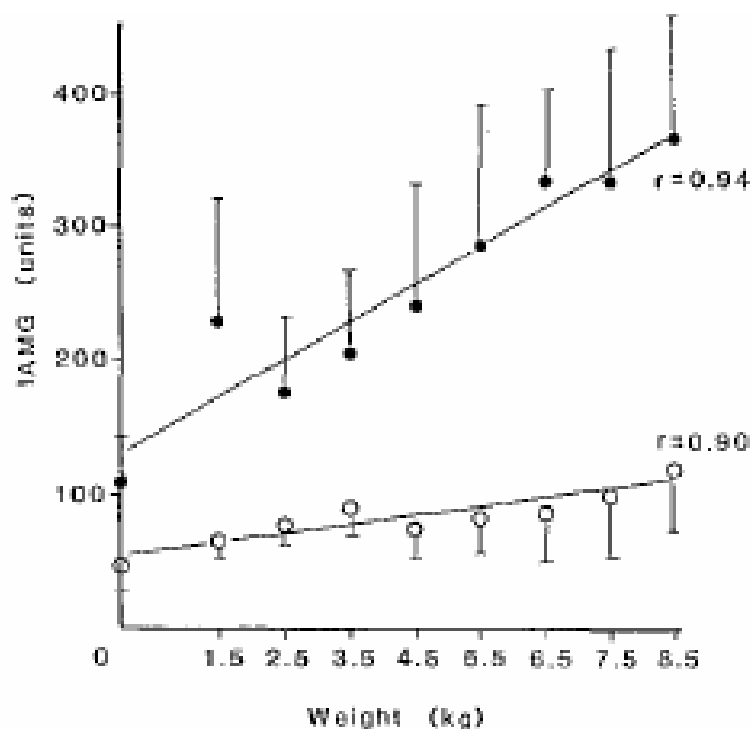


Figure 3. Mechanomyographic (MMG) amplitude (indicated as IAMG in this figure) for the biceps brachii with increases in forearm flexion torque during concentric (solid symbols) and eccentric (open symbols) dynamic constant external resistance muscle actions. Notice that for every given torque level, MMG amplitude was lower during the eccentric than the concentric muscle actions. Also notice that the patterns of responses were very linear during both types of muscle actions. *Reprinted with permission from Dalton and Stokes (1991).

however, torque may be increased primarily by motor unit recruitment (Dalton and Stokes 1991, 1993). Petitjean et al. (1992) also examined the MMG amplitude versus torque relationships for the biceps brachii and brachioradialis during submaximal concentric DCER muscle actions of the forearm flexors. The results showed that MMG amplitude for both muscles increased linearly with concentric torque (Petitjean et al. 1992).

Several studies from our laboratory have investigated the MMG amplitude and/or MPF versus concentric or eccentric torque relationships, but during isokinetic, rather than DCER muscle actions. For example, Beck et al. (2006) reported that during submaximal to maximal eccentric isokinetic muscle actions of the forearm flexors at a velocity of $30^{\circ}\cdot\text{s}^{-1}$, MMG amplitude for the biceps brachii increased from 10% to approximately 60% of the isokinetic peak torque value, and then plateaued from 60-100% peak torque. In addition, MMG MPF for the biceps brachii increased linearly from 10-100% peak torque. Thus, it was concluded that eccentric torque production is increased by motor unit recruitment and firing rate modulation from 10-60% peak torque, followed by increases in firing rates from 60-100% peak torque (Beck et al. 2006). Coburn et al. (2004) also examined the MMG amplitude and MPF responses during submaximal to maximal eccentric isokinetic muscle actions at a velocity of $30^{\circ}\cdot\text{s}^{-1}$, but the muscle examined was the vastus medialis. The results showed that both MMG amplitude and MMG MPF increased linearly with eccentric torque from 10-100% peak torque.

Thus, it was concluded that for the vastus medialis muscle, motor unit recruitment and firing rate modulation may occur throughout the entire range of eccentric torque production (Coburn et al. 2004). Madeleine et al. (2001) reported that during both concentric and eccentric DCER muscle actions of the first dorsal interosseous, there were no changes in MMG amplitude or MPF with increases in torque. Since these responses were quite different from those of previous studies for the biceps brachii and vastus medialis, it is possible that they reflected muscle-specific differences in the motor control strategies that modulate eccentric torque production (Madeleine et al. 2001). Furthermore, in two separate studies, Beck et al. (2004a,b) found that MMG amplitude for the biceps brachii muscle increased linearly with torque during submaximal to maximal concentric isokinetic muscle actions of the forearm flexors at a velocity of $30^{\circ}\cdot\text{s}^{-1}$, but there was no change in MMG MPF. Thus, it was suggested that for the biceps brachii, concentric torque production may have been modulated primarily by motor unit recruitment, with little change in motor unit firing rates (Beck et al. 2004a,b). In addition, Coburn et al. (2004) examined the patterns of responses for MMG amplitude and MPF for the vastus medialis during submaximal to maximal concentric isokinetic muscle

