Analysis of sEMG amplitude temporal change during low-intensity sustained muscle contraction

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Abstract

Context: Surface electromyography (sEMG) is widely used to evaluate muscle fatigue; however, conventional amplitude- and frequency-based parameters may be insensitive to early changes during low-intensity sustained contractions.

Aims: This study aimed to characterize temporal changes in motor unit recruitment during low-intensity sustained isometric elbow flexion using conventional and higher-order sEMG analyses, with a focus on identifying how early fatigue-related changes can be detected for clinical assessment.

Settings and Design: An experimental laboratory study was conducted with healthy young adults performing sustained isometric elbow flexion at a submaximal load until task failure.

Methods and Material: Seventeen healthy adults performed sustained isometric elbow flexion at 25% of maximum voluntary isometric contraction until task failure. sEMG signals from the biceps brachii were divided into 11 equal intervals. Average amplitude, median frequency, zero-crossing rate, mean turn amplitude, kurtosis, skewness, and amplitude probability distribution function (APDF) across normalized amplitude bands were calculated.

Statistical analysis used: Temporal changes were assessed using repeated-measures ANOVA followed by Dunnett's post hoc tests ($\alpha = 0.05$).

Results: Mean endurance time was 680.3 ± 180.5 s. Average amplitude increased from the 40% interval, whereas median frequency, zero-crossing rate, and turn amplitude decreased from the 90% interval. APDF showed early reductions in low-amplitude bands (0-5% peak) and progressive increases in higher bands from the 10% interval.

Conclusions: These findings suggest that recruitment-related adjustments begin early during sustained low-intensity contraction. APDF detected such changes earlier than conventional parameters, indicating its utility for identifying early fatigue-related alterations.

Key-words: muscle fatigue, sustained low-intensity contraction, surface electromyography

Key Messages: Detailed analysis of the sEMG waveform revealed an early redistribution of amplitude from low- to higher-amplitude components that was not apparent in conventional amplitude- and frequency-based measures, indicating that conventional EMG fatigue parameters do not adequately capture early fatigue-related changes during sustained contractions.

Introduction

Surface electromyography (sEMG) is a convenient, noninvasive method for detecting muscle action potentials using electrodes placed on the skin surface. These action potentials are visualized as electromyographic waveforms and provide information about motor unit recruitment through various parameters. Typical parameters include mean amplitude, peak amplitude, integrated EMG, and spectral measures such as mean or median frequency. The integrated EMG value has been reported to reflect the number of active motor units, because it depends on the amplitude, duration, and frequency of action potentials.[1-3] Other parameters, such as zero-crossing rate[4] and turn amplitude[5-7], are selected according to the specific aims of the analysis.

In addition to these conventional parameters, several alternative approaches have been proposed to capture more detailed features of the sEMG waveform. One such method, Amplitude probability distribution function (APDF) analysis[8] evaluates muscle activity based on the probability distribution of sEMG amplitude and has been reported to reflect muscular load and function.[9, 10] Furthermore, in recently years, higher-order statistical measures[11], such as kurtosis and skewness, have been used to characterize the shape of the sEMG amplitude distribution and have shown potential in motion and fatigue analysis.[12-14] These newer parameters may provide additional information about motor unit firing characteristics that is not fully captured by simple amplitude or frequency parameters.

Many studies on muscle fatigue have traditionally used frequency in addition to the mean amplitude value. During moderate to high-intensity exertion, fatigue is often accompanied by two well-known electrophysiological phenomena: increase in amplitude reflecting motor unit recruitment and decrease in the median frequency. However, during low-intensity sustained contractions, only a small number of motor units are recruited to generate the required force, and these units can recover between activation intervals. As a result, force production is sustained for a long time, and conventional parameters based on amplitude and frequency reveal only subtle or delayed changes. This makes it difficult to detect temporal changes in motor unit recruitment under such conditions. Given these limitations, it is necessary to re-examine the characteristics of sEMG parameters observed during low-intensity, sustained isometric muscle contractions. Therefore, in this study, not only conventional fatigue-related parameters (mean amplitude, median frequency, zero-crossing rate, turn amplitude) but also higher-order statistical indicators (kurtosis and skewness) and temporal changes in amplitude distribution were calculated from surface electromyography waveforms during low-intensity sustained isometric elbow flexion. This reveals the characteristics of the temporal changes in each parameter, enabling the elucidation of the characteristics of motor unit recruitment regulation occurring during sustained contraction.

