Sensitivity of 24-h EMG duration and intensity in the human vastus lateralis muscle to threshold changes

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Klein CS, Peterson LB, Ferrell S, Thomas CK. Sensitivity of 24-h EMG duration and intensity in the human vastus lateralis muscle to threshold changes. J Appl Physiol 108: 655–661, 2010. First published December 10, 2009; doi:10.1152/japplphysiol.00757.2009.—Few studies have quantified lower limb muscle activity over 24 h using electromyographic (EMG) signals. None have described the changes in EMG duration and intensity when data are analyzed with different thresholds. Continuous bilateral EMG recordings were made from vastus lateralis (VL) in 10 subjects (20–48 yr) for 24 h. Before and after this recording, voluntary quadriceps forces and VL EMG at 25%, 50%, 75%, and 100% of the maximal voluntary contraction (MVC), percentage voluntary activation (twich interpolation), and compound action potentials (M-waves) were recorded. Offline, the 24-h EMG integrals (IEMG, 10-ms time constant) were normalized to the MVC IEMG. Total EMG duration and mean IEMG ranged from 1–3 h and 3.2–12.1% MVC, respectively, when the data were analyzed using the baseline (+3 SD) as threshold. When analysis was done with progressively higher thresholds, from baseline up to 4% MVC, the total EMG duration declined curvilinearly. In some cases the decline in duration was 50–60% for a 1% MVC threshold increment. The mean 24-h IEMG increased by 1.5–2% MVC as threshold. Therefore, a small change in the threshold used to separate EMG from the electromyogram; long-term electromyogram recording; voluntary activation; electromyogram threshold; maximal voluntary contraction

THE EXTENT to which skeletal muscles are used during everyday living is not well understood. The most direct approach to characterizing daily muscle activity is to record long-term electromyographic (EMG) activity (1, 10, 11, 13, 18, 23, 26). In humans, long-term EMG recordings of upper limb muscles have been made during various occupations to identify risk factors for muscular complaints (24, 26, 34). Howe and Rafferty (15) compared quadriceps EMG activity between patients with knee osteoarthritis and healthy controls, while Jakobi et al. (16) characterized the differences in EMG activity between healthy older adults and one person who had sustained a stroke. Investigators have also compared daily EMG among upper and lower limb muscles in healthy adults and found that the amount of activity can vary widely between muscles and individuals (up to 6-fold) (7, 18, 23, 30).

Although differences in daily EMG activity between individuals or muscles are often attributed to biological and behavioral factors (13, 18, 23), few investigators have comprehensively addressed the role that methodological factors may play. Differences in the threshold used to separate EMG from the baseline, and the maximal EMG used to normalize the data, would be expected to alter the derived EMG duration and intensity. For example, in a study of nocturnal trapezius muscle activity, Mork and Westgaard (25) reported that setting the threshold visually was a more sensitive criterion than the same absolute threshold for all individuals because it captured more EMG activity. Monster and colleagues (23) used a threshold equal to 8% of the 90th percentile of the amplitude distribution in the analysis of daytime EMG recordings of agonist-antagonist muscle pairs. Depending on the activities performed during the recording period, the 90th percentile may reflect widely different contraction intensities across individuals. In most of the recent studies of long-term EMG in the lower limb, a relative threshold (2% of the MVC) was used to analyze the data (16, 18, 30), although a value of 10% has also been employed (15). Some low-level activity may have been unaccounted for in these previous investigations since laboratory experiments have shown that activity below 2% MVC occurs during different phases of gait (5, 6, 8) and postural tasks (27). Activation levels during an MVC are also often <100% (2, 9, 21). Thus both the MVC EMG and derived thresholds (%MVC) are likely to be underestimated. Twitch interpolation (29) has not been used to assess muscle activation during MVCs recorded during studies of long-term EMG. Hence, the relationships between MVC EMG, the threshold for separating EMG from baseline noise, and the duration and intensity of muscle activity derived from 24-h EMG data are not well understood.

The purpose of this study was to quantify vastus lateralis (VL) muscle activity over the course of a typical day in healthy adults by recording EMG continuously for 24 h. The two primary aims were 1) to quantify the total duration of EMG and mean EMG intensity (integrated EMG, IEMG) over 24 h, as well as the individual IEMG-duration profiles; and 2) to determine the percentage change in 24-h EMG duration and mean IEMG that results from analyzing the data with different thresholds.

