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Article

Analysis of fatigue of construction workers based on electromyographic signals

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ABSTRACT

Aiming to address the fatigue issue of construction workers resulting from high-intensity physical labor, this paper proposes a fatigue analysis method based on surface electromyographic signals (sEMG), focusing on the handling operation as the research object, to explore the fatigue characteristics of construction workers' muscles and significant monitoring indices. By collecting sEMG signals under different fatigue levels, we analyze the trends of time-frequency domain indicators (root mean square value RMS, integral EMG value IEMG, median frequency MF, mean power frequency MPF, and over-zero rate ZCR). The experimental results show that with the increase of fatigue, the RMS and IEMG of brachioradialis and erector spinae increase significantly, while the MF and MPF decrease significantly, which reflects the physiological mechanism of the decrease of muscle contraction efficiency and the enhancement of neural drive. The changes in the indexes of erector spinae are more significant than those of brachioradialis due to the higher stability load and the activation characteristics of fast muscle fibers. Through the test of intergroup variability, RMS, IEMG, MF, and MPF are selected as the core indicators for fatigue monitoring. This study provides an objective, quantitative basis for labor protection in the construction industry and lays a theoretical foundation for the real-time monitoring of occupational fatigue and the optimization of work efficiency.

1. Introduction

As a vital pillar of the national economy, the construction industry plays a crucial role in driving high-quality economic development [1]. However, due to the high labor intensity and poor working environment faced by construction workers, the safety accident rate in the construction industry has long been higher than that of other industries [2]. Construction workers are often required to perform physically demanding tasks in awkward working postures for extended periods, making them prone to occupational fatigue [3]. This condition can lead to the occurrence of unsafe behaviors that increase the risk of safety accidents and other occupational health problems [4]. Fatigue has been recognized as one of the main causes of safety accidents in the construction industry, so research on fatigue in construction workers is very important. Most of the fatigue produced by construction workers is physiological fatigue, and the reason for this fatigue is due to the lack of metabolic capacity of the body caused by prolonged labor or strenuous exercise, resulting in a significant accumulation of lactic acid and carbon dioxide and other metabolites in the muscle, this local acidic environment will interfere with the process of calcium ions and calponin binding in the myocyte, which will inhibit the normal contraction of the muscle, and ultimately lead to the physiological fatigue state of the organism [5]. At present, numerous scholars have conducted research on human fatigue. Bai Wei et al. [6] proposed a method of judging driver fatigue by testing surface electromyographic signals through electromyography experiments for the problem of muscle fatigue and injury that can be easily caused by the process of drivers getting into the car. Yang Yanpu et al. [7] Effective identification of upper limb muscle fatigue state in hand-over-head operation based on support vector machine by collecting surface EMG signals of the subjects as well as subjective fatigue state. Xin Yunsheng et al. [8] analyzed the muscle fatigue of monorail crane drivers by conducting electromyographic testing studies on 16 muscles prone to fatigue. Liang Zhanhun et al. [9] analyzed and researched the local muscle fatigue of climbing workers through surface EMG signals, explored the characteristic pattern of change of surface EMG signals and its relationship with the subjective fatigue evaluation value in the process of operation, and provided data support for objectively evaluating the local muscle fatigue of climbing operation and preventing work-related musculoskeletal disorders. Xu Zhao et al. [10] introduced sEMG signal recognition and motion capture technology into the process of fatigue state monitoring, proposing a fatigue analysis method that integrates an improved EMG fatigue threshold algorithm and biomechanical analysis. Wang Hongpeng et al. [11] selected a typical road section of the Pamir Plateau in Xinjiang to conduct a real driving test to investigate the fatigue characteristics of the neck muscles of plateau highway drivers under the effect of continuous driving time and altitude by means of surface electromyographic signals. Antwi-Afari et al. [12] analyzed the loading conditions of different body parts of the workers in carrying out a study related to manual material handling operations, which showed that Reasonable control of lifting weight, improvement of working posture, and reduction of repetitive operations can effectively reduce the probability of fatigue. Wang et al. [13] conducted a study on roofing operations and found that different working postures and frequency of operations can cause significant changes in the electromyographic activity level of the lower back muscles of the workers, which suggests that the effect of the mode of operation on the muscular fatigue should not be ignored. Shariatzadeh et al. [14] designed and manufactured a novel wearable sensor system with sEMG electrodes and motion tracking sensors for monitoring dynamic muscle movements in the human body.

Currently, there are few studies on the analysis of operational fatigue of construction workers, and few studies for the analysis of physiological fatigue of construction workers. Therefore, this paper analyzes the operation fatigue of construction workers based on EMG signals and combined with subjective fatigue perception, to explore the intrinsic connection between fatigue perception and EMG signals, to reveal the dynamic change law of the fatigue state of construction workers, so as to improve the efficiency of construction workers, to reduce the unsafe behaviors triggered by physical fatigue, and to reduce the probability of safety accidents.