actions of the leg extensors at a velocity of $30^{\circ}\cdot\text{s}^{-1}$. The results indicated that both MMG amplitude and MPF increased linearly with torque, and it was suggested that these torque-related increases may have reflected concurrent motor unit recruitment and firing rate modulation (Coburn et al. 2004).

Several studies have also investigated the MMG amplitude and/or MPF responses during fatiguing concentric or eccentric isokinetic muscle actions. Specifically, Perry-Rana (2002) examined the patterns for MMG amplitude for the vastus lateralis, rectus femoris, and vastus medialis muscles during 50 consecutive maximal concentric isokinetic leg extensions at velocities of 60, 180, and $300^{\circ}\cdot\text{s}^{-1}$. The results showed that at 60 and $300^{\circ}\cdot\text{s}^{-1}$, there were quadratic decreases in MMG amplitude for the vastus lateralis and vastus medialis muscles, but linear decreases for the rectus femoris (Figure 4). In addition, at $180^{\circ}\cdot\text{s}^{-1}$, MMG amplitude decreased in a quadratic fashion for the vastus medialis muscle, but there were linear decreases for the rectus femoris and vastus lateralis. Furthermore, the decreases in MMG amplitude at each velocity were greater for the rectus femoris than the vastus lateralis and vastus medialis. Finally, the decrease in concentric isokinetic leg extension torque at $60^{\circ}\cdot\text{s}^{-1}$ was best fit with a quadratic model, but at 180 and $300^{\circ}\cdot\text{s}^{-1}$, the PT patterns were best fit with cubic models.

Thus, it was hypothesized that the decreases in MMG amplitude with fatigue at the three velocities may have been due to reduced compliance and/or muscle wisdom, where the central nervous system decreases motor unit firing rates to compensate for the fatigue-induced increases in muscle fiber relaxation times (Perry-Rana et al. 2002). Beck et al. (2004) followed up the study by Perry-Rana et al. (2002) by examining the MMG amplitude and MPF responses for the biceps brachii during 50 consecutive maximal concentric isokinetic muscle actions of the forearm flexors at a velocity of $180^{\circ}\cdot\text{s}^{-1}$. The results showed that there were linear decreases in both MMG amplitude and MPF across the 50 repetitions, and a cubic decrease in isokinetic peak torque of approximately 70%. Thus, it was hypothesized that the decreases in MMG amplitude and MPF could have been due to fatigue-induced reductions in motor unit firing rates and/or decreased compliance in the biceps brachii muscle. It was also suggested, however, that de-recruitment of fast-twitch motor units with fatigue could, theoretically, have caused the reductions in MMG amplitude and MPF (Beck et al. 2004). Perry-Rana et al. (2003) also examined the patterns of responses for MMG amplitude from the rectus femoris, vastus lateralis, and vastus medialis during 25 consecutive maximal eccentric isokinetic muscle actions of the leg extensors at a velocity of $120^{\circ}\cdot\text{s}^{-1}$. The results showed that for the vastus lateralis and vastus medialis, MMG amplitude decreased linearly across the 25 repetitions. The rectus femoris muscle, however, showed a cubic pattern for MMG amplitude that was characterized

