Transworld Research Network
37/661 (2), Fort P.O., Trivandrum-695 023, Kerala, India

Applications of Mechanomyography for Examining Muscle Function, 2010, 37-51
ISBN : 978-81-7895-449-3 Editor: Travis W. Beck

3

Surface mechanomyographic responses to muscle fatigue

Travis W. Beck
Biophysics Laboratory, Department of Health and Exercise Science, University of Oklahoma, Norman, Oklahoma 73019-6081, USA

Abstract

Many studies have examined the mechanomyographic (MMG) amplitude and/or center frequency [mean power frequency (MPF) or median frequency] responses during fatiguing isometric muscle actions. An important common finding from these investigations is that the MMG responses are always dependent on the relative force level that is being examined, as well as the time duration of the muscle action that is being performed. There is also evidence to suggest that the muscle being examined and its corresponding fiber type composition can affect the MMG responses to fatigue. Simultaneous

---

Correspondence/Reprint request: Dr. Travis W. Beck, Biophysics Laboratory, Department of Health and Exercise Science, University of Oklahoma, 1401 Asp Avenue, Norman, Oklahoma, 73019-6081, USA
E-mail: tbeck@ou.edu

detection of MMG and surface electromyographic (EMG) signals has been used to examine the dissociation between the electrical and mechanical aspects of fatigue, as well as the motor control strategies used by various muscles to maintain isometric force production. There is still a great deal of work that needs to be done, however, to determine the mechanisms underlying the MMG amplitude and center frequency responses during various types of fatiguing isometric muscle actions. Future research should focus on the possible clinical applications of these patterns, and if they can be used in orthopaedic and/or rehabilitative settings.

Introduction

A great deal of research has been performed to examine the behavior of the mechanomyographic (MMG) signal during fatiguing isometric muscle actions. The first study to directly investigate the MMG amplitude responses during muscle fatigue was performed by Barry et al. (1985). Specifically, the experimental protocol required the subjects to perform a sustained isometric muscle action of the forearm flexors at 75% of the maximum voluntary contraction (MVC). Once the 75% MVC force level could no longer be maintained, the subjects were required to continue the muscle action until their force production had decreased to 35% of the original MVC. The surface MMG signal was detected from the biceps brachii throughout the entire duration of the sustained muscle action. The results showed that MMG amplitude was highly correlated with force production (i.e., MMG amplitude remained stable at the beginning of the muscle action, and then decreased after the 75% MVC force level could not be maintained). In addition, even small increases in force production during the sustained muscle action produced large bursts of activity in the MMG signal. Thus, it was suggested that MMG amplitude may be a more sensitive indicator of changes in force when fatigue develops rapidly than electromyographic (EMG) amplitude, which does not always follow force production during fatiguing activities (Barry et al. 1985). The investigation by Barry et al. (1985) was followed up with a very important study by Orizio et al. (1989), which examined the changes in MMG amplitude for the biceps brachii during sustained isometric muscle actions of the forearm flexors at 20%, 40%, 60%, and 80% MVC. Each muscle action was performed to exhaustion, and a surface EMG signal was detected from the biceps brachii simultaneously with the MMG signal. The results indicated that during the sustained muscle action at 20% MVC, MMG amplitude increased linearly across time, and it was hypothesized that this response was due to motor unit recruitment, increases in firing rates, and synchronization of firing times as the motor units that were recruited at the beginning of the muscle action became fatigued. At 40% MVC, however, MMG amplitude fluctuated around a steady value from the beginning of the muscle action up to exhaustion. It was suggested that at this force level, the information contained in the MMG signal regarding motor control strategies may be masked by changes in the muscle environment due to loss of perfusion. During the sustained muscle actions at 60% and 80% MVC, however, MMG amplitude decreased curvilinearly across time, and it was suggested that at these force levels, lengthening of the muscle fiber relaxation time could have resulted in fusion of motor unit twitches and a subsequent decrease in MMG amplitude (Figure 1).

It was also hypothesized, however, that high levels of muscle stiffness and intramuscular fluid pressure could have affected MMG amplitude at these force levels. In contrast, the results for EMG amplitude showed increases across time at all force levels. Thus, it was concluded that the MMG signal may provide more information than EMG regarding the motor control strategies used during fatiguing isometric muscle actions (Orizio et al. 1989). This study was followed up by a second investigation (Orizio et al. 1992) that used the same experimental protocol, but examined the MMG and EMG mean power frequency (MPF) responses for the biceps brachii. The results showed that