2. Experimental design and method

2.1 Subjects

Since construction workers are predominantly male and generally have good physical fitness, 12 healthy adult male construction workers were selected as subjects in this study. All subjects have high physical fitness and typically exercise for more than 1 hour per day. The specific physical data are as follows: age 22-26 years old, height 170-182cm, weight 65-80kg, BMI 22.02-24.17. Before the experiment, to ensure that all the subjects can experiment with the best physical state, the subjects are required to maintain sufficient sleep, prohibit alcohol, coffee, sports drinks and other beverages, and the experimental time is selected in the morning or the afternoon, to maximize the experimental time was chosen in the morning or afternoon to maximize the simulation of the construction time in the building construction site.

2.2 Research methods

Adopting the research method of laboratory simulation, the above research objects were selected to simulate the work of construction workers in the laboratory. The manual handling operation was chosen as the experimental task, which has lower requirements for the laboratory environment and can be carried out in a controlled setting. The Noraxon Ultium EMG wireless surface EMG instrument was used to monitor EMG signals during the experiments, and the Borg scale was used to quantify the physical state objectively.

2.3 Electrode arrangement of EMG equipment

EMG signals are measured by electrodes placed on the surface of the skin, which are capable of recording the signals of electrical activity of the muscles in response to nerve stimulation, thus reflecting the physiological state and functional changes of the muscles. Based on the results of related research [15-17], the brachioradialis and erector spinae muscles are selected as the target muscle groups in this paper. The electrode arrangement position of EMG signals is shown in Figure 1, and only one side of the muscle can be measured in the measurement, so the right half of the muscle of the subject is chosen to be measured.

Figure 1. Myoelectric electrode arrangement (① is the brachioradialis muscle, and ② is the erector spinae muscle)

2.4 Experimental procedure

Before the beginning of the experiment, wear the physiological monitoring equipment for the subject correctly and make sure that the physiological monitoring equipment can work normally. Then, the subjects entered the resting session and kept sitting still for 10 minutes in order to bring their physiological status to the basal level. At the end of the resting period, the experiment began with subjects lifting a 25 kg weight from point "A" and stacking five weights to point

"B" according to the diagonal path shown in Figure 2. After completing each set of tasks, the subjective fatigue perception according to the Borg scale was filled in, and then the weights were carried from point "B" to point "A" one by one. This process was repeated until the subject felt completely exhausted and signaled the termination of the experiment. Physiological indexes of the subjects were recorded throughout the experiment.

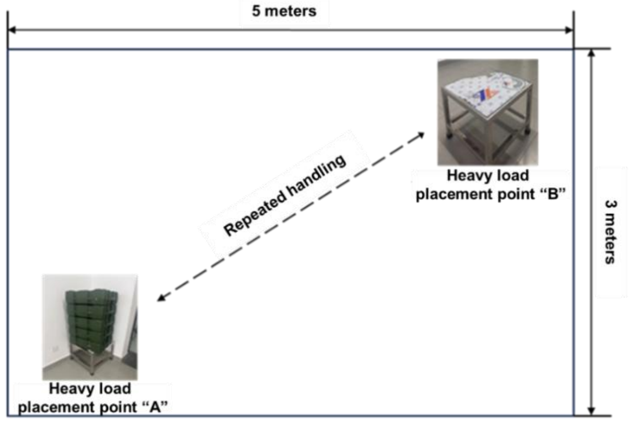


Figure 2. Manual handling simulation operation

2.5 Data collection and recording

2.5.1 Subjective fatigue scale

The Borg Perceived Exercise Intensity Scale (RPE) was used in the experiment, which ranges from 0-10, indicating the subject's perception of fatigue in accomplishing a specific task, from "no feeling" to "maximum effort". The Borg scale score was recorded once after each subject completed five lifting tasks until the fatigue level reached its limit. In order to systematically analyze the fatigue of construction workers and reflect the subjective fatigue state of the subjects in a more detailed way, the Borg scale scores of the subjects in the process of lifting and carrying tasks were divided into three fatigue levels: 0-3 points were divided into the low-fatigue group, 4-6 points were divided into the moderate-fatigue group, and 7-10 points were divided into the severe-fatigue group.

2.5.2 Pre-processing of EMG signals

The EMG signal will be interfered by the measurement environment noise, inherent noise of the equipment and baseline drift in the process of acquisition and recording, so to accurately extract the surface EMG signal that can reflect the fatigue state of the body, it is necessary to use the corresponding filtering method to preprocess the original EMG signal.

(1) Inherent noise of the acquisition instrument: In the process of EMG signal acquisition, the inherent noise of the measuring instrument is one of the main sources affecting the signal quality. In order to minimize the noise interference in signal acquisition, the skin surface where the target muscle group is located is cleaned as necessary before the experiment, and the distance between the electrodes on the paired surfaces is reasonably controlled.

(2) Measurement of environmental noise: Environmental noise refers to the noise pollution introduced by the peripheral electrical equipment during the signal acquisition process, of which industrial frequency interference is the most important form of interference. According to China's power system standards, the operating frequency of the AC power supply network is set to 50Hz, which causes the spectral energy of industrial frequency interference to show significant aggregation characteristics near the 50Hz frequency point. Therefore, this paper adopts a Butterworth-type bandpass filter to suppress the industrial frequency interference, and the filter parameters are set to a 49- 51Hz passband range.