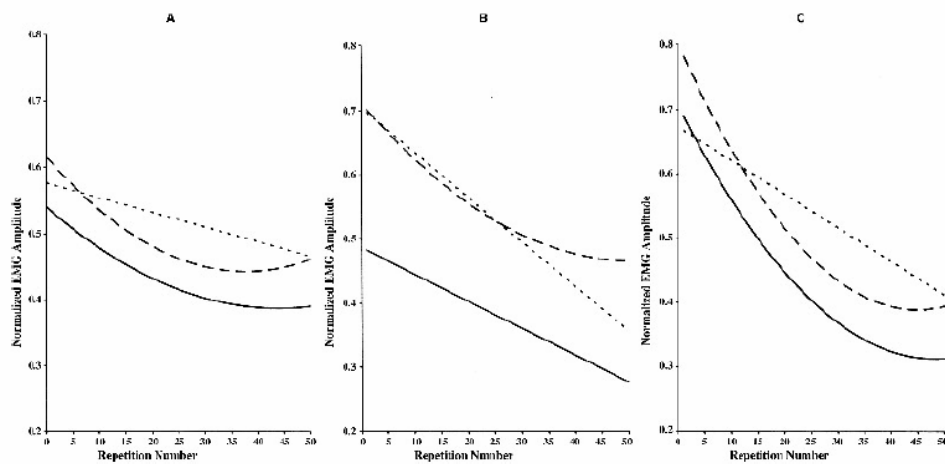


Figure 4. Changes in mechanomyographic (MMG) amplitude for the vastus lateralis (solid line), rectus femoris (dotted line), and vastus medialis (dashed line) during 50 consecutive maximal concentric isokinetic muscle actions of the leg extensors at velocities of 60 (A), 180 (B), and $300^{\circ}\cdot\text{s}^{-1}$ (C). Notice that MMG amplitude decreased at all velocities due to fatigue, but the patterns were different for each muscle. *Reprinted with permission from Perry-Rana et al. (2002).

by a slight increase during repetitions 1-5, a decrease during repetitions 5-20, and another increase during repetitions 20-25. In addition, the pattern for eccentric isokinetic peak torque was best fit with a cubic model, where peak torque increased during the first 10 repetitions, and then remained relatively stable from repetitions 11-25. Thus, it was suggested that the decreases in MMG amplitude for each muscle may have been due to the effects of muscle wisdom and/or reduced muscle compliance. Furthermore, the muscle-specific differences in the MMG amplitude patterns could have been due to differences among the three muscles for fiber type composition and/or architecture (Perry-Rana et al. 2003).

Several studies have also examined the MMG amplitude and/or center frequency responses during incremental or constant power output cycle ergometry. For example, Stout et al. (1997) reported that during an incremental cycle ergometer test, both MMG amplitude for the vastus lateralis and VO_2 increased linearly with power output. Furthermore, 20 of the 24 subjects that participated in the study showed linear slope coefficients for the normalized MMG amplitude and VO_2 versus power output relationships that were statistically equivalent. Thus, it was concluded that MMG may be useful for quantifying muscular activity and monitoring changes in exercise intensity during incremental cycle ergometry. In addition, the similar slope coefficients for the normalized MMG amplitude and VO_2 versus power output relationships for most subjects suggested that there may be a close relationship

between the metabolic and mechanical aspects of muscle activity during cycle ergometry (Stout et al. 1997). Interestingly, Shinohara et al. (1997) also found that MMG amplitude for the vastus lateralis increased linearly with power output during incremental cycle ergometry. In fact, MMG amplitude was more linearly related to power output than was EMG amplitude, which tended to increase curvilinearly at high power outputs (Shinohara et al. 1997). Perry et al. (2001b) reported similar results for the vastus lateralis during incremental cycle ergometry. In particular, the majority of the subjects that were tested (7 out of 9) showed linear increases in MMG amplitude with power output, but EMG amplitude increased curvilinearly. The authors also found that the linear slope coefficients for the increases in normalized heart rate and ratings of perceived exertion were statistically equivalent to that for the normalized MMG amplitude versus power output relationship. Thus, it was concluded that during incremental cycle ergometry, there may be close relationships among the mechanical (MMG), heart rate, and perception of effort aspects of muscle activity (Perry et al. 2001b). In addition, the results from a second study (Perry et al. 2001c) showed that there was no change in MMG MPF for the vastus lateralis, but a linear increase in MMG amplitude with increases in power output during an incremental cycle ergometer test that was performed to exhaustion. Thus, it was concluded that during incremental cycle ergometry, motor unit recruitment may be the primary mechanism for increasing power output, rather than changes in motor unit firing rates (Perry et al. 2001c).

Previous studies have also examined the MMG amplitude responses during continuous cycle ergometer workouts performed at constant, submaximal power outputs. Specifically, Housh et al. (2000) investigated the patterns of responses for MMG amplitude for the vastus lateralis and vastus medialis during continuous, constant power output workouts at 50, 65, 80, and 95% of the peak power achieved during an incremental cycle ergometer test performed to exhaustion. Interestingly, the MMG amplitude responses were dependent on the power output at which the workout was performed, as well as the muscle that was examined. For example, MMG amplitude for the vastus lateralis and vastus medialis muscles decreased during the workouts at 50% and 65% of the peak power, but remained stable at 80% of the peak power. At 95% of the peak power, however, MMG amplitude increased for the vastus medialis muscle, but remained relatively stable for the vastus lateralis. Thus, it was suggested that the decreases in MMG amplitude for both muscles at 50% and 65% of the peak power may have been due to fatigue-induced decreases in motor unit firing rates. At 80% of the peak power, however, the lack of a significant change in MMG amplitude for either the vastus lateralis or vastus medialis may have been due to a balance between the influences of recruitment, which can increase MMG amplitude, and decreases in motor unit