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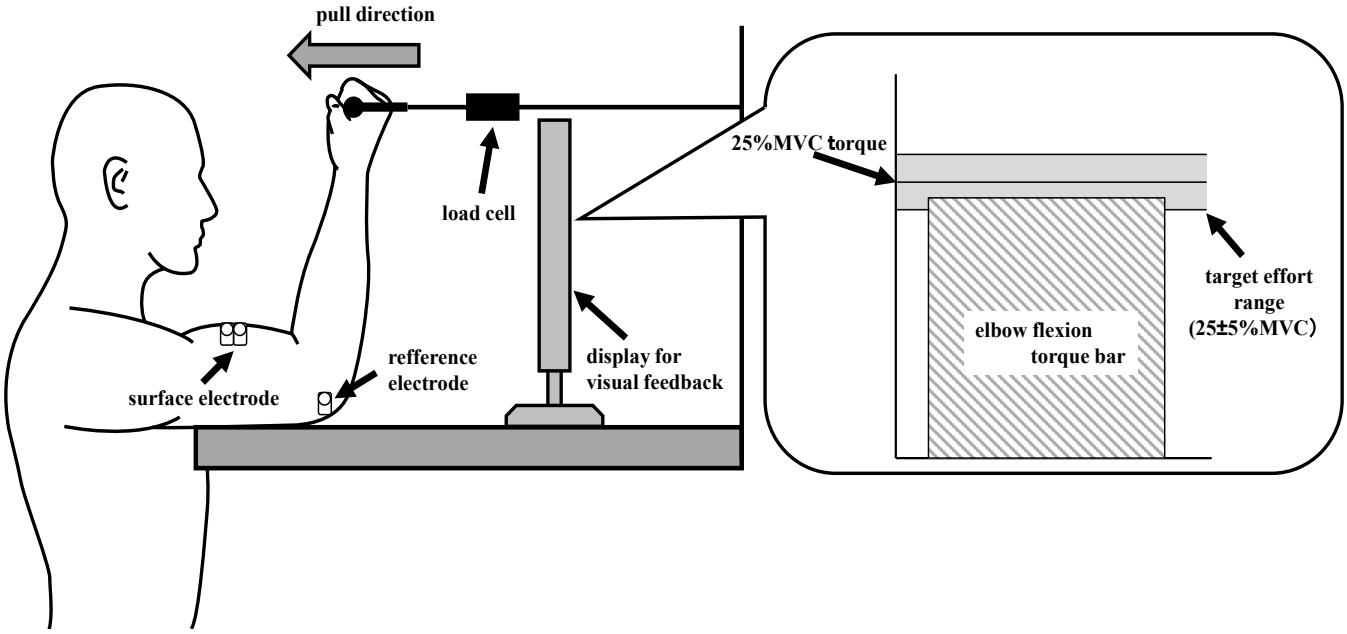
Figure 1: Experimental setting.
The participants sat in a chair, gripped a handle, and performed isometric elbow flexion with visual feedback of their force output.



Given these limitations, there is a need to re-examine motor unit recruitment regulation during low-intensity, sustained contractions using a broader set of sEMG parameters. Therefore, in this study, not only conventional fatigue-related parameters (mean amplitude, median frequency, zero-crossing rate, turn amplitude rate) but also higher-order statistical parameters (kurtosis and skewness) and temporal changes in amplitude distribution derived from sEMG waveforms during low-intensity sustained isometric elbow flexion were analyzed. By performing a detailed, time-resolved analysis of these parameters over the entire duration of the task, the aim of this study was to elucidate changes in motor unit recruitment regulation during sustained low-intensity isometric elbow flexion and to clarify how early such changes can be detected in the sEMG waveform. Such knowledge may serve as a basis for designing strengthening programs that minimize excessive load in individuals with muscle weakness and help reduce the risk of overuse.

Participants and Methods

Participant

This study involved 17 healthy young adults (seven females and ten males). The characteristics of the participants are shown in Table 1. Individuals with functional impairments of the dominant arm due to previous injury or disease were excluded. All participants received oral and written explanations of the study procedures and provided written informed consent before participation.