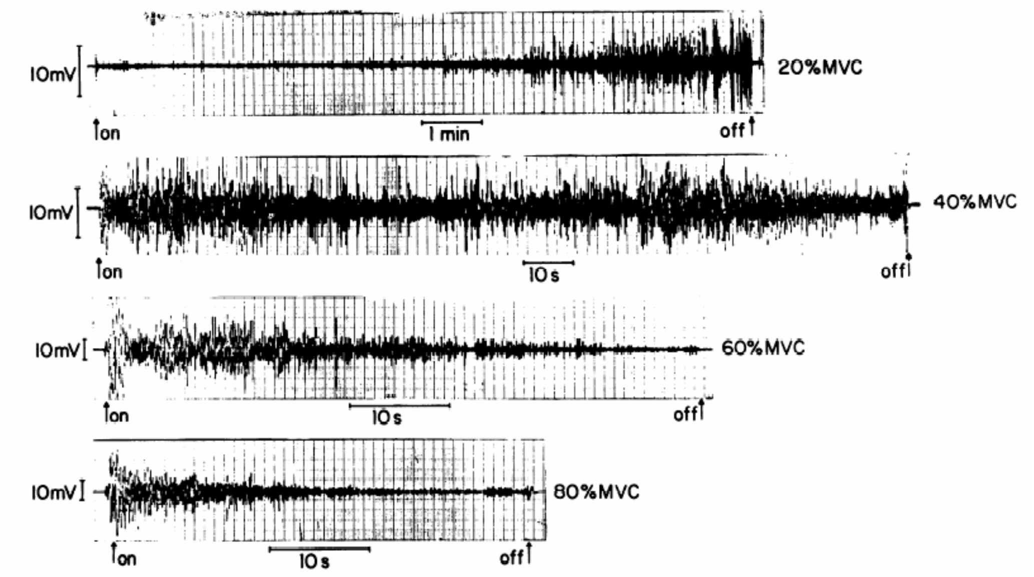

Figure 1. Mechanomyographic (MMG) signals from the biceps brachii of one subject during sustained isometric muscle actions of the forearm flexors to exhaustion at 20%, 40%, 60%, and 80% MVC. The appropriate time and amplitude scales are shown for each signal. Notice that at 20% MVC, MMG amplitude increased over time, but it remained relatively stable at 40% MVC. In addition, MMG amplitude decreased over time during the sustained muscle actions at 60% and 80% MVC. *Reprinted with permission from Orizio et al. (1989).

during the sustained muscle action at 80% MVC, MMG MPF increased during the first 30% of the muscle action and then decreased for the remainder. It was hypothesized that this response was due to initial increases in motor unit firing rates, followed by decreases due to increases in muscle fiber relaxation time that provided proprioceptive feedback to the central nervous system (i.e., muscle wisdom). During the sustained muscle action at 20% MVC, however, MMG MPF increased slightly during the first 30% of the muscle action and then remained relatively stable for the remainder. It was suggested that this response likely reflected relatively stable motor unit firing rates throughout the contraction. During the sustained muscle actions at 40% and 60% MVC, however, the MMG MPF responses were about halfway between those at 20% and 80% MVC. Specifically, at 40% MVC, MMG MPF increased slightly during the first 10% of the muscle action and then decreased slowly. At 60% MVC, however, MMG MPF remained relatively stable during the first 40% of the muscle action, and then decreased slowly. Thus, it was hypothesized that at these force levels, the MMG MPF responses reflected recruitment of new motor units with high firing rates, followed by no change in the average motor unit firing rate throughout the remainder of the muscle action. In addition, during all four sustained muscle actions, EMG MPF decreased throughout the duration of the contraction. Thus, the authors (Orizio et al. 1992) suggested that when combined with EMG, MMG may be useful for investigating the neural and peripheral mechanisms underlying muscle fatigue. These studies (Orizio et al. 1989, 1992) were followed up by Goldenberg et al. (1991), who examined the changes in MMG amplitude for the abductor digiti minimi during isometric muscle actions sustained to exhaustion at 15%, 25%, 50%, and 75% MVC. The results showed that during the sustained muscle action at 75% MVC, MMG amplitude remained relatively stable, but at 50% MVC, MMG amplitude decreased throughout the contraction. In addition, during the sustained muscle actions at 15% and 25% MVC, MMG amplitude increased over time. Thus, it was suggested that the increases in MMG amplitude during the sustained muscle actions at 15% and 25% MVC may have reflected recruitment of new motor units to maintain the required force level. In turn, the decrease in MMG amplitude during the sustained muscle action at 50% MVC may have been due to fatigue of fast-twitch motor units and increases in firing rates that resulted in fusion of motor unit twitches. In addition, the lack of a significant change in MMG amplitude during the sustained muscle action at 75% MVC could have been due to the relatively short duration of the muscle action and the inability of the slow-twitch fibers to maintain the required force as the larger fast-twitch fibers became fatigued. Thus, it was suggested (Goldenberg et al. 1992) that during a fatiguing isometric muscle action, MMG amplitude may be much more dependent on fiber type composition and motor control strategies than on absolute force production. Mealing et al. (1990) also conducted a very interesting study that examined changes in the shape of the MMG power spectrum for the rectus femoris during a sustained isometric muscle action of the leg extensors at 80% MVC. The authors (Mealing et al. 1990) reported that during the fatiguing muscle action, the MMG power spectrum tended to cycle between wide and narrow bandwidths, and it was hypothesized that this cycling may have been due to rotation of activity between different fiber types. Stokes and Dalton (1991) also used an interesting approach to examine the effects of muscle fatigue on the MMG signal. Specifically, the subjects in their study were required to perform sustained isometric muscle actions of the leg extensors at 10%, 25%, 50%, 60%, 75%, and 100% MVC while MMG and EMG signals were detected from the rectus femoris. When all muscle actions had been completed, the subjects performed a fatiguing protocol of repeated voluntary contractions (10-s on, 10-s off) at 75% MVC until only 40% of the original MVC could be produced. The subjects were then allowed to rest for 15 minutes, and the separate muscle actions at 10%, 25%, 50%, 60%, 75%, and 100% MVC were performed again. The results showed that before and after the fatiguing protocol, the MMG and EMG amplitude versus force relationships were linear. After the fatiguing protocol, however, the linear slope of the EMG amplitude versus force relationship increased, while that for the MMG amplitude versus force relationship remained the same. Thus, it was hypothesized that MMG may be a more useful method for assessing force production in the fatigued state than EMG (Stokes and Dalton 1991).