firing rates, which can decrease MMG amplitude. Furthermore, the increases in MMG amplitude for the vastus medialis muscle at 95% of the peak power indicated that recruitment may have had a greater influence on MMG amplitude than potential fatigue-induced decreases in motor unit firing rates. In contrast, the vastus lateralis showed no change in MMG amplitude at 95% of the peak power, and it was suggested that the tendonous iliotibial band that covers the vastus lateralis could have affected the muscle fiber oscillations that were being transmitted to the skin surface, thereby influencing MMG amplitude (Housh et al. 2000). Perry et al. (2001a) also examined the MMG amplitude responses from the vastus lateralis muscle during continuous, constant power output cycle ergometry. The results showed that MMG amplitude decreased during the continuous workouts at 28%, 35%, and 42% of the peak power output. Thus, these results were consistent with those of Housh et al. (2000) for the vastus lateralis and vastus medialis muscles at 50% and 65% of the peak power output, and it was suggested that the decreases in MMG amplitude may have been due to the effects of muscle wisdom and/or reductions in muscle compliance (Perry et al. 2001a). Bull et al. (2000) investigated the MMG amplitude responses for the vastus lateralis muscle during continuous cycle ergometry at a submaximal workload known as critical power. Theoretically, critical power is the maximal power output that can be accomplished without fatigue, and, therefore, should be characterized by steady state VO_2 and no change in muscle activation. Thus, MMG amplitude should also remain stable at critical power. Bull et al. (2000), however, reported that there was a quadratic decrease in MMG amplitude for the vastus lateralis during a 60-minute cycle ergometer workout at critical power. It is important to note that critical power is often a fatiguing workload, and it is possible that the fatigue-related factors, such as muscle wisdom and/or reduced muscle compliance could have contributed to the decreases in MMG amplitude reported by Bull et al. (2000) for the vastus lateralis muscle.

Several studies have also investigated the possibility of using MMG to examine the neuromuscular adaptations that occur during a resistance training program. For example, Cerquiglini et al. (1973) investigated the effects of two months of DCER strength training on MMG frequency in two sedentary subjects and two Olympic weightlifters. The subjects were tested weekly for maximum isometric strength in two “typical lifting positions” while MMG signals were detected from the vastus lateralis and the medial head of the gastrocnemius. The results showed that the resistance training program caused a “...relative increase of higher frequencies (above 70 Hz)” in the MMG signals from the vastus lateralis and gastrocnemius muscles. Thus, it was suggested that the frequency content of the MMG signal could potentially be

used by trainers and/or athletes to monitor the changes in muscle function that occur during a resistance training program (Cerquiglini et al. 1973). Evetovich et al. (1998, 2000) also examined the effects of resistance training on MMG amplitude and MPF. Specifically, the subjects were randomly assigned into either a training or a control group. The subjects in the training group performed maximal concentric isokinetic leg extensions of the non-dominant limb at a velocity of $90^{\circ}\cdot\text{s}^{-1}$ three times per week for twelve weeks. The subjects in both the training and control groups were tested for maximal concentric isokinetic leg extension peak torque at a velocity of $90^{\circ}\cdot\text{s}^{-1}$ prior to the training program and every four weeks thereafter, while MMG signals were detected from the vastus lateralis. The results showed that there was a significant increase in leg extension peak torque following the training for the training group, but not for the control group. There were, however, no changes in MMG amplitude or MPF for the vastus lateralis muscle from week 0 to week 12 for either group. Thus, it was hypothesized that the lack of significant changes in MMG amplitude and MPF for the vastus lateralis muscle following training could have been due to compression of hypertrophied fibers by the iliotibial band and/or training-induced adaptations in muscles other than the vastus lateralis (Evetovich et al. 1998, 2000). Esposito et al. (2005) examined the effects of a dynamic resistance training program on the MMG amplitude and MPF versus isometric torque relationships for the vastus lateralis muscle in elderly men. Specifically, the training program required the subjects to perform maximal concentric isokinetic muscle actions of the dominant leg extensors at velocities of 120 and $240^{\circ}\cdot\text{s}^{-1}$. This training was performed twice per week for twelve weeks. The results showed that the training program had no effect on the MMG amplitude values for the vastus lateralis at any of the relative torque levels (20, 40, 60, 80, and 100% MVC). At 80% and 100% MVC, however, the training program caused significant increases in MMG MPF. In addition, the MMG power density spectrum for the vastus lateralis during an isometric MVC before training was unimodal, with a well-defined peak at about 11 Hz. After training, however, the MMG power density spectrum became bimodal, with a large peak at approximately 15 Hz and a smaller peak at about 30 Hz.