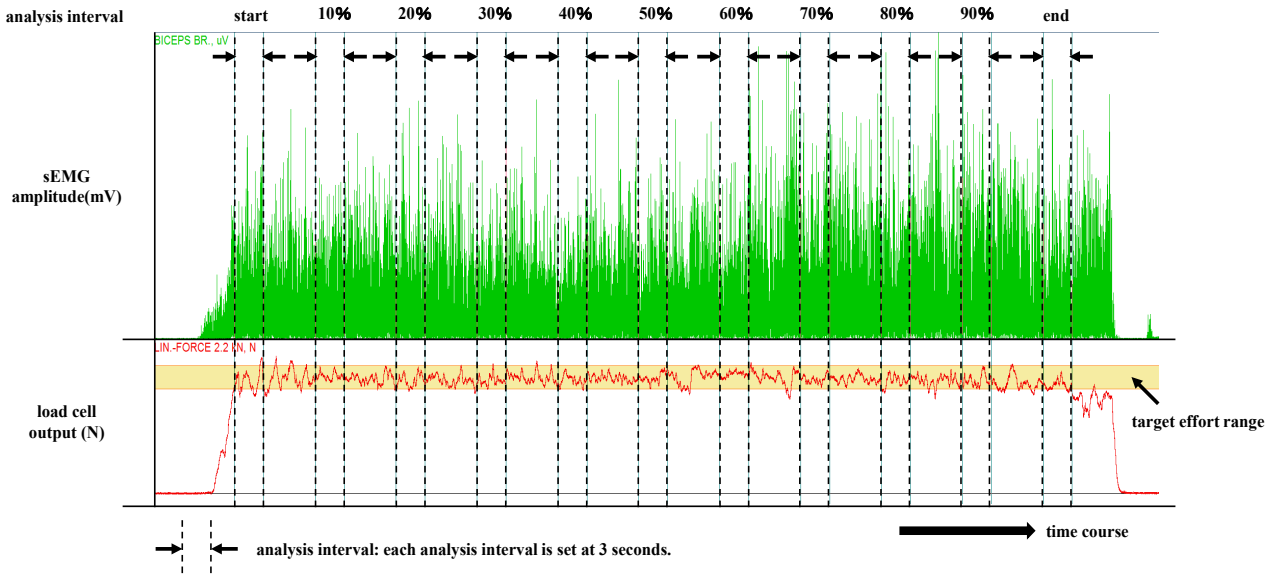
Table 1: Age and anthropometric data of participants

Age (years)	21.6 (0.6)
Height (cm)	163.8 (7.9)
Weight (kg)	55.9 (7.9)

Experimental procedure

Surface electromyography (sEMG) data were recorded from the biceps brachii muscle on the dominant side using a portable EMG system (MyoTrace 400, Noraxon Corp., Arizona, USA) with a sampling rate of 1000 Hz and an analog bandwidth of 10-500 Hz. The skin over the muscle belly was prepared using an abrasive skin preparation gel (Skin Pure, NIHON KOHDEN Corp., Tokyo, Japan). Ag/AgCl surface electrodes (BlueSensor N-00-S, Ambu Corp., Copenhagen, Denmark) were placed over the mid-portion of the muscle belly, parallel to the muscle fiber orientation, with an inter-electrode distance of 2 cm. The reference electrode was placed over the lateral epicondyle of the humerus. This inter-electrode distance and bipolar configuration are commonly used in surface EMG recordings to reduce cross-talk while maintaining an adequate myogenic signal.[15] After electrode placement, inter-electrode impedance was measured; if it exceeded 5 kΩ, as recommended by the International Society of Electrophysiology and Kinesiology (ISEK), skin

Figure 2: Analysis interval setting.
The time period during which the load cell output was maintained within the target effort range was identified, and the eleven 3-s analysis intervals were positioned so that they were evenly distributed within this period.



preparation and electrode placement were repeated until the impedance was below this threshold.