Like Mealing et al. (1990), Herzog et al. (1994) examined the influence of fatigue on the frequency content of the MMG signal. Specifically, EMG and MMG signals were detected simultaneously from the rectus femoris and vastus lateralis during an isometric muscle action of the leg extensors sustained to exhaustion at 70% MVC. The results indicated that for both the vastus lateralis and rectus femoris, EMG and MMG median frequency decreased during the sustained muscle action. The authors reported, however, that at least part of the decrease in MMG median frequency was due to muscle tremor. Nevertheless, it was suggested that muscle tremor was an important part of the MMG signal during fatigue, and it should not be removed because it originates from the muscle(s) of interest and is a result of the fatigue protocol (Herzog et al. 1994). Vaz et al. (1996) used a similar experimental protocol to examine the influence of fatigue on MMG amplitude and median frequency responses. The experimental protocol required the subjects to perform submaximal isometric muscle actions of the leg extensors at 70% MVC prior to, and 20 seconds, 50 seconds, 2, 3, 4, 5, 6, 7, 8, 9, 10, and 15 minutes after a fatigue test. The fatigue test was an isometric muscle action of the leg extensors at 70% MVC that was sustained until 50% of the original MVC could no longer be achieved. Surface EMG and MMG signals were detected simultaneously from the vastus lateralis and rectus femoris during the muscle actions performed before and after the fatigue test. The results showed that there were differences between the vastus lateralis and rectus femoris for the MMG amplitude responses to the fatigue protocol. Specifically, the rectus femoris showed a decrease in MMG amplitude during the fatigue protocol, but returned to baseline values fairly quickly during the recovery period. For the vastus lateralis, however, MMG amplitude increased significantly when the target force could no longer be maintained, and then it remained constant during the recovery period. The authors (Vaz et al. 1996) suggested that muscle tremor had an important influence on the MMG signal during fatiguing activities, and changes in the signal were independent of those in the EMG signal. Esposito et al. (1998) also examined the MMG and EMG time and frequency domain responses during fatiguing isometric muscle actions. Specifically, the subjects were required to perform a submaximal isometric muscle action of the forearm flexors at 80% MVC until the required force level could no longer be maintained. The subjects then rested for 10 minutes and performed repeated (6-s on, 4-s off) isometric muscle actions of the forearm flexors at 50% MVC. The subjects then rested for 9-min, followed by performance of an MVC. Immediately after the MVC, the subjects performed a second sustained isometric muscle action to exhaustion at 80% MVC. The results showed that during both sustained muscle actions at 80% MVC, EMG amplitude increased over time for the first 10 seconds and then remained relatively stable, while EMG MPF decreased continuously over time. The findings for MMG amplitude, however, showed that during the first fatiguing muscle action, MMG amplitude decreased during the first 7 seconds and then remained stable. For the second sustained muscle action, however, MMG amplitude remained relatively stable over time. In addition, the results for MMG MPF showed that during the first fatiguing muscle action, MMG MPF increased over time for the first 5 seconds and then decreased over time. During the second fatiguing muscle action, however, MMG MPF decreased throughout the entire muscle action. Thus, it was suggested that the effects of fatigue on the muscle may be more accurately reflected in the MMG signal than the EMG signal (Esposito et al. 1998).

Kouzaki et al. (1999) used a slightly different experimental design to examine the effects of muscle fatigue on the amplitude and frequency contents of the MMG and EMG signals. Specifically, the subjects were required to perform 50 consecutive maximal isometric muscle actions of the leg extensors (3-s on, 3-s off), and MMG and EMG signals were detected from the vastus lateralis, rectus femoris, and vastus medialis. The results showed that the average isometric leg extension MVC decreased 49.5% from the beginning to the end of the fatigue test. In addition, both EMG amplitude and EMG median frequency decreased curvilinearly at a similar rate for each muscle during the fatigue test. The results for MMG amplitude also showed curvilinear decreases over time for each muscle, although the rate at which it decreased was much greater for the rectus femoris than the vastus lateralis and vastus medialis. In addition, MMG median frequency decreased curvilinearly during the fatigue test for all three muscles. The initial value and the rate at which MMG median frequency decreased were much greater, however, for the rectus femoris than the vastus lateralis and vastus medialis. Thus, these findings were important from a practical standpoint because they indicated that both MMG amplitude and MMG median frequency were sensitive to differences in the fatigue characteristics of muscles that have a common innervation (i.e., the femoral nerve) but differ in architecture and, possibly, fiber type composition (Kouzaki et al. 1999).