Thus, it was concluded that the training-induced increases in MMG MPF for the vastus lateralis at 80% and 100% MVC, combined with the changes in the shape of the MMG power density spectrum, reflected a “retrieval” of fast-twitch motor units, which can be lost in some muscles during the aging process (Esposito et al. 2005). Coburn et al. (2006) recently examined the effects of three days of velocity-specific isokinetic training on the MMG amplitude and MPF values from the rectus femoris, vastus lateralis, and vastus medialis muscles. Specifically, the subjects were randomly assigned to one of three

groups: a) a control group, b) a slow velocity training group, or c) a fast velocity training group. The subjects in the two training groups performed three separate training sessions that consisted of maximal concentric isokinetic muscle actions of the nondominant leg extensors at a velocity of 30 (slow velocity training group) or $270^{\circ}\cdot\text{s}^{-1}$ (fast velocity training group). In addition, the subjects in the training groups were tested for maximal concentric isokinetic leg extension peak torque at velocities of 30, 150, and $270^{\circ}\cdot\text{s}^{-1}$ prior to, and following the training program. The subjects in the control group were also tested for leg extension peak torque at the same velocities, but did not perform any training. The results showed that there were training-induced increases in leg extension peak torque for the fast velocity training group at $270^{\circ}\cdot\text{s}^{-1}$ and for the slow velocity training group at 30, 150, and $270^{\circ}\cdot\text{s}^{-1}$. In addition, when compared to the control group, there were training-induced increases in MMG amplitude (averaged across the vastus lateralis, rectus femoris, and vastus medialis) for the fast velocity training group at $270^{\circ}\cdot\text{s}^{-1}$ and for the slow velocity training group at $150^{\circ}\cdot\text{s}^{-1}$. The isokinetic leg extension training had no effect, however, on the mean MMG MPF values for any of the muscles at any velocity. Thus, it was concluded that the training-induced increases in MMG amplitude may have been due to reduced muscle compliance. Specifically, it is possible that reduced coactivation in the biceps femoris, semitendinosus, and semimembranosus following the isokinetic training could have increased the net leg extension peak torque and reduced compliance in the quadriceps femoris muscles, thereby increasing MMG amplitude (Coburn et al. 2006).

Several recent studies have also examined the acute effects of stretching on MMG amplitude and/or MPF. For example, Evetovich et al. (2003) investigated the acute effects of static stretching of the forearm flexors on isokinetic peak torque, MMG amplitude, and EMG amplitude during maximal concentric isokinetic muscle actions of the forearm flexors at velocities of 30 and $270^{\circ}\cdot\text{s}^{-1}$. The results showed that the stretching caused a significant decrease in forearm flexion peak torque and increases in MMG amplitude for the biceps brachii muscle at both velocities. The stretching had no effect, however, on the EMG amplitude values for the biceps brachii muscle at either velocity. Thus, it was concluded that the stretching-induced decreases in forearm flexion peak torque and increases in MMG amplitude for the biceps brachii may have been due to reduced muscle stiffness (Evetovich et al. 2003). Cramer et al. (2005) examined the acute effects of static stretching of the dominant leg extensors on peak torque, mean power output, MMG amplitude, and EMG amplitude during maximal concentric isokinetic leg extensions at velocities of 60 and $240^{\circ}\cdot\text{s}^{-1}$. The results showed that the stretching caused