Participants sat on a chair without a backrest and placed their dominant upper limb on a height-adjustable table. The table height was adjusted so that the shoulder joint was flexed to approximately 90°. The elbow joint was flexed to 90°, and the forearm was positioned in 90° supination. A grip handle connected to a wall-mounted force transducer was held in the hand (Figure 1). To determine maximal voluntary isometric contraction (MVIC) force of the biceps brachii, participants were instructed to pull the grip handle with maximal effort for 5 s while maintaining the standardized posture. Three MVIC trials were performed with at least 3 min of rest between trials, and the higher force value was defined as the MVIC force. This value was used to set the target force corresponding to 25% MVIC for the sustained contraction task. A target level of 25% MVIC was based on previous reports that low-intensity contractions in the range of approximately 10-30% MVIC can induce localized muscle fatigue while allowing prolonged performance, and because such contraction levels are representative of many occupational and rehabilitation tasks.[16, 17]After at least 5 min of rest to minimize the influence of prior exertion, participants performed the sustained low-intensity contraction task. They were instructed to pull the grip handle to match and maintain 25% of their MVIC force, which was displayed in real time on a monitor. Fluctuations within ±5% of the target force were permitted during the task. Therefore, each participant maintained 20-30% of their MVIC throughout the task. Data recording was continued while participants maintained the force within this range. Task failure was defined as the inability to maintain the target force within ±5% for at least 5 s, consistent with the definition of muscle fatigue as a failure to sustain the required force. The sustained contraction task was performed once per participant to avoid carry-over effects of fatigue from repeated long-duration contractions; this single-trial design is acknowledged as a limitation with respect to test-retest reproducibility and is addressed in the Discussion.

Data Analysis

For each participant, the total task duration from the onset of the sustained contraction to task failure was divided into ten equal intervals, and eleven equally spaced 3-second analysis intervals were defined at 0% (start), 10%, 20%, …, 90%, and 100% (end) of the total duration. The peak sEMG amplitude obtained during the MVIC task was used as the reference amplitude. For APDF analysis, the amplitude range from 0% to 100% of this peak amplitude was divided into amplitude components with 2.5% intervals, and the APDF value for each component was calculated as the ratio of the number of data points within that component to the total number of data points measured from the start to the end of the task (Figure 2). In addition to APDF, the following conventional sEMG parameters were calculated for each analysis interval: mean amplitude, median frequency, zero-crossing rate, and turn amplitude. Higher-order statistical parameters, kurtosis and skewness of the amplitude distribution, were also computed as exploratory measures of distribution shape. Changes in APDF, mean amplitude, and median frequency were considered primary outcomes, whereas zero-crossing rate, turn amplitude, kurtosis, and skewness were treated as secondary or exploratory outcomes. Temporal changes across the eleven intervals were assessed using one-way repeated-measures analysis of variance (ANOVA) for each parameter.

Table 2: Temporal change of sEMG parameters during 25%MVC sustained muscle contraction

	start	10%	20%	30%	40%	50%
Mean Amplitude (mV)	87.9 (36.0)	125.9 (48.4)	145.8 (66.6)	154.9 (56.9)	* 166.6 (57.4)	** 186.8 (66.5)
Median Frequency (Hz)	59.2 (11.3)	58.2 (9.8)	56.9 (8.2)	55.6 (8.4)	56.2 (8.2)	55.7 (8.8)
Zero-crossing rate (times/sec)	72.8 (14.0)	72.5 (10.3)	72.3 (8.0)	71.4 (8.6)	70.1 (9.0)	69.9 (8.5)
Turn Amplitude (times/sec)	264.8 (38.0)	264.6 (24.9)	267.9 (21.0)	267.8 (24.8)	262.4 (29.2)	260.7 (28.3)

	60%	70%	80%	90%	end
Mean Amplitude (mV)	** 200.5(56.7)	** 229.3 (63.0)	** 267.2 (97.0)	** 286.5 (97.0)	** 323.4 (144.7)
Median Frequency (Hz)	54.3 (7.4)	54.4 (8.6)	53.2 (9.9)	* 50.5 (9.8)	** 47.9 (10.4)
Zero-crossing rate (times/sec)	69.1 (7.8)	68.0 (7.9)	64.8 (9.3)	* 61.4(10.4)	** 59.2 (10.7)
Turn Amplitude (times/sec)	254.0 (30.1)	248.5 (29.1)	244.2 (30.8)	** 228.1 (30.7)	** 221.9 (41.9)

mean (standard deviation) *: $p<0.05$, **: $p<0.01$

If a significant main effect of time was detected ($\alpha = 0.05$), Dunnett's post hoc test was applied to compare each analysis interval with the start interval. Because multiple parameters and APDF components were examined, the analyses were considered exploratory, and the increased risk of type I error due to multiple comparisons was acknowledged as a limitation when interpreting statistically significant findings. The procedures for this study were conducted with the approval of the research ethics committee of Seijoh University (2023C0007).