Yoshitake et al. (2001) used a slightly different approach to examine the effects of fatigue on the MMG signal. Specifically, the authors recorded EMG and MMG signals simultaneously during a 60-second sustained isometric muscle action of the erector spinae as the subject supported their own body weight. Near-infrared spectroscopy was also used to assess muscle blood volume and tissue oxygenation levels. The results showed that EMG MPF decreased linearly throughout the fatigue test, while EMG amplitude increased during the first 36 seconds and then plateaued. In contrast, there was no change in MMG MPF during the test, and MMG amplitude increased during the first 20 seconds, and then decreased thereafter. Thus, it was hypothesized (Yoshitake et al. 2001) that restriction of blood flow due to high intramuscular mechanical pressure may be one of the most important factors underlying lumbar muscle fatigue and the subsequent lower back pain. In addition, MMG may be a useful method for examining the neural and mechanical aspects of muscle fatigue (Yoshitake et al. 2001).

Another very interesting study was performed by Søgaard et al. (2003) to determine if the MMG and EMG signals were sensitive to changes in muscle function induced by long term fatigue. In particular, the experimental protocol required the subjects to perform an isometric MVC of the forearm flexors, followed by separate muscle actions at 5% and 80% MVC. The subjects then performed intermittent isometric muscle actions at 30% MVC (6-s on, 4-s off) for a time period of 30 minutes to induce fatigue. Following the fatigue protocol, the subjects performed isometric MVCs to measure strength 10 minutes and 30 minutes after the fatiguing protocol. The subjects also performed submaximal isometric muscle actions at 80% of the new MVC and 5% of the pre-fatigue MVC. The results showed that even after 30 minutes of recovery, the isometric MVC was reduced by as much as 16%, and the MMG and EMG amplitude values were greater during the post-fatigue 5% MVC contraction than at the same force level before the fatiguing protocol. Thus, it was hypothesized (Søgaard et al. 2003) that MMG and EMG may be sensitive to subtle changes that occur in the muscle during long term fatigue. Another very important study was recently performed by Madeleine et al. (2006), who examined changes in the amplitude of the MMG signal, as well as the MPF, variance, and skewness of the MMG power spectrum for the biceps brachii during a 3-minute sustained isometric muscle action of the forearm flexors at 30% MVC. The results showed that MMG amplitude increased during the first 135 seconds of the muscle action and then plateaued. In contrast, MMG MPF and the skewness of the power spectrum decreased across time. The variance of the power spectrum, however, showed a complex behavior, where it decreased during the first 90 seconds of the muscle action, increased for the next 60 seconds, and then decreased for the remainder of the contraction. Thus, it was suggested that the fatigue-induced changes in the shape of the MMG power spectrum cannot be described exclusively by measures of center frequency (e.g., MPF or median frequency).Instead, the spectrum shows complex changes in bandwidth (i.e., variance) and skewness that are important when describing the effects of fatigue on the muscle being investigated. It is important to point out that these results were from an accelerometer, and a condenser microphone provided different patterns for all of the variables examined. Nevertheless, the findings from this study clearly indicated that the effects of fatigue on the MMG signal cannot be fully described by examining a single amplitude and/or center frequency parameter (Madeleine et al. 2006).

Previous studies have also used joint time-frequency signal processing techniques to examine the effects of muscle fatigue on the frequency content of the MMG signal. Itoh et al. (2004) used the short-time Fourier transform to investigate the changes in MMG MPF for the biceps brachii during sustained isometric muscle actions of the forearm flexors at 20% and 80% MVC. During both muscle actions, the subjects were required to continue contracting until their force production had dropped to 50% of the target force. The results showed that during the sustained muscle action at 20% MVC, MMG amplitude increased curvilinearly over time, while MMG MPF increased for the first 30% of the total contraction time, remained stable from 30% to 70% of the total contraction time, and decreased throughout the remainder of the muscle action. During the sustained muscle action at 80% MVC, however, MMG amplitude decreased curvilinearly over time, and MMG MPF increased for the first 30% of the total contraction time and then decreased thereafter (Figure 2). Thus, it was suggested that both the amplitude and frequency contents of the MMG signal are useful when examining the neural and mechanical aspects of muscle fatigue (Itoh et al. 2004).