decreases in peak torque for the stretched limb at 60 and $240^\circ\cdot s^{-1}$, as well as for the unstretched limb at $60^\circ\cdot s^{-1}$. There were also stretching-induced decreases in EMG amplitude for the rectus femoris and vastus lateralis muscles of both the stretched and unstretched limbs at 60 and $240^\circ\cdot s^{-1}$. The stretching had no effect, however, on mean power output and MMG amplitude for the rectus femoris or vastus lateralis muscles for either limb at 60 and $240^\circ\cdot s^{-1}$. Thus, it was hypothesized that the decreases in leg extension peak torque and EMG amplitude following the static stretching may have been due, at least partially, to reduced muscle activation in the rectus femoris and vastus lateralis muscles (Cramer et al. 2005). Marek et al. (2005) examined the acute effects of static and proprioceptive neuromuscular facilitation (PNF) stretching on peak torque, mean power output, EMG amplitude, and MMG amplitude during maximal concentric isokinetic leg extensions at velocities of 60 and $300^\circ\cdot s^{-1}$. The results showed that both static and PNF stretching caused decreases in PT, mean power output, and EMG amplitude for the rectus femoris and vastus lateralis muscles at 60 and $300^\circ\cdot s^{-1}$. There was also an increase in MMG amplitude following the static stretching, but only for the rectus femoris muscle at $60^\circ\cdot s^{-1}$. Thus, it was concluded that the stretching-induced decreases in peak torque, mean power output, and EMG amplitude for the rectus femoris and vastus lateralis may have been due to a combination of reduced muscle activation and decreases in muscle stiffness (Marek et al. 2005).

Several studies have also used dynamic muscle actions to test the effects of different interventions on the MMG signal. For example, Bajaj et al. (2002) examined the MMG amplitude responses for the first dorsal interosseus during a series of concentric, isometric, and eccentric muscle actions. For each series of muscle actions, the subjects performed a single abduction movement (concentric muscle action), followed immediately by a 2-sec isometric muscle action of the first dorsal interosseus with the index finger in the fully abducted position, and then a single adduction movement of the index finger (eccentric muscle action). These muscle actions were performed at four different relative torque levels (0, 25, 50, 75, and 100% of the isometric MVC) prior to, immediately following, and 24 and 48 hours after a series of maximal eccentric muscle actions of the first dorsal interosseus. The purpose of the eccentric muscle actions was to elicit muscle damage and cause delayed-onset muscle soreness. The results showed that the mean MMG amplitude values (averaged across the type of muscle action and percentage of the MVC) immediately after the eccentric muscle actions were greater than the values recorded before exercise and following 24 and 48 hours of rest. Thus, it was hypothesized that the increase in MMG amplitude immediately after the eccentric exercise could have been due to greater physiological tremor and/or increased edema in the muscle fibers of the first dorsal interosseus. The

authors also reported increased subjective pain ratings immediately after the eccentric exercise. Thus, it was suggested that the eccentric exercise may have allowed for greater muscle fiber vibrations that resulted in activation of “mechanosensitive deep tissue nociceptors”. Activation of these receptors could then have contributed to the increased pain sensations felt immediately after the eccentric exercise (Bajaj et al. 2002). Petitjean et al. (1992) used MMG to examine “phonomechanical delay” (i.e., the time interval between the onsets of the MMG and acceleration signals) in the biceps brachii and brachioradialis during submaximal concentric DCER muscle actions of the forearm flexors performed against a 3-kg weight. The concentric muscle actions required the subjects to accelerate the weight at slow ($20\text{-}120\text{ radians}\cdot\text{s}^{-2}$), intermediate ($120\text{-}240\text{ radians}\cdot\text{s}^{-2}$), and fast ($240\text{-}360\text{ radians}\cdot\text{s}^{-2}$) angular velocities. The results showed that the phonomechanical delay for the biceps brachii and brachioradialis muscles increased with acceleration, and it was hypothesized that the onsets of the MMG signals may have reflected the development of tension in the contractile components of the muscles. Thus, it was hypothesized that phonomechanical delay could potentially reflect the contributions of fast versus slow-twitch muscle fibers to dynamic torque production (Petitjean et al. 1992).

In addition, Vedsted et al. (2006) recently investigated the MMG amplitude responses for the biceps brachii during concentric, isometric, and eccentric DCER muscle actions of the forearm flexors at 10% and 20% of the isometric MVC. Muscle tissue oxygenation levels were also measured from the biceps brachii to provide information regarding the energy requirements of each type of muscle action. The results showed that the mean MMG amplitude values for the biceps brachii were greater during the concentric and eccentric muscle actions than during the isometric muscle actions. There were no differences, however, among the concentric, isometric, and eccentric muscle actions for muscle tissue oxygenation levels. Thus, it was suggested that during the concentric and eccentric muscle actions, low motor unit firing rates in the biceps brachii could have resulted in less fusion of motor unit twitches and a “...more distinct mechanical twitching...” that allowed larger muscle fiber oscillations and greater MMG amplitude values. For the isometric muscle actions, however, high motor unit firing rates could have resulted in greater fusion of motor unit twitches and reduced MMG amplitude values. Therefore, it was concluded that selective recruitment of superficially located fast-twitch motor units, particularly during the eccentric muscle actions, could have allowed the active motor units to “...influence more directly the MMG generation process”, thereby resulting in greater MMG amplitude values (Vedsted et al. 2006). Evetovich et al. (2002, 2004) recently examined the