Results

Average time from start to finish of the experimental task The mean duration for which participants were able to maintain 25% MVIC was 680.3 ± 180.5 s.

Mean amplitude, median frequency, zero-crossing rate, and turn amplitude

Mean amplitude showed a significant increase from the 40% analysis interval onward ($p < 0.05$), whereas median frequency, zero-crossing rate, and turn amplitude showed significant decreases from the 90% analysis interval ($p < 0.05$; Table 2).

Kurtosis and skewness

There were no significant temporal changes in either kurtosis or skewness across the analysis intervals (Table 3).

APDF analysis

Table 4 summarizes the statistical significance of APDF values at each analysis interval relative to the start interval. The APDF values of the lowest amplitude components (0-2.5% and 2.5-5.0% of peak amplitude) decreased as the task progressed, whereas the APDF values of components at 5.0% of peak amplitude and above increased. The APDF values of the three components below 7.5% of peak amplitude already showed significant changes at the 10% analysis interval compared with the start interval. Furthermore, the 7.5-10.0% peak amplitude component began to increase significantly from the 30% analysis interval, and other higher-amplitude

Table 3: Temporal change of kurtosis and skewness of sEMG amplitude value during 25%MVC sustained muscle contraction

	start	10%	20%	30%	40%	50%
Kurtosis	0.95(0.76)	0.86(0.69)	1.86(0.66)	0.77(0.49)	0.77(0.49)	0.94(0.82)
Skewness	0.014(0.228)	-0.012(0.178)	0.051(0.198)	0.021(0.198)	0.024(0.234)	0.064(0.220)

	60%	70%	80%	90%	end
Kurtosis	0.90(0.82)	0.73(0.61)	0.90(0.73)	1.12(0.69)	0.88(0.61)
Skewness	-0.060(0.207)	-0.004(0.207)	-0.023(0.178)	-0.122(0.223)	-0.036(0.213)

mean (standard deviation)

Table 4: Statistical significance of each analysis interval relative to the start interval

	10%	20%	30%	40%	50%	60%	70%	80%	90%	end
0-2.5%peak	*	**	**	**	**	**	**	**	**	**
2.5-5.0%peak	**	**	**	*						
5.0-7.5%peak	*	**	**	**	**	**	**	**	**	**
7.5-10.0%peak			**	**	**	**	**	**	**	**
10.0-12.5%peak				*	**	**	**	**	**	**
12.5-15.0%peak					*	**	**	**	**	**
15.0-17.5%peak						*	**	**	**	**
17.5-20.0%peak							**	**	**	**
20.0-22.5%peak								**	**	**
22.5-25.0%peak								**	**	**
25.0-27.5%peak								**	**	**
27.5-30.0%peak								*	**	**
30.0-32.5%peak								*	*	**
32.5-35.0%peak									**	**
35.0-37.5%peak								*	*	**
37.5-40.0%peak									*	**
40.0-42.5%peak									*	**
42.5-45.0%peak										**
45.0-47.5%peak										**
47.5-50.0%peak										**

*: $p<0.05$, **: $p<0.01$

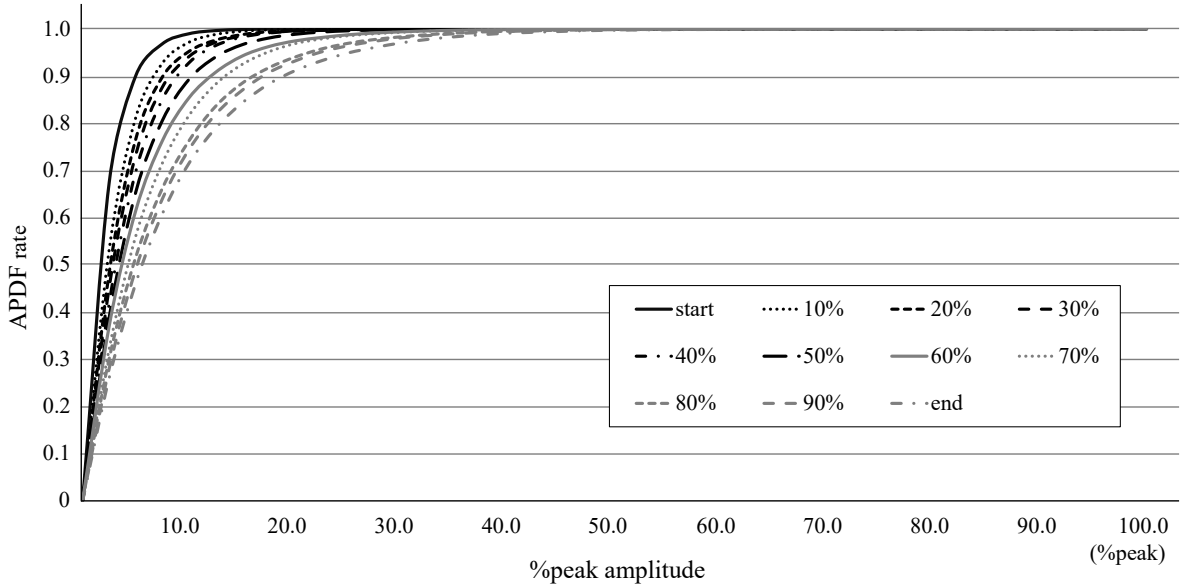
components also showed significant temporal increases in ascending order of their ratio to the peak amplitude. These APDF curves exhibited systematic changes over time without intersecting each other (Figure 3).