(3) Time-frequency domain feature index extraction: In order to comprehensively evaluate the change rule of EMG signals under fatigue state, this paper calculates the root mean square (RMS) and integral electromyography (IEMG) of the filtered EMG signals of the brachioradialis and erector spinae through the average value of the sliding window of 500 milliseconds. Meanwhile, the median frequency (MF), mean power frequency (MPF), and zero-crossing rate (ZCR) were derived after calculating the power spectral density using the ScipyWelch function. In addition, the time-domain features of EMG, RMS, and IEMG were normalized by the corresponding values of maximum muscle force (MVC) of the respective muscles. These feature indicators reflect the degree of muscle fatigue from multiple dimensions, such as signal intensity, total activity, and frequency distribution, respectively, and have good sensitivity and stability in muscle fatigue detection. The specific calculation process of each feature index is as follows:

RMS: It is a kind of feature indicator reflecting the overall amplitude of the signal, mainly used to assess the intensity of muscle activity, commonly used in fatigue monitoring and action recognition. The calculation formula is shown in Equation (1).

$$RMS = \sqrt{\frac{1}{N}\sum_{i=1}^{N} x_i^2} \quad (1)$$

Where x_i is the signal value of the ith sampling point; N is the total number of sampling points.

IEMG: It is a feature that sums the absolute values of the signals and is used to assess the overall output of the muscle activity, which is suitable for the analysis of muscle fatigue over a long period of time. The calculation formula is shown in Equation (2).

$$IEMG = \sum_{i=1}^{N} |x_i| \quad (2)$$

MF: is the frequency in the power spectrum that divides the total power into two equal parts, commonly used in fatigue monitoring. MF usually drifts to lower frequencies as the muscle fatigues. The formula is shown in Equation (3).

$$\int_0^{MF} P(f)df = \int_{MF}^{f_{max}} P(f)df \quad (3)$$

Where $P(f)$ is the power spectral density of the signal, f_{max} is the maximum frequency.

MPF: is the weighted average of the frequency distribution of the signal, similar to MF, used to assess muscle fatigue. The calculation formula is shown in Equation (4).

$$MPF = \frac{\int_0^{f_{max}} f \cdot P(f)df}{\int_0^{f_{max}} P(f)df} \quad (4)$$

ZCR: is the number of times the signal passes through the zero point within a certain time window and is used to analyze the frequency changes of EMG signals, especially the frequency dynamics during rapid muscle contraction and relaxation. The calculation formula is shown in Equation (5).

$$ZRC = \sum_{N-1}^{i=1} 1((x_i \cdot x_{i+1}) < 0) \quad (5)$$

3. Results and discussion

3.1 Subjective fatigue

According to the statistical results, there were 57 low fatigue groups, 262 moderate fatigue groups, and 141 severe fatigue groups, and the difference between the three groups was statistically significant ($P< 0.05$). With the progress of the handling task, the subjective fatigue perception of the subjects gradually deepened, and the Borg score showed a significant upward trend. The mean value of the scores in the low fatigue group remained at a low level, approximately in the range of 1-3 points, reflecting that the subjects' fatigue perception was relatively light at this fatigue level; whereas the scores in the moderate fatigue group were in the range of 4-6 points, showing an increase in fatigue perception; the mean value of the scores in the severe fatigue group was significantly higher than that of the previous two groups, usually in the range of more than 7 points, showing that the fatigue perception of the subjects reached the peak in the state of severe fatigue, as shown in Figure 3.

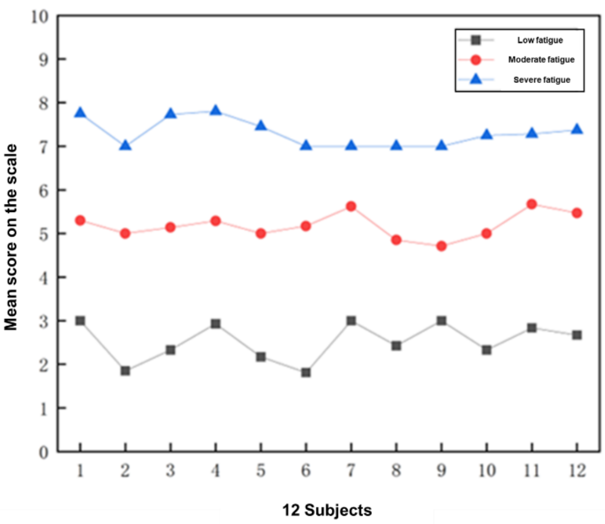


Figure 3. Mean values of scores of different subjects at three levels of fatigue

3.2 EMG signal analysis

3.2.1 Descriptive analysis of EMG signal characteristics indicators

Based on the three different fatigue groupings, the mean values of the characteristic indexes of the subjects under different fatigue levels were calculated. The changes of the mean values of the physiological indexes of the 12 subjects from low fatigue to severe fatigue states are shown in Figure 4 (a, b, c, d, e). From Figure 4 (a) to (e), it can be seen that as the fatigue level rises, the time-frequency domain indexes of EMG signals of brachioradialis and erector spinae, such as RMS and IEMG indexes, show an upward trend; such as the MF and MPF indexes, show a downward trend; and the trend of change of the ZCR indexes is not obvious, and the trend of change of each subject is not consistent. Specifically:

(1) RMS of brachioradialis muscle increased from low fatigue (0.05± 0.30) to severe fatigue (0.08± 0.04), and IEMG low fatigue (0.06± 0.07) to severe fatigue (0.09± 0.10).