effects of dehydration and hyperhydration on concentric isokinetic forearm flexion peak torque, MMG amplitude, and MMG MPF for the biceps brachii muscle. Isokinetic peak torque was assessed at a velocity of $90^{\circ}\cdot\text{s}^{-1}$, and dehydration was achieved through restriction of water intake. The subjects were considered dehydrated if there was a change in body weight of more than 2.0%, and the urine specific gravity was greater than 1.020. In addition, hyperhydration was achieved through injection of glycerol, which causes fluid retention in all water compartments of the body. The results showed that neither dehydration nor hyperhydration had any effect on isokinetic peak torque, MMG amplitude, or MMG MPF. Thus, it was concluded that the MMG signal may be influenced more by motor control strategies and the intrinsic contractile properties of muscle than by the fluids that surround muscle fibers (Evetovich et al. 2002, 2004).

Ebersole and Malek (2008) recently used MMG to examine changes in electromechanical efficiency during fatiguing dynamic muscle actions. The subjects were required to perform 75 consecutive maximal concentric isokinetic muscle actions of the leg extensors at a velocity of $180^{\circ}\cdot\text{s}^{-1}$. During each muscle action, surface EMG and MMG signals were detected from the vastus lateralis and vastus medialis, and the ratio of MMG amplitude/EMG amplitude was calculated for both muscles as a measure of electromechanical efficiency. The results showed that the ratio of MMG amplitude/EMG amplitude decreased in a quadratic fashion for the vastus medialis, while the corresponding pattern for the vastus lateralis was best fit with a cubic model.

Thus, the authors performed a log transformation of the MMG amplitude/EMG amplitude ratio data, which forced the patterns of responses during the fatiguing task to be linear. Even after the log transformation, however, the linear slope coefficients for the MMG amplitude/EMG amplitude ratio were the same for the vastus lateralis and vastus medialis. Thus, it was suggested that the decreases in the MMG amplitude / EMG amplitude ratios for the vastus lateralis and vastus medialis were due to fatigue of fast-twitch muscle fibers and their subsequent inability to produce oscillations and contribute to torque production with fatigue. It was also hypothesized, however, that the MMG and EMG responses could have reflected changes in motor control strategies due to fatigue. Regardless of the exact mechanism, these results suggested that the MMG amplitude / EMG amplitude ratio may be capable of discriminating between healthy and injured muscle in individuals that suffer from atrophy or some type of dysfunction of the vastus lateralis or vastus medialis that could potentially cause patellofemoral pain (Ebersole and Malek 2008).

Kawczyński et al. (2007) recently investigated the effects of eccentric exercise on MMG and EMG amplitude for the trapezius muscle. Specifically,

the subjects were required to perform shoulder elevation muscle actions (both dynamic and isometric) prior to, and immediately following a bout of eccentric muscle actions that was designed to induce delayed-onset muscle soreness. The concentric and isometric muscle actions were repeated 24 and 48 hours after the eccentric exercise. The results showed that MMG amplitude was higher immediately after the eccentric exercise when compared with the corresponding values before exercise, as well as 24 and 48 hours after exercise. There were no changes, however, in the mean MMG MPF, EMG amplitude, or EMG MPF values after the eccentric exercise. Thus, it was suggested that the eccentric exercise likely changed the viscoelastic properties of the trapezius muscle, thereby allowing greater muscle fiber oscillations and increases in MMG amplitude (Kawczyński et al. 2007). Hendrix et al. (2008) performed an interesting study to examine the effects of pedaling cadence and power output on the MMG amplitude and MPF responses for the vastus lateralis during submaximal cycle ergometry. The subjects were required to perform an incremental cycle ergometer test to exhaustion, as well as continuous, 8-minute rides at power outputs that corresponded to 35%, 50%, and 65% of the peak power output achieved during the incremental test to exhaustion. In addition, during each 8-minute ride at a constant power output, the subjects pedaled at either 50 or 70 revolutions per minute during the first 4 minutes, and then switched to the alternate cadence during the second 4 minutes. The results showed that MMG amplitude was closely related to power output, but not pedaling cadence, and MMG MPF was not affected by power output or pedaling cadence. Thus, it was concluded that during cycle ergometry, MMG amplitude is not affected by pedaling cadence, but is greatly influenced by the changes in muscle activity that must accompany increases in power output (Hendrix et al. 2007).