Discussion

Muscle fatigue has been defined as a "failure to maintain the required or expected force"[18]. In accordance with this definition, the task in the present study was continued until participants were unable to maintain 25% of their maximum voluntary output. Performing at a low output relative to maximum output results in the recruitment of a relatively small number of motor units. Once a motor unit has been activated, it has sufficient time to recover before being activated again. Consequently, sustained output must be maintained for a relatively long time before task failure occurs. In this study, the mean task duration was approximately 680 s, indicating that the applied load represented a typical low-intensity, long-duration condition rather than a short, high-intensity fatigue task.

To maintain muscle output at a constant level, it is necessary to constantly alter the number of motor units recruited. This regulation consists of a combination of recruitment, firing rate and synchronization, and muscle activity potentials constantly alter during task execution.[19, 20] Despite the progression of muscle fatigue, the maintenance

Figure 3: Temporal change of each amplitude component of APDF
The occurrence frequency of high-amplitude components gradually increased as the task progressed.



of constant muscle output indicates that the demands on the muscles for task performance are increasing. In such cases, the firing rate shifts from low to high, and the motor unit recruitment pattern shifts from asynchronous to synchronous. These mechanisms cause an increase in amplitude values[21] and delays in sEMG waveforms. Chafin[22] reported that sustaining 11% of maximum voluntary contraction force for 1 to 5 minutes slowed the conduction velocity of action potentials along muscle fiber directions and reduced muscle action potential and twitch frequencies. Such muscle fatigue is thought to be related to insufficient blood flow to the muscles, depletion of energy sources, and accumulation of metabolic products (excess hydrogen ions) in muscle tissue.[1] Therefore, when it is necessary to maintain sustained muscle contraction, two electrophysiological phenomena are often observed before the target output can no longer be maintained due to muscle fatigue. One is an increase in amplitude indicating an increase in the number of motor units recruited, and the other is a decrease in the average frequency of the sEMG waveform power spectrum.[21]The present findings partly agree with this classical pattern but also highlight important differences at low intensity. Mean amplitude showed a significant increase from the 40% analysis interval, whereas median frequency showed a significant decrease only from the 90% interval. According to conventional EMG fatigue parameters, this pattern would suggest that fatigue-related changes became clearly apparent only in the late phase of the task. Zero-crossing rate and turn amplitude also showed significant decreases from the 90% interval, similar to median frequency. Because zero-crossing rate and turn amplitude measures reflect the rate of polarity changes in the waveform, they are closely related to the frequency content of the sEMG signal and therefore behaved similarly to median frequency. These results confirm that traditional amplitude- and frequency-based parameters can detect fatigue-related changes even during low-intensity sustained contractions, but primarily when the performance is close to failure.

In contrast, higher-order statistical parameters (kurtosis and skewness) did not exhibit significant temporal changes during the low-intensity sustained contraction. Previous studies have reported that kurtosis tends to approach a Gaussian distribution as contraction intensity increases and that changes in kurtosis may reflect the ability to maintain a constant contraction level.[14, 23] In the present study, however, a constant low isometric tension was maintained, and the variability of the amplitude distribution may have been too small for kurtosis and skewness to detect systematic temporal changes. This suggests that higher-order statistics, at least in their conventional form, may have limited sensitivity for tracking fatigue-related changes under low-intensity, long-duration conditions.