(2) The RMS of the erector spinae muscle increased from low fatigue (0.46± 0.67) to severe fatigue (1.05± 1.73), and IEMG from low fatigue (0.10± 0.08) to severe fatigue (0.22± 0.26).

(3) MF of the brachioradialis muscle decreased from low fatigue (0.13± 0.11) to severe fatigue (0.11± 0.09), and MPF decreased from low fatigue (0.15± 0.12) to severe fatigue (0.13± 0.11).

(4) MF decreased from low fatigue (0.93± 0.31) to severe fatigue (0.74± 0.22), and MPF decreased from low fatigue (0.89± 0.27) to severe fatigue (0.72± 0.18) in the erector spinae muscle.

(5) The ZCR of the brachioradialis and erector spinae muscles showed a small increase in their mean values, although the trend was not significant. ZCR increased from low fatigue (0.10± 0.02) to severe fatigue (0.11± 0.03) for brachioradialis, and from low fatigue (0.10± 0.02) to severe fatigue (0.11± 0.03) for erector spinae.

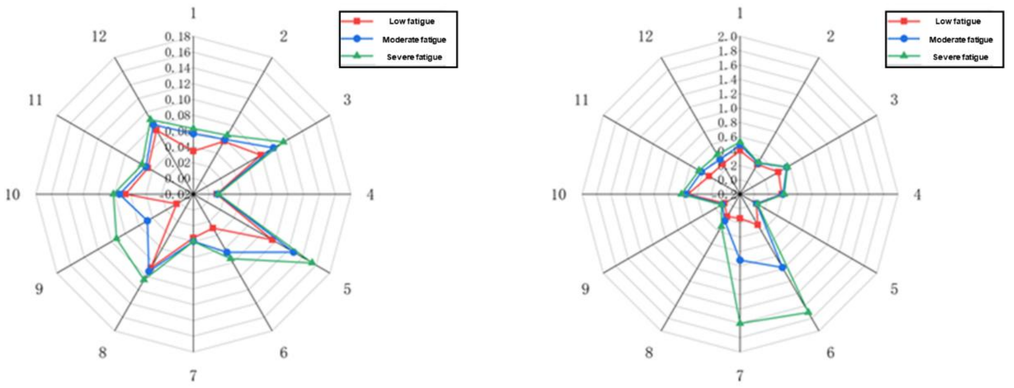
As above, the trend of RMS vs. IEMG suggests that as the lifting operation progresses, the subjects' muscle fatigue builds up, resulting in less efficient muscle contraction and higher neural drive is required to maintain force output.The trend of MF vs. MPF suggests that as the muscle fatigue builds up, the muscle's fast muscle fibers (Type II) take the lead in fatigue due to lactic acid buildup and energy depletion, and the slow muscle fibers (Type I) dominate the contraction, resulting in a slowing of action potential conduction and an increase in the proportion of low-frequency components.

The trend of ZCR shows that fatigue results in a widening of the action potential waveform, a decrease in high-frequency oscillations, and a decrease in the number of times the signal crosses the baseline (zero point) per unit time. Among them, by comparing the change amplitude of the characteristic indexes in the time-frequency domain of the erector spinae and brachioradialis, it can be found that the change amplitude of the characteristic indexes of the erector spinae is significantly larger than that of the brachioradialis. The mechanism can be summarized as the following three points [18,19]:

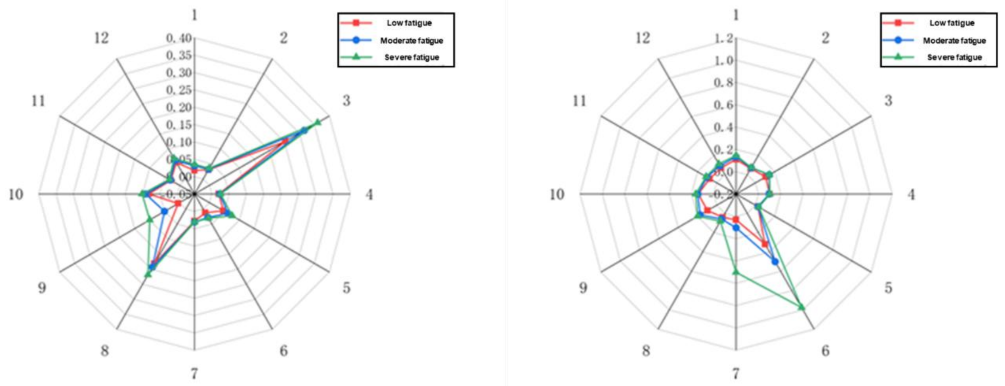
(1) Biomechanical load differences: the erector spinae muscle is continuously subjected to spinal compression and shear forces during handling operations, and the muscle fibers (especially type II fast muscle fibers) are more prone to fatigue;