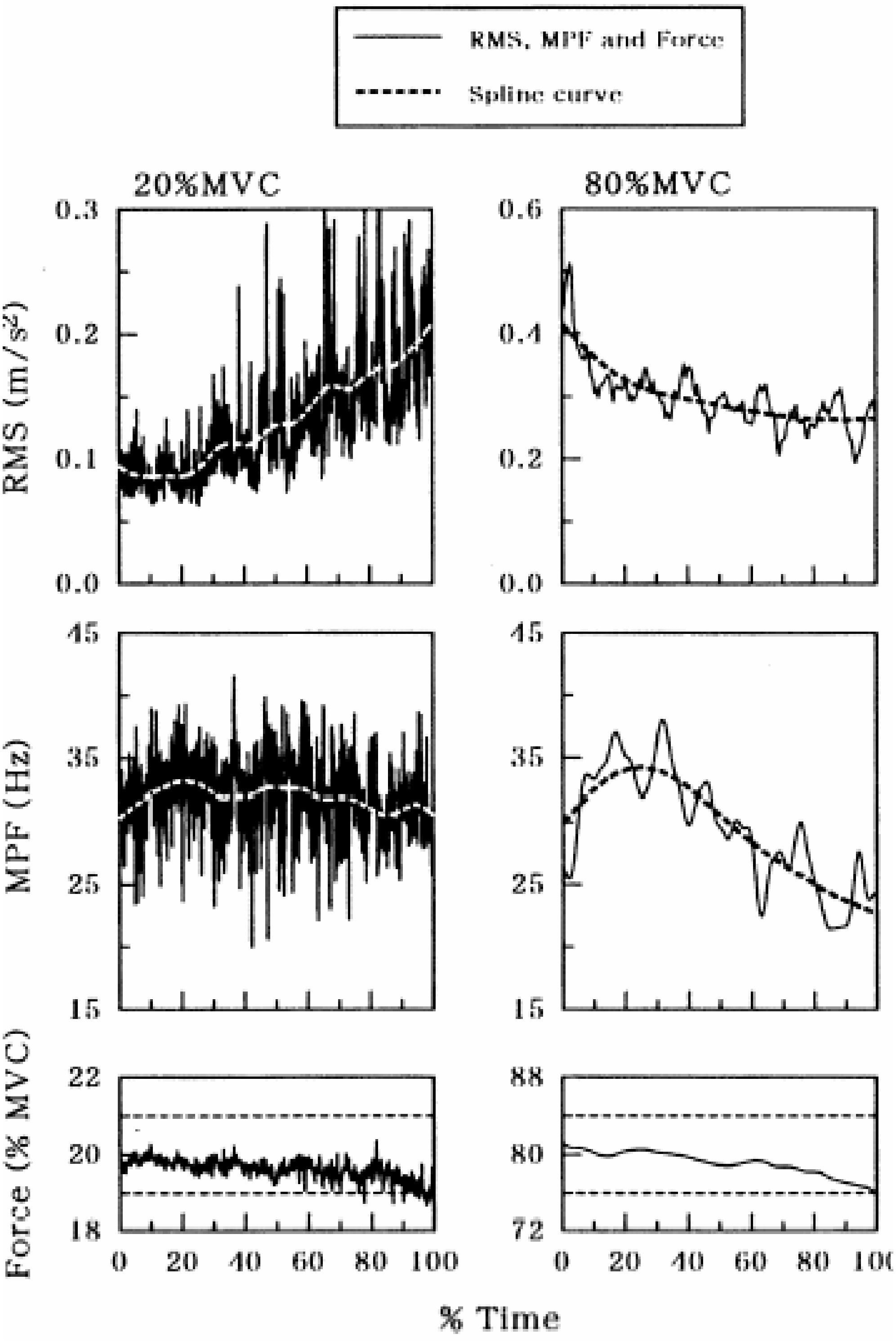

Figure 2. Mechanomyographic (MMG) amplitude and mean power frequency (MPF) for the biceps brachii during submaximal isometric muscle actions of the forearm flexors that were sustained to exhaustion at 20% and 80% MVC. The relative force signals are shown in the bottom graphs. Notice the differences in the patterns of responses between the 20% and 80% MVC muscle actions for both MMG amplitude and MPF. *Reprinted with permission from Itoh et al. (2004).

Weir et al. (2000) examined the influence of differences in muscle length on the MMG and EMG amplitude and MPF responses for the tibialis anterior during a 60-s sustained isometric muscle action of the dorsiflexors at 50% MVC. The results showed that at the long muscle length (when the foot was in 40° of plantar flexion), the rate at which MMG and EMG amplitude increased over time was greater than at the short muscle length (when the foot was in 5° of dorsiflexion). There were no differences, however, between the long and short muscle lengths for the changes in EMG and MMG MPF over time. Thus, it was hypothesized that the amplitudes of the MMG and EMG signals may be useful for examining the rate of motor unit recruitment during a fatiguing task at a submaximal force level. In addition, the rate of motor unit recruitment may be greater during a fatiguing muscle action at a long muscle length when compared to a short muscle length (Weir et al. 2000). Madeleine et al. (2002) also used an interesting experimental design to examine the effects of muscle fatigue on the MMG signal. Specifically, the subjects were required to perform sustained isometric muscle actions of the forearm flexors at 10% and 30% MVC in continuous or intermittent static format and with either visual or proprioceptive feedback.The results indicated that when the subjects were provided with proprioceptive feedback, the rate at which MMG and EMG amplitude increased over time was greater than when the subjects were given visual feedback. Thus, it was suggested that the combined use of MMG and EMG was helpful for identifying differences between the fatigue characteristics of visual versus proprioceptive feedback modes (Madeleine et al. 2002). In addition, Tarata (2003) used simultaneous recording of MMG and EMG signals to examine muscle fatigue for the biceps brachii and brachioradialis during an isometric muscle action of the forearm flexors sustained to exhaustion at 25% MVC. The results indicated that both MMG and EMG amplitude increased throughout the duration of the muscle action, while MMG and EMG MPF decreased (Figure 3). Thus, it was concluded that simultaneous examination of the MMG and EMG amplitude and MPF responses is useful for describing the neural and mechanical aspects of task-specific muscle fatigue (Tarata 2003).