Cramer et al. (2007c) recently examined the effects of three days of resistance training with or without creatine supplementation on isokinetic leg extension peak torque, mean power output, and EMG and MMG amplitude and median frequency. The subjects were required to perform maximal concentric isokinetic muscle actions of the leg extensors at velocities of 30, 150, and $270^{\circ}\cdot\text{s}^{-1}$ prior to, and following three days of resistance training (three sets of ten maximal muscle actions at a velocity of $150^{\circ}\cdot\text{s}^{-1}$). The resistance training was performed with either creatine supplementation or a placebo. The results showed that the creatine supplementation had no effect on isokinetic peak torque, mean power output, or any of the EMG and MMG parameters. There were, however, significant increases in isokinetic peak torque, as well as EMG and MMG median frequency for both the creatine and placebo groups, but these changes were not consistent at all velocities. Thus, it was concluded

that creatine supplementation combined with a short-term resistance training program had no effect on EMG and MMG amplitude and median frequency (Cramer et al. 2007c). A recent study by Cramer et al. (2007a) also examined the acute effects of static stretching on the isokinetic angle-torque relationship, as well as surface EMG and MMG amplitude values. The subjects were required to perform maximal concentric isokinetic muscle actions of the leg extensors at velocities of 1.04 and 5.23 radians per second prior to, and immediately following static stretching of the leg extensors. During all muscle actions, surface EMG and MMG signals were detected from the rectus femoris muscle. The results showed that stretching caused a decrease in isokinetic peak torque, acceleration time, and EMG amplitude, but there were no changes in work, the joint angle at peak torque, or MMG amplitude. Thus, it was concluded that the stretching-induced changes in peak torque and acceleration time were not consistently reflected in the corresponding EMG and MMG signals (Cramer et al. 2007a). This study was followed up by a second investigation (Cramer et al. 2007b) that examined the acute effects of static stretching of the leg extensors on maximal eccentric isokinetic peak torque (60 and $180^{\circ}\cdot\text{s}^{-1}$ velocities), the joint angle at peak torque, mean power output, and MMG and EMG amplitude and MPF for the vastus lateralis and rectus femoris. The results showed that the stretching had no effect on peak torque, the joint angle at peak torque, mean power output, or EMG and MMG amplitude and MPF. Thus, it was concluded that static stretching did not affect maximal eccentric PT and mean power output, nor did it have any effect on muscle activation levels during eccentric muscle actions (Cramer et al. 2007b). Rana (2006) recently investigated the MMG and EMG amplitude responses for the vastus lateralis, rectus femoris, and vastus medialis during the Wingate Test (i.e., 30 seconds of maximal cycling). The results showed that although there were decreases in power output over the 30-second test, there was no change in EMG amplitude. The MMG amplitude values for each muscle, however, decreased during the test, with the rectus femoris showing the greatest decrease. Thus, it was concluded that MMG may provide more useful information regarding fatigue-related changes in the mechanical properties of muscle than EMG, and could be reflective of changes in power output for each muscle. Therefore, the results from this study provided yet another indication that during dynamic muscle actions, MMG amplitude is closely related to muscle power output (Rana 2006).

Kimura et al. (2008) examined the MMG amplitude responses for the vastus lateralis and rectus femoris during incremental cycle ergometry. The subjects were required to perform an incremental cycle test in which the power output started at 20 Watts and was increased by 30 Watts every minute until the subject could no longer continue. The results showed that MMG amplitude

for both the vastus lateralis and rectus femoris increased nonlinearly with workload. In addition, the onset of the ventilatory threshold corresponded with abrupt changes in the MMG signals for both muscles, as MMG amplitude began to plateau for the vastus lateralis, but increased rapidly for the rectus femoris. Thus, it was concluded that MMG may reflect the fatigue-related changes in the muscle's mechanical properties that occur with fatigue at the ventilatory threshold. In addition, since electret condenser microphones were used to detect the MMG signals from the rectus femoris and vastus lateralis, these sensors may be more appropriate than accelerometers when recording MMG signals during dynamic muscle actions (Kimura et al. 2008).

The results from the studies that were reviewed in this chapter indicated that MMG provides valuable information regarding muscle activity during dynamic muscle actions. A particularly interesting relationship is that between MMG amplitude and muscle power output. Given that many training programs are designed to increase power output, rather than just strength, it is possible that MMG may be useful for monitoring the training status of individual muscles or muscle groups. Certainly, more work needs to be done before this application can be used on a widespread basis, but it is suggested that future work in the area of dynamic MMG should focus on identifying the mechanisms underlying the relationship between MMG amplitude and muscle power output.

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