On the other hand, APDF analysis revealed changes that were not apparent in these conventional parameters. The APDF values of the lowest amplitude components (0-2.5% and 2.5-5.0% of peak amplitude) decreased significantly from the 10% analysis interval, while those of the slightly higher components (5.0-7.5% of peak amplitude) increased significantly from the same early stage. Subsequently, significant increases were observed sequentially in components with higher peak amplitude ratios. This pattern indicates a gradual redistribution of the sEMG amplitude toward higher levels over time, even though traditional amplitude and frequency parameters only showed marked changes in the late phase of the task. In other words, detailed analysis of the amplitude distribution suggested that adjustments in motor unit recruitment regulation begin early during

sustained low-intensity contraction, whereas conventional EMG fatigue parameters mainly reflected the later stages of these changes.[24, 25] From a physiological perspective, the early decrease in low-amplitude components and the progressive increase in higher-amplitude components may reflect a gradual increase in the number and/or size of recruited motor units as fatigue develops in initially active units. Under low-intensity conditions, force can be maintained for a long time by rotating the active motor unit pool and by recruiting additional motor units when needed. The present APDF results support the notion that this adjustment process begins long before conventional fatigue parameters indicate a clear change, and that the surface EMG waveform contains subtle information about motor unit recruitment regulation that is not captured by global amplitude or spectral measures alone.[26] Taken together, these findings indicate that during low-intensity sustained elbow flexion at 25% MVIC, neuromuscular adjustments related to motor unit recruitment occur much earlier than suggested by conventional EMG fatigue parameters. Mean amplitude and spectral parameters showed prominent changes only in the late phase, whereas the amplitude distribution began to shift toward higher levels soon after the onset of the task. Such knowledge may serve as a basis for designing strengthening programs that minimize excessive load in individuals with muscle weakness and help reduce the risk of overuse in low-intensity, long-duration tasks.[17, 27]Conclusion

The present study demonstrated that adjustments in motor unit recruitment regulation during sustained low-intensity isometric elbow flexion at 25% MVIC occur from the early phase of the contraction. These early changes were only minimally reflected in conventional EMG fatigue parameters, which showed pronounced alterations mainly in the late phase of the task, but were clearly detected by a detailed analysis of the amplitude probability distribution of the sEMG waveform. The observed early decrease in low-amplitude components and progressive shift of the amplitude distribution toward higher levels indicate that subtle adjustments in motor unit recruitment are already taking place while global amplitude and spectral parameters remain relatively stable.

This finding suggests that reliance on traditional mean-value and spectral parameters alone may obscure early fatigue-related changes during low-intensity, long-duration contractions, and underscores the utility of amplitude-distribution-based analyses for capturing these phenomena. Although the present investigation was conducted in healthy young adults, it is reasonable to assume that in individuals with muscle weakness or reduced endurance capacity, similar neuromuscular adjustments would occur earlier for a given absolute load, leading to an earlier increase in the proportion of higher-amplitude components and a greater local mechanical load, which may contribute to overuse. Such knowledge may serve as a basis for designing strengthening and exercise programs that minimize excessive load in vulnerable populations and help reduce the risk of overuse during low-intensity, long-duration tasks. Future studies should extend this approach to moderate- and high-intensity contractions and to other muscle groups in order to further elucidate the intensity dependence of motor unit recruitment regulation and to refine objective EMG-based parameters for safe load prescription in clinical and occupational settings.

Limitations

This study has several limitations. First, the sample size was small and limited to healthy young adults, so the generalizability of the findings to older or clinical populations and to other muscles is uncertain. Second, only one sustained contraction trial was performed per participant, which prevented assessment of test-retest reliability and the stability of the observed changes. Third, bipolar sEMG recordings were obtained from a single muscle with a bandwidth of 10-500 Hz and a sampling rate of 1000 Hz, which may not capture all low- and high-frequency components and limits inferences about other muscles or recording configurations. Fourth, multiple parameters and APDF components were analyzed within the same repeated-measures ANOVA framework, increasing the risk of type I error and reinforcing the exploratory nature of the statistical analysis. Finally, the task involved only sustained isometric elbow flexion at 25% MVIC; therefore, caution is needed when extrapolating these results to dynamic or task-specific activities in occupational or rehabilitation settings.

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