MATERIALS AND METHODS

Subjects. The subjects were five men and five women, 33 ± 3 yr old (range 21–48 yr old). They were students or employees of the University of Miami. A few participants regularly engaged in recreational exercise, but none of the subjects were highly trained. Informed written consent was obtained from each subject before the experiment, which involved a 24-h EMG recording and laboratory measurements before and after that recording. The Institutional Review Board of the University of Miami approved this study, and the
procedures conformed to the standards set by the Declaration of Helsinki.

**Twenty-four-hour EMG recording.** The skin over the distal portion of the VL was shaved, abraded, and cleansed with alcohol. Self-adhering electrodes (Superior Silver, no. 626SS, Uni-Patch, Wabasha, MN) were trimmed (1 cm × 3 cm) and positioned over the distal third of the muscle bilaterally in a bipolar configuration (4-cm interelectrode distance). Biceps femoris, tibialis anterior, and medial gastrocnemius EMG were also collected bilaterally, but these data are not reported here. A ground electrode (1 cm × 3 cm) was positioned on each of the four muscles bilaterally, 4 cm proximal to the other two electrodes. The electrodes were covered with Hypafix surgical tape. The VL signals were amplified on site (×400; Motion Lab Systems, Baton Rouge, LA), filtered (30 Hz–1 kHz), and sampled continuously at 1 kHz for 24 h to a 1-GB flashcard in a microcontroller-based, digital data-logger. This device was custom made, battery powered, and portable (32). During the 24-h recording, the device was usually carried in a hip pack worn about the subject’s waist. However, during sleep and some periods of stationary work the pack was placed beside the subject. The participants wore compression stockings for the 24-h period to secure all electrodes and cables. They reported that this recording set-up did not encumber them or restrict their daily activities. M-waves recorded before and after the 24-h recordings were similar (Fig. 1C), which suggests an absence of fatigue.

**Pre-post 24-h measurements.** Subjects sat on a custom-designed padded plinth with the trunk stabilized with a hip strap. The angle between the trunk and thigh was ~100° and the knee was flexed to 100°, placing the quadriceps under stretch (0° = full extension). A padded strap was placed around the shin just proximal to the ankle joint. A cable connected this strap to a force transducer (no. 363-B10-200-25P1, Revere Transducers, Tustin, CA) that was secured to the frame of the plinth. The strain gauge was calibrated with known weights and gave a linear response ($R^2 = 0.99$).

To stimulate the femoral nerve, pulses (50-µs duration, model DS7H, Digitimer stimulator, Hertfordshire, UK) were applied over the inguinal crease via a bipolar bar electrode (1-cm discs, 3-cm spacing; ...
Twenty-four-hour EMG. Complete recordings for 24 h were obtained from 9 of 10 subjects. In one participant the final 4 awake hours were not recorded due to a battery failure. EMG duration and mean IEMG for these 4 h were assumed to equal the average awake values recorded in this subject. Based on a brief exit interview and review of an activity log completed during the 24 h, subjects spent most of the day attending lectures or working at a computer station. Some completed work-related tasks standing at a work bench. Subjects walked for brief periods (e.g., to campus buildings or the bus) but did not participate in any sport or fitness training. Over 24 h, subjects were awake for an average of 14.8 ± 0.7 h (range: 11.8–17.2 h) and the sleep period lasted 9.1 ± 0.7 h (6.8–12.2 h). Typical examples of EMG recorded during an awake hour and the relative paucity of EMG present during a sleep hour are shown in Fig. 1B.

Twenty-four-hour EMG duration. The total duration of EMG activity over 24 h (total EMG integration time above baseline threshold) ranged from 1.0 to 3.0 h (mean ± SE: 2.0 ± 0.2 h; n = 10), corresponding to 4.2–12.5% of the day (mean, 8.6 ± 0.9%). The majority of this activity (>99%) occurred during the awake period. Total EMG duration corresponded to 13.3 ± 1.1% of the awake period. EMG activity during the sleep period ranged from 0.2 to 12.5 min or 0.01 to 0.86% of the day (mean, 4.5 ± 1.2 min). The 24-h EMG duration was not significantly different between the five men (1.7 ± 0.25 h) and five women (2.3 ± 0.28 h) (P = 0.13), consistent with results from VL using burst analysis (18).