(2) Distribution of muscle fiber types: the vertical spine muscle has a higher proportion of fast muscle fibers (about 60%), which enter anaerobic metabolism earlier under sustained loading, leading to lactic acid accumulation and left shift of the frequency spectrum;

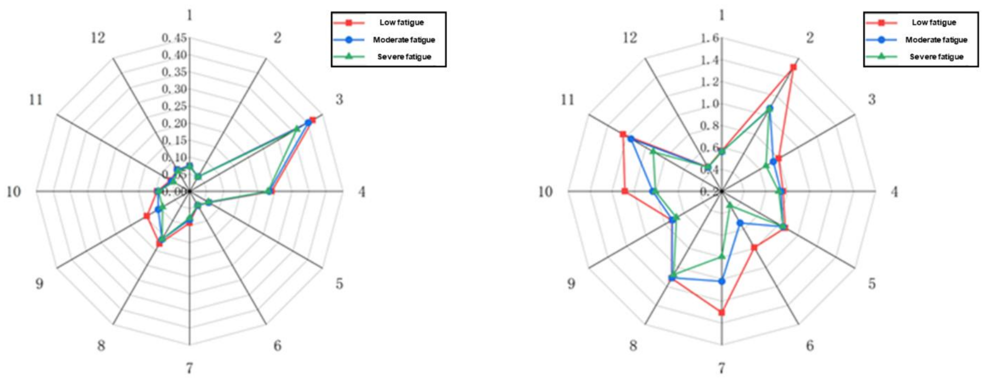
(3) Recruitment pattern of motor units: the erector spinae muscle needs to maintain postural stability, and the motor units showed high-threshold synchronized activation, with greater central nervous system drive intensity.



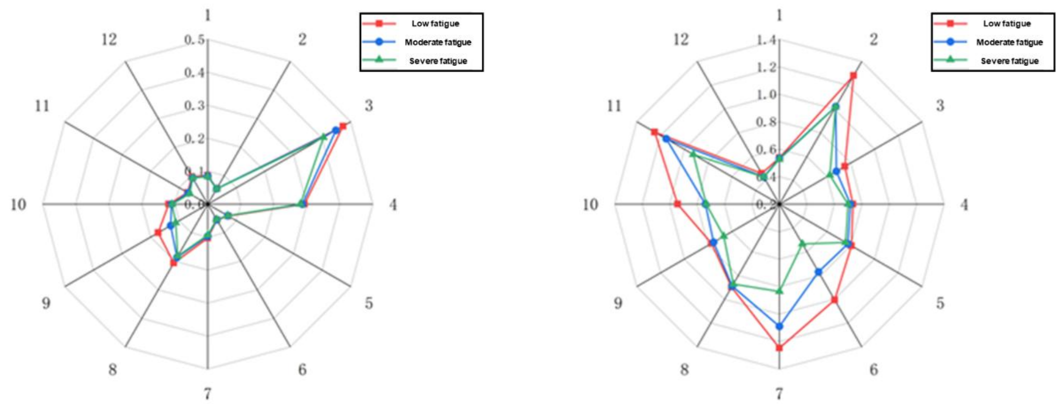
a) RMS change trend chart for test subjects



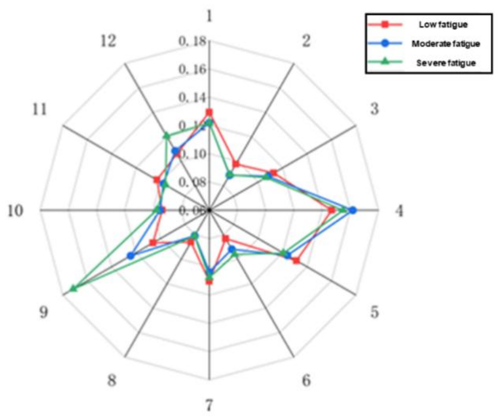
b) IEMG change trend chart for test subjects

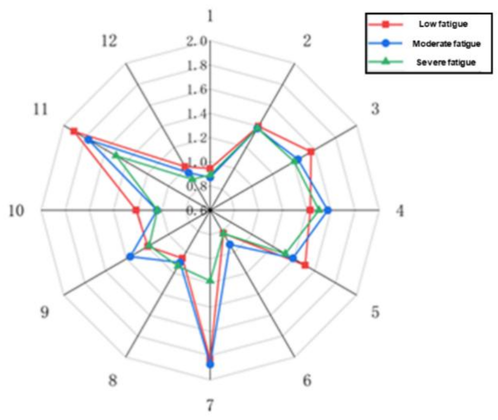


c) MF change trend chart for test subjects



d) MPF change trend chart for test subjects





e) ZCR change trend chart for test subjects

Figure 4. Changes in the mean values of physiological indicators under different fatigue states of the subjects (left figures: Brachioradialis muscle, right figures: Erector spinae muscle)

In summary, although some subjects, due to individual differences, have outstanding anti-fatigue ability of the muscle groups of their forearms or erector spinae, and the trend of the time-frequency domain characteristic indexes is not obvious, the overall trend is the same as the findings obtained by the previous research [20,21], which confirms that the standard EMG acquisition equipment used in this paper can effectively capture muscle fatigue under dynamic operating environments, and further verifies the reliability of the experimental data.