In addition, Blangsted et al. (2005) used simultaneous detection of MMG and EMG signals to examine low-frequency fatigue. Specifically, the experimental protocol required the subjects to perform a 10-minute sustained isometric muscle action of the wrist extensors at 10% MVC to induce fatigue. Prior to this fatiguing activity, the subjects went through an electrical stimulation procedure (a 10-s train at 1 Hz, two 2.5-s trains at 20 Hz, and two2-s trains at 100 Hz), in addition to performing an isometric MVC, and separate 20-s muscle actions at 5% and 80% MVC. The same electrical stimulation protocol and series of voluntary muscle actions were performed 10,

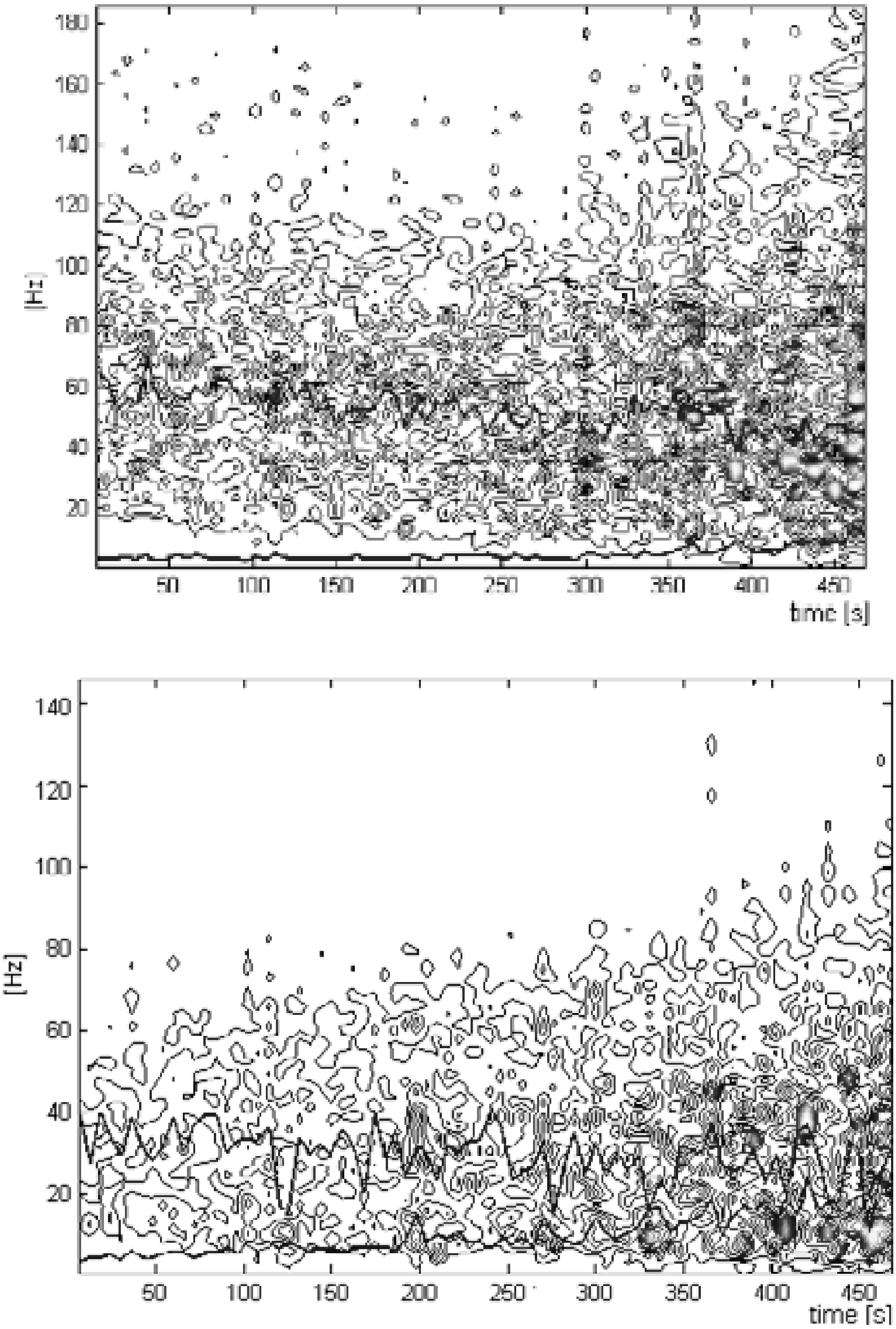

Figure 3. Contour plot of changes in electromyographic (EMG; top plot) and mechanomyographic (MMG; bottom plot) amplitude and frequency for the biceps brachii during a 450-second sustained muscle action of the forearm flexors at 25% of the isometric maximum voluntary contraction (MVC). Changes in the density of the contour plot reflect changes in MMG amplitude. *Reprinted with permission from Tarata (2003).