The baseline noise (i.e., no EMG) was very similar across subjects, averaging 0.055 ± 0.001 μV·s (range, 0.048–0.060) or 5.5 ± 0.1 μV (4.8–6.0). The baseline (±3 SD) threshold was 0.068 ± 0.002 μV·s (range, 0.060–0.080) corresponding to 1.7 ± 0.2% MVC IEMG (range, 0.9–2.6, n = 10). Across subjects, the 24-h duration was not significantly related to the
baseline threshold (µV·s or %MVC), the MVC IEMG (µV·s), or voluntary muscle activation. These findings suggest that the likely source of the variability in 24-h duration is real subject differences in daily physical activity rather than variation in the MVC.

Mean 24-h IEMG. To assess the intensity of EMG activity over 24 h, the IEMG above baseline threshold was divided by the MVC IEMG. The mean IEMG for 24 h ranged from 3.2 to 12.1% MVC (mean, 6.7 ± 1.0%, n = 10). For the awake period, the mean IEMG ranged from 3.2 to 12.2% (mean, 6.9 ± 1.0%). These values were similar to the corresponding data for the sleep period (3.7–10.5%; mean, 6.4 ± 0.8%, P > 0.05). Similar to the study by Kern and colleagues (18), the 24-h mean IEMG was not significantly different between the men (5.6 ± 1.1% MVC) and women (7.8 ± 1.6% MVC) (P = 0.30).

Twenty-four-hour IEMG-duration profile. Individual subject plots of 24-h EMG duration (expressed in minutes and as a percentage of the total EMG duration) vs. IEMG (%MVC) are displayed in Fig. 2. The majority of activity was of low intensity. On average, 66 ± 6% (range: 39–86) of the total EMG duration occurred at 5% MVC IEMG or less (Fig. 2B). The corresponding values at and below 10%, 20%, and 50% MVC IEMG were 84 ± 4% (64–95), 93 ± 2% (85–99), and 99 ± 0.4% (97–100) of the total EMG duration, respectively. On average, 6.2 ± 1.8% (1.0–14) of the total EMG duration, corresponding to a mean duration of 8.9 ± 3.2 min (1.1–23), occurred above 20% MVC IEMG. Only 0.1 ± 0.06% (0.005–0.5) of the total EMG duration, corresponding to a maximum of 1 min, was above 80% MVC IEMG.

Effects of different thresholds on 24-h EMG duration and intensity. The effects of applying different EMG thresholds on 24-h EMG duration and mean IEMG (%MVC) are shown in Fig. 3 for all subjects. With application of progressively higher thresholds, from baseline up to 4% MVC, the derived 24-h EMG duration declined in a curvilinear manner (Fig. 3A). The magnitude of the reduction in EMG duration for a 1% MVC threshold increment varied across subjects. For example, in two subjects the EMG duration was shortened by 95 min (60% less) and 50 min (50% less) when data were processed using a 2% MVC threshold compared with a baseline (%MVC) threshold (Fig. 3A, lowest two traces). In others, EMG duration declined by 20% for a 1% increase in threshold above the baseline threshold (%MVC threshold compared with a baseline (~1% MVC) threshold (Fig. 3A, lowest two traces). In others, EMG duration declined by 20% for a 1% increase in threshold above the baseline threshold (~2.5% MVC, Fig. 3A, two upper most traces). Although the threshold-related drop in relative EMG duration was less in these two subjects, this still reflected a 20- to 30-min reduction in activity. On average, the EMG duration was 13.5% less (range, 6–25%) when the 24-h data were processed with a 4% MVC threshold compared with a 3% MVC threshold (n = 10, P < 0.05). The corresponding data for a 3% vs. a 2% threshold was 17.5% (range, 11–24%, n = 6). The mean IEMG increased by 1.5–2% MVC for each 1% MVC increment in threshold (Fig. 3B). For example, the mean IEMG increased from 10 ± 1.1% MVC to 12 ± 1.2% MVC.