3.2.2 Screening of fatigue significant indicators of EMG signals

By statistically analyzing the characteristic indicators of the EMG signals of the brachioradialis and erector spinae muscles, the significant indicators under different fatigue levels were screened. Since the data in this paper belongs to the relevant samples, the normality test was firstly performed on the above characteristic indexes. For the data that satisfy the normality test, single-group repeated-measures ANOVA and Bonferroni post-hoc two-by-two comparisons were carried out. For the data that do not satisfy the normality test, Friedman's test and Wilcoxon signed-rank test were carried out to carry out post-hoc two-by-two comparisons. A normality test was done for the dependent variable as shown in Table 1, and due to the small sample size, the Shapiro-Wilk test results were chosen to be used. From the results of the Shapiro-Wilk normal distribution test, it can be seen that the P value of RMS and ZCR indexes of brachioradialis muscle and MF, MPF, and ZCR indexes of erector spinae muscle in different fatigue groups were all greater than 0.05, obeying normal distribution; the rest of the indexes did not obey normal distribution.

A single-group repeated-measures ANOVA was performed on the above indexes that obeyed normal distribution, and Mauchly's test of sphericity was performed on the dependent variable, and the results are shown in Table 2. Mauchly's test of sphericity showed that the data of RMS and ZCR indexes of the brachioradialis muscle, and the data of MF and MPF indexes of the erector spinae muscle, did not satisfy the assumption of sphericity ($P1=0.000<0.05$, $P2=0.001<0.05$, $P(3)=0.001<0.05$, and $P(4)=0.001<0.05$, and $P(4)=0.001<0.05$, $P3=0.012<0.05$, $P4=0.021<0.05$), when the dependent variable violates the conditions of the spherical assumption needs to be epsilon (ε) correction, as can be seen in Table 2, the Huynh-Feldt method was chosen to be more effective in the correction, and after the correction of $\varepsilon1=0.553$, $\varepsilon2=0.559$, $\varepsilon3=0.672$, $\varepsilon(4)=0.702$. The data of the ZCR index for the erector spinae muscle satisfied the spherical assumption ($W=0.654$, $P=0.120>0.05$), so the results under the spherical assumption were read directly.

The results of the within-subjects effect test for each level of the dependent variable are shown in Table 3, and combined with the results of the analysis above, it can be seen that by the Shapiro-Wilk test, the dependent variables in each group of the RMS and ZCR indexes for the brachioradialis muscle and the MF, MPF, and ZCR indexes for the erector spinae muscle obeyed a normal distribution ($P>0.05$). The dependent variables of RMS (brachioradialis), ZCR (brachioradialis), MF (erector spinae), and MPF (erector spinae) indexes did not satisfy the assumption of sphericity by Mauchly's sphericity hypothesis test, and $\varepsilon1=0.553$, $\varepsilon2=0.599$, $\varepsilon3=0.672$, and $\varepsilon4=0.702$ after correction by Huynh-Feldt's method. After correction, $F(1)(1.105,12.160)=12.958$, $P1=0.003<0.05$, i.e., the difference is statistically significant; $F2(1.197,13.171)=0.736$, $P2=0.430>0.05$, i.e., the difference is not statistically significant; $F3(1.344,14.787)=9.843$, $P3=0.004<0.05$, i.e., the difference is statistically significant; $F4(1.403,15.437)=11.738$, $P4=0.002<0.05$, i.e., the difference is statistically significant.

The dependent variable of ZCR (erector spinae muscle) index satisfies the assumption of sphericity, and under the degree of sphericity, $F(2,22)=4.082$, $P=0.031<0.05$, i.e., the difference is statistically significant. The results of the Bonferroni correction for the above statistically significant indicators are shown in Table 4.

Table 1. Normality test of characteristic indexes of EMG signals

Characteristic index	Fatigue level	Kolmogorov-Smirnov [a]			Shapiro-Wilk		
		Statistic	df	Sig.	statistic	df	Sig.
RMS (brachioradialis)	Low fatigue	.123	12	.200	.960	12	.785
	Moderate fatigue	.106	12	.200	.986	12	.998
	Severe fatigue	.102	12	.200	.986	12	.998
IEMG (brachioradialis)	Low fatigue	.296	12	.005	.717	12	.001
	Moderate fatigue	.329	12	.001	.660	12	.000
	Severe fatigue	.301	12	.004	.696	12	.001
MF (brachioradialis)	Low fatigue	.287	12	.007	.740	12	.002
	Moderate fatigue	.305	12	.003	.704	12	.001
	Severe fatigue	.343	12	.000	.712	12	.001
MPF (brachioradialis)	Low fatigue	.268	12	.017	.763	12	.004
	Moderate fatigue	.285	12	.008	.730	12	.002
	Severe fatigue	.326	12	.001	.736	12	.002
ZCR (brachioradialis)	Low fatigue	.170	12	.200	.948	12	.606
	Moderate fatigue	.174	12	.200	.908	12	.199
	Severe fatigue	.211	12	.145	.890	12	.119
RMS (erector spinae)	Low fatigue	.378	12	.000	.539	12	.000
	Moderate fatigue	.384	12	.000	.525	12	.000
	Severe fatigue	.433	12	.000	.558	12	.000
IEMG (erector spinae)	Low fatigue	.273	12	.014	.752	12	.003
	Moderate fatigue	.311	12	.002	.654	12	.000
	Severe fatigue	.367	12	.000	.628	12	.000
MF (erector spinae)	Low fatigue	.170	12	.200	.963	12	.825
	Moderate fatigue	.142	12	.200	.942	12	.521
	Severe fatigue	.110	12	.200	.972	12	.934
MPF (erector spinae)	Low fatigue	.157	12	.200	.937	12	.458
	Moderate fatigue	.203	12	.187	.955	12	.708
	Severe fatigue	.104	12	.200	.986	12	.998
ZCR (erector spinae)	Low fatigue	.127	12	.200	.961	12	.802
	Moderate fatigue	.152	12	.200	.937	12	.456
	Severe fatigue	.139	12	.200	.930	12	.377

Table 2. Mauchly's test of sphericity for each indicator

Within-subjects effect	Indicator	Mauchly's W	Approximate chi-square	df	Sig.	Epsilon		
						Greenhouse-Geisser	Huynh-Feldt	Lower limit
Fatigue	RMS (brachioradialis)	.149	19.040	2	.000	.540	.553	.500
	ZCR (brachioradialis)	.260	13.465	2	.001	.575	.599	.500
	MF (Vertebrae)	.410	8.912	2	.012	.629	.672	.500
	MPF (Vertebrae)	.463	7.708	2	.021	.650	.702	.500
	ZCR (Vertebrae)	.654	4.245	2	.120	.743	.832	.500

As can be seen from Table 4, RMS (brachioradialis muscle), MF (erector spinae muscle), and MPF (erector spinae muscle) indices were found to be statistically significant in the low fatigue group versus the moderate fatigue group ($P1=0.012<0.05$, $P2=0.035<0.05$, and $P3=0.017<0.05$), and in the low fatigue group versus the severe fatigue group ($P1=0.011<0.05$, $P2=0.018<0.05$, $P3=0.011<0.05$), moderate fatigue group versus severe fatigue group ($P1=0.022<0.05$, $P2=0.032<0.05$, $P3=0.015<0.05$) differed significantly, indicating that RMS (brachioradialis muscle), MF (erector spinae muscle), and MPF (vertical spine muscle) indexes were significantly different between different fatigue groups, and the effect on fatigue ZCR (erector spinae) indexes no significant difference between different fatigue groups ($P>0.05$), which means that they were not significant for fatigue.

Friedman's nonparametric test was performed on the indicators of IEMG (brachioradialis), MF (brachioradialis), MPF (brachioradialis), RMS (erector spinae), and IEMG (erector spinae) that did not obey normal distribution, and the results of the test are shown in Table 5. The P-value of a certain indicator in Friedman's test is less than 0.05, indicating that at least one group of the indicators between different fatigue grades has a significant difference.

As can be seen from the table, IEMG ($P=0.000<0.05$), MF ($P=0.000<0.05$), MPF ($P=0.000<0.05$) for brachioradialis muscle, and RMS ($P=0.000<0.05$), IEMG ($P=0.000<0.05$) for erector spinae muscle indicated that at least one group had significant differences between different fatigue levels. To further screen the indicators that were significant for fatigue among different fatigue groups, the Wilcoxon signed rank test was performed to compare the above indicators two by two, as shown in Table 6. All indicators in the table have significant differences between different fatigue groups (P＜0.05), indicating that the indicators in the table are significant for fatigue.

Table 3. Within-subjects effect test for each indicator

Indicator		Type III sum of squares	df	mean square	F	Sig.	η^2
RMS (brachioradialis)	Sphericity-assumed	.004	2	Sphericity-assumed .004 2	12.958	.000	.376
	Greenhouse-Geisser	.004	1.080	.004	12.958	.003	.376
	Huynh-Feldt	.004	1.105	.004	12.958	.003	.376
	Lower limit	.004	1.000	.004	12.958	.004	.376
ZCR (brachioradialis)	Sphericity-assumed	.000	2	.000	.736	.490	.033
	Greenhouse-Geisser	.000	1.150	.000	.736	.425	.033
	Huynh-Feldt	.000	1.197	.000	.736	.430	.033
	Lower limit	.000	1.000	.000	.736	.409	.033
MF (erector spinae)	Sphericity-assumed	.222	2	Sphericity-assumed .222 2	9.843	.001	.314
	Greenhouse-Geisser	.222	1.258	.177	9.843	.005	.314
	Huynh-Feldt	.222	1.344	.166	9.843	.004	.314
	Lower limit	.222	1.000	.222	9.843	.009	.314
MPF (erector spinae)	Sphericity-assumed	.178	2	Sphericity-assumed .178 2	11.738	.000	.353
	Greenhouse-Geisser	.178	1.301	.136	11.738	.002	.353
	Huynh-Feldt	.178	1.403	.127	11.738	.002	.353
	Lower limit	.178	1.000	.178	11.738	.006	.353
ZCR (erector spinae)	Sphericity-assumed	.131	2	.066	4.082	.031	.159
	Greenhouse-Geisser	.131	1.486	.088	4.082	.047	.159
	Huynh-Feldt	.131	1.664	.079	4.082	.040	.159
	Lower limit	.131	1.000	.131	4.082	.068	.159

Table 4. Post hoc tests for each indicator (Bonferroni correction)

Indicators	(I) Fatigue group	(J) Fatigue group	Mean difference (I-J)	Standard error	Significance	95% significant interval	
						Lower limit	Upper limit
RMS (brachioradialis)	Low fatigue	Moderate Fatigue	-.015*	.004	.012	-.027	-.003
		Severe fatigue	.027* -.007	.007	.011	-.048	-.006
	Moderate fatigue	Severe fatigue	-.012* -.004	.004	.022	-.022	-.002
MF (erector spinae)	Low fatigue	Moderate fatigue	.120*	.042	.035	.000	.239
		Severe Fatigue	.191*	.056	.018	.032	.349
	Moderate Fatigue	Severe fatigue	.071*	.026	.032	-.002	.144
MPF (erector spinae)	Low fatigue	Moderate fatigue	.094*	.027	.017	.017	.172
		Severe fatigue	.172*	.047	.011	.040	.304
	Moderate Fatigue	Severe fatigue	.078*	.029	.015	-.004	.159
ZCR (erector spinae)	Low fatigue	Moderate fatigue	.017	.033	1.000	-.077	.111
		Severe fatigue	.136	.060	.137	-.034	.306
	Moderate Fatigue	Severe fatigue	.119	.057	.188	-.043	.281

Table 5. Friedman non-parametric test for each indicator

Indicator	χ^2	**df**	**Sig.**	**Kendall's W**
IEMG (brachioradialis)	24	2	.000	.727
MF (brachioradialis)	24	2	.000	.727
MPF (brachioradialis)	24	2	.000	.727
RMS (erector spinae muscle)	24	2	.000	.727
IEMG (erector spinae)	22.167	2	.000	.671

Table 6. Wilcoxon signed rank test for each indicator

Indicator	Fatigue level	Z	Sig.	r
IEMG (brachioradialis)	Moderate fatigue-low fatigue	-3.059	.002	-.883
	Severe fatigue-low fatigue	-3.059	.002	-.883
	Heavy fatigue-moderate fatigue	-3.059	.002	-.883
MF (brachioradialis)	Moderate fatigue-low fatigue	-3.059	.002	-.883
	Severe fatigue-low fatigue	-3.059	.002	-.883
	Heavy fatigue-moderate fatigue	-3.059	.002	-.883
MPF (brachioradialis)	Moderate fatigue - low fatigue	-3.059	.002	-.883
	Severe fatigue-low fatigue	-3.059	.002	-.883
	Heavy fatigue-moderate fatigue	-3.059	.002	-.883
RMS (erector spinae)	Moderate fatigue-low fatigue	-3.059	.002	-.883
	Severe fatigue-low fatigue	-3.059	.002	-.883
	Heavy fatigue-moderate fatigue	-3.059	.002	-.883
IEMG (erector spinae)	Moderate fatigue-low fatigue	-2.824	.005	-.815
	Severe fatigue-low fatigue	-3.059	.002	-.883
	Heavy fatigue-moderate fatigue	-3.059	.002	-.883

4. Conclusions

In this paper, the fatigue state of construction workers was analyzed using EMG signals, and the fatigue significant indicators of EMG signals were screened and the following conclusions were drawn:

(1) The brachioradialis and erector spinae muscles are common. During lifting operations, indicators of brachioradialis and erector spinae such as RMS and IEMG increased with increasing fatigue level, whereas MF and MPF decreased with increasing fatigue level, reflecting that as fatigue builds up, the muscle contraction efficiency decreases, resulting in the need for subjects to exert greater neural drive to maintain force output. Among them, the erector spinae muscle showed more obvious changes in EMG signal characteristics than the brachioradialis muscle, which was mainly attributed to the greater stability and strength support demands assumed in the lifting operation, and the percentage of fast muscle fibers and the activation pattern of high-threshold motor units made its response to fatigue more significant.

(2) Significant indicator screening. By statistically analyzing the characteristic indexes of EMG signals of brachioradialis and erector spinae, the RMS, IEMG, MF, and MPF indexes of brachioradialis and erector spinae had significant differences between different fatigue groups ($P < 0.05$), indicating that they can be used as core indexes for fatigue monitoring when evaluating EMG characteristics.

The study in this paper not only verifies the feasibility of EMG signals in occupational fatigue monitoring but also provides a scientific basis for the quantification of labor intensity, the optimization of operating posture, and the management of occupational health of construction workers.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the corresponding author.

Conflict of interest

The authors declare no potential conflict of interest.

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