30, 90, and 150 minutes after the fatiguing muscle action. The results showed that during both the 5% and 80% MVC muscle actions, the mean MMG amplitude values 30 minutes after fatigue were greater than those before fatigue. In addition, the MMG/EMG amplitude ratio (used as a measure of electromechanical efficiency) during the 80% MVC muscle action was elevated even 150 minutes after the fatigue protocol. The authors also reported decreased performance in many of the twitch parameters measured during electrical stimulation, including peak twitch force, time to peak force, maximum rate of force development, the rate of force decay, half-contraction time, half-relaxation time, and the force-time integral following the fatigue protocol. Each of these performance parameters was depressed 10, 30, 90, and 150 minutes after the fatigue protocol. Thus, it was concluded that MMG may be a useful technique for studying the mechanical aspects of low frequency fatigue. In addition, the combination of MMG and EMG could potentially be used to assess fatigue that develops over extended time periods, such as that associated with low back pain and fatigue that develops during a work day (Blangsted et al. 2005). A second study by Blangsted et al. (2005) used a similar experimental design to examine the potential relationships between changes in EMG and MMG amplitude and MPF during a sustained muscle action and the intramuscular pressure and tissue oxygenation levels. Specifically, the subjects were required to perform a 10-minute sustained isometric muscle action of the forearm flexors at 10% MVC, and MMG and EMG signals were detected simultaneously from the biceps brachii. The results indicated that MMG amplitude increased over time during the sustained muscle action, but there was no change in EMG amplitude, and both MMG MPF and EMG MPF decreased. There was also a significant increase in the MMG amplitude/EMG amplitude ratio. Furthermore, all subjects were required to perform an isometric muscle action at 5% MVC before, as well as 10 and 30 minutes after the fatiguing muscle action. The results from these muscle actions showed that during the 5% MVC muscle action 10 and 30 minutes after fatigue, MMG amplitude was higher, and MMG MPF lower than before fatigue. In addition, EMG amplitude was elevated 30 minutes after fatigue, and EMG MPF was depressed 10 minutes after fatigue. Interestingly, however, the changes in tissue oxygenation and intramuscular pressure could not explain the corresponding patterns for MMG and EMG amplitude and MPF. In particular, the tissue oxygenation level returned to the resting level very quickly after fatigue, and intramuscular pressure did not change during the fatiguing muscle action. Thus, it was concluded that the combined use of MMG and EMG may be sensitive to fatigue-induced changes in skeletal muscle function that are not reflected in the tissue oxygenation and intramuscular pressure levels (Blangsted et al. 2005).

Orizio et al. (1999) also used a unique approach to examine the effects of electrically-stimulated fatigue on several measures of twitch mechanics and MMG parameters. Specifically, the experimental protocol required the subjects to go through an electrical stimulation procedure that involved six single twitches separated by a 1-second time interval, followed by a 5-second period of repetitive stimulation where the frequency was increased by 1 Hz between one stimulation and the next in the range from 1-50 Hz. A fatigue protocol was then performed where the muscle was stimulated at 35 Hz for 40 seconds. The contractile properties of the muscle were then tested in the same manner as before the fatiguing stimulation. The results indicated that the fatiguing protocol reduced several of the twitch parameters, including the force peak, the peak rate of force production, the peak of the acceleration of force production, as well as increased contraction time and half-relaxation time. In addition, the peak-to-peak amplitude of the MMG signal decreased immediately after the fatiguing protocol, but returned to pre-fatigue levels within two minutes of recovery. Furthermore, MMG amplitude was highly correlated with the peak of the acceleration of force production during recovery. Thus, it was suggested that MMG may be a useful tool for examining changes in muscle mechanics due to fatigue, particularly when the force output of the muscle cannot be measured directly (Orizio et al. 1999). Al-Zahrani et al. (in press) examined the reliability of MMG amplitude, MPF, and median frequency during a fatiguing isometric muscle action. Specifically, the subjects were required to perform three separate 40-second sustained isometric muscle actions of the leg extensors at 75% MVC. The same experimental protocol was also followed on two more testing occasions that were separated by at least 48 hours. The results of the study generally indicated that the linear slope coefficients for the changes in MMG amplitude, MMG MPF, and MMG median frequency across time were not reliable, but the overall amplitude, MPF and median frequency values were. Thus, it was suggested that caution should be used when interpreting the linear slope coefficients for MMG amplitude, MMG MPF, and MMG median frequency during a fatiguing isometric muscle action (Al-Zahrani et al. in press).

Overall, the results from the studies that have examined the MMG amplitude and/or center frequency responses during fatiguing isometric muscle actions have shown that the behavior of the MMG signal is largely dependent on the duration and relative intensity of the sustained muscle actions. It is also dependent, however, on the muscle being examined and the experimental protocol that is used. It is important to point out that this variability likely reflects the sensitivity of the MMG signal to the demands of the fatiguing task. Thus, the MMG amplitude and center frequency responses during fatigue reflect the interaction between the motor control strategies that are being used to maintain performance during the activity and the mechanical properties of the muscle.

References

1. Al-Zahrani E, Gunascharan C, Callaghan M, Gaydecki P, Benitez D, Oldham J. Within-day and between-days reliability of quadriceps isometric muscle fatigue using mechanomyography on healthy subjects. Journal of Electromyography and Kinesiology (In Press).
2. Barry DT, Geiringer SR, Ball RD. Acoustic myography: A noninvasive monitor of motor unit fatigue. Muscle & Nerve 1985;8:189-194.
3. Blangsted AK, Sjøgaard G, Madeleine P, Olsen HB, Søgaard K. Voluntary low-force contraction elicits prolonged low-frequency fatigue and changes in surface electromyography and mechanomyography. Journal of Electromyography and Kinesiology 2005;15:138-148.
4. Blangsted SK, Vedsted P, Sjøgaard G, Søgaard K. Intramuscular pressure and tissue oxygenation during low-force static contraction do not underlie muscle fatigue. Acta Physiologica Scandinavica 2005;183:379-388.
5. Esposito F, Orizio C, Veicsteinas A. Electromyogram and mechanomyogram changes in fresh and fatigued muscle during sustained contraction in men. European Journal of Applied Physiology 1998;78:494-501.
6. Goldenberg MS, Yack HJ, Cerny FJ, Burton HW. Acoustic myography as an indicator of force during sustained contractions of a small hand muscle. Journal of Applied Physiology 1991;70:87-91.
7. Herzog W, Zhang Y-T, Vaz MA, Guimaraes ACS, Janssen C. Assessment of muscular fatigue using vibromyography. Muscle & Nerve 1994;17:1156-1161.
8. Itoh Y, Akataki K, Mita K, Watakabe M, Itoh K. Time-frequency analysis of mechanomyogram during sustained contractions with muscle fatigue. Systems and Computers In Japan 2004;35:26-36.
9. Kouzaki M, Shinohara M, Fukunaga T. Non-uniform mechanical activity of quadriceps muscle during fatigue by repeated maximal voluntary contraction in humans. European Journal of Applied Physiology 1999; 80:9-15.
10. Madeleine P, Ge H-Y, Jaskólska A, Farina D, Jaskólski A, Arendt-Nielsen L. Spectral moments of mechanomyographic signals recorded with accelerometer and microphone during sustained fatiguing contractions. Medical & Biological Engineering and Computing 2006;44:290-297.
11. Madeleine P, Jørgensen LV, Søgaard K, Arendt-Nielsen L, Sjøgaard G. Development of muscle fatigue as assessed by electromyography and mechanomyography during continuous and intermittent low-force contractions: effects of the feedback mode. European Journal of Applied Physiology 2002;87:28-37.
12. Mealing D, McBride JW, Khan AZ. Frequency domain analysis of muscle sound during fatigue of human quadriceps. Proceeding of the Annual International Conference of the IEEE Engineering In Medicine and Biology Society, 1990; 12:2215-2216.

13. Orizio C, Diemont B, Esposito F, Alfonsi E, Parrinello G, Moglia A, Veicsteinas A. Surface mechanomyogram reflects the changes in the mechanical properties of muscle at fatigue. European Journal of Applied Physiology 1999;80:276-284.
14. Orizio C, Perini R, Diemont B, Veicsteinas A. Muscle sound and electromyogram spectrum analysis during exhausting contractions in man. European Journal of Applied Physiology 1992;65:1-7.
15. Orizio C, Perini R, Veicsteinas A. Changes of muscular sound during sustained isometric contraction up to exhaustion. Journal of Applied Physiology 1989;66:1593-1598.
16. Søgaard K, Blangsted AK, Jørgensen LV, Madeleine P, Sjøgaard G. Evidence of long term muscle fatigue following prolonged intermittent contractions based on mechano- and electromyograms. Journal of Electromyography and Kinesiology 2003;13:441-450.
17. Stokes MJ, Dalton PA. Acoustic myography for investigating human skeletal muscle fatigue. Journal of Applied Physiology 1991;71:1422-1426.
18. Tarata MT. Mechanomyography versus Electromyography, in monitoring the muscular fatigue. BioMedical Engineering OnLine 2003;2:1-10.
19. Vaz MA, Zhang Y-T, Herzog W, Guimaraes ACS, MacIntosh BR. The behavior of rectus femoris and vastus lateralis during fatigue and recovery: an electromyographic and vibromyographic study. Electromyography and Clinical Neurophysiology 1996;36:221-230.
20. Weir JP, Ayers KM, Lacefield JF, Walsh KL. Mechanomyographic and electromyographic responses during fatigue in humans: influence of muscle length. European Journal of Applied Physiology 2000;81:352-359.
21. Yoshitake Y, Ue H, Miyazaki M, Moritani T. Assessment of lower-back muscle fatigue using electromyography, mechanomyography, and near-infrared spectroscopy. European Journal of Applied Physiology 2001;84:174-179.