Fig. 2. Duration-intensity relationships. Individual subject plots (n = 9) of 24-h EMG duration in minutes (A), and as a cumulative percentage of the total EMG duration (B), at a given EMG integral (IEMG) (bin width: 1% MVC). In A, the EMG duration for the weakest bin of each subject reflects a threshold that was close to the cutoff for that bin. Data for 1 subject were excluded because the last 4 h of data were not recorded.
when data were processed using thresholds of 3% and 4% MVC (n = 10, P < 0.05), and from 7.8 ± 1.6% MVC to 9.9 ± 1.8% MVC for thresholds of 2% and 3%, respectively (n = 6).

**Voluntary muscle activation.** Mean voluntary activation was 95.2 ± 0.6% (range 91.3–97.9%, n = 10). During MVCs, there was a threefold range in the recorded maximal IEMG across subjects (2.3–8.4 μV-s, mean 4.6 ± 0.7 μV-s). The intersubject differences can be partially attributed to peripheral factors since the MVC IEMG was positively correlated with the maximal M-wave area (R² = 0.74, P = 0.001). Group mean normalized force-activation and force-IEMG relationships are plotted together in Fig. 4.

**Maximal M-waves.** Maximal M-waves evoked from the VL of a subject before and after the 24-h recording are shown in Fig. 1C. The pre- and post-24-h M-wave integrals were similar. For the group, there were no significant differences between the pre- and post-24-h M-wave integrals in either leg. The pre-post ICC for M-wave area was above 0.97 for both legs. The repeatability of the M-waves before and after the 24-h recording provides strong evidence of electrode integrity during the 24-h recording.

**DISCUSSION**

This study demonstrates that the VL was active for a short amount of time and at low intensities during a typical 24-h period. The mean 24-h EMG duration and IEMG were only 2 h and 6.7% MVC, respectively. Less than 1% (or 4.5 min) of the 24-h EMG duration occurred during the sleep period. Furthermore, the mean IEMG during the awake and sleep periods were similar (6.9% MVC and 6.4% MVC, respectively). In all subjects, over 80% of the total EMG duration was below 20% MVC. No more than 4 min of EMG was above 50% MVC and 1 min above 80% MVC. Given that the mean EMG amplitude during gait and static postures is <15% MVC (5, 8, 27), our EMG profiles are a reasonable description of daily muscle activity for people with relatively sedentary life styles.

**Effect of different EMG thresholds on 24-h EMG duration and intensity.** Although it was anticipated that the 24-h EMG duration and IEMG would be sensitive to changes in the threshold, no one has addressed this issue systematically. Our findings demonstrate a curvilinear decline in total EMG duration as the threshold used to analyze the data was progressively increased. In some cases, total EMG duration was 50–60% less when data were analyzed with a higher threshold (i.e., 2% MVC) compared with the lower baseline threshold (i.e., 1% MVC) (Fig. 3A). Hence in these individuals, a large amount of low-intensity activity would be excluded if a 2% MVC threshold was applied to characterize the data. This finding is consistent with an earlier report where visually derived thresholds in each subject captured more EMG activity than the same threshold for all subjects (25). Since previous investigators have used thresholds equal to 2% MVC and greater, a significant amount of lower amplitude activity may not have been accounted for in some of their subjects (15, 16, 18, 24, 30). The mean 24-h IEMG (%MVC) increased linearly with the application of higher thresholds. Thus, for each 1% MVC increment in threshold, the mean 24-h IEMG increased by about 1.5–2% MVC. Our findings reveal that a slight change in threshold of 1–2% MVC leads to a relatively large percentage change in 24-h duration and a moderate change in 24-h IEMG.

Careful consideration should be given to the threshold used since the derived 24-h duration and intensity may impact the physiological and clinical conclusions. For example, chronic electrical stimulation studies reveal that as little as 7.2 min, or 0.5% of 24 h, is sufficient to alter muscle properties (19). This amount of activity is less than the differences in EMG duration associated with a 1% MVC change in threshold in the present study. Ultimately, the type of analysis and thresholds employed will be determined by various factors including the study purpose, recording quality, whether the MVC can be measured, and practical matters such as software capabilities. For example, if the purpose of the study is to characterize daily low-level activity associated with postural work, then it may be prudent to use the lowest possible baseline threshold in each subject rather than a threshold derived from the MVC (25).

A number of human studies have characterized long-term EMG activity as a series of bursts and/or gaps (18, 24, 26). We cannot conclude definitively whether the 24-h EMG duration and intensity and threshold-related effects described here would alter dramatically if the recordings were analyzed using burst analysis. However, daytime EMG amplitude (%MVC) derived using the present approach and burst analysis were compared in the trapezius and three back muscles by Mork and Westgaard (24). At a given threshold (i.e., 2% MVC), they found that the mean burst amplitude was 1–3% MVC higher than the mean amplitude of all of the activity. If the total EMG duration derived from the two approaches is equal, then the pattern of threshold-related changes in EMG is likely to be similar.

**MVC EMG.** The recorded MVC EMG is a critical measurement because changes in the threshold (%MVC) influence both 24-h EMG duration and IEMG. Various approaches have been employed to determine the MVC EMG in studies of long-term EMG. In the case of the quadriceps, some studies did record force (18), but none have employed twitch interpolation (15, 16). In the present study, the percentage activation of the quadriceps averaged 95%. Although the recorded MVC IEMG was probably less than maximal and is likely indicative of suboptimal motor unit recruitment and/or discharge rates (2, 9, 21, 28, 29, 31), the 24-h EMG duration was independent of the absolute or relative baseline threshold, the MVC, and voluntary activation. Thus the range of EMG durations measured in this study.

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**Fig. 4.** Group mean (±SE, n = 10) normalized force-EMG and force-percentage activation relationships.
probably reflects genuine differences in muscle activity across subjects.

**EMG normalization.** The surface EMG reflects neural drive to the muscle (e.g., motor unit recruitment, rate coding, synchronization) and peripheral processes, including electrode location and configuration, and signal cancellation (3). Indeed, in our subjects, the absolute MVC IEMG and M-wave area were significantly related ($R^2 = 0.74$), meaning that those with larger M-wave areas tended to have greater MVC IEMG.

Usually, the EMG signal is normalized to minimize variation induced by the electrode site and to allow data from different subjects (muscles) to be more accurately compared (4). Options for reference EMG values include a specific percentile, peak, or mean value associated with locomotor activity (23), or a value obtained during an isometric or dynamic MVC or submaximal contraction (4, 18, 35). Some may question the validity of normalizing daily EMG activity to an isometric contraction as done here rather than a dynamic contraction. However, it can be argued that isometric contractions occur frequently during the day for postural maintenance and during dynamic tasks such as climbing stairs. Furthermore, some have concluded that normalizing data to a dynamic (isokinetic) MVC rather than an isometric MVC does not reduce intra- or interindividual variability in gait EMG, or provide a more representative measure of muscle activation (4).

In the present study, the 24-h EMG was normalized to the mean of the highest 20 consecutive integrals (i.e., a 200-ms period) recorded during the MVC. This approach to normalization is similar to previous studies of daily quadriceps EMG activity, where the peak MVC EMG recorded over 100 ms was defined as the maximal value (15, 16, 18). However, a higher MVC EMG can be employed by using shorter segments and/or defining the maximal value in a different way. For example, when the MVC IEMG was defined as the top 10% of integrals over 2 s of the MVC (i.e., twenty 10-ms integrals that were not necessarily consecutive), the MVC IEMG was 1.5 times (or 50%) greater compared with the value based on 20 consecutive integrals. Assuming that the top 10% of integrals is less attenuated from signal cancellation than consecutive integrals over a longer time (17), the former may be closer to the true MVC EMG during maximal efforts.

**Comparison to workday EMG.** Daytime recordings have been made from lower limb muscles including the VL (15, 18, 23, 30). Various thresholds were used to analyze the data, including 8% of the 90th percentile of the amplitude distribution derived from the recording (23) or 10% MVC (15). A few investigators analyzed the EMG activity as a series of bursts, in which a burst was defined as EMG greater than 2% MVC (16, 18, 30). Indeed, in our subjects, the absolute MVC IEMG and M-wave area were significantly related ($R^2 = 0.74$), meaning that those with larger M-wave areas tended to have greater MVC IEMG.

### References


24-h EMG FROM VASTUS LATERALIS


