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Evaluation of upper limb muscle fatigue based on surface electromyography

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Fatigue is believed to be a major contributory factor to occupational injuries in machine operators. The development of accurate and usable techniques to measure operator fatigue is therefore important. In this study, we used a novel method based on surface electromyography (sEMG) of the biceps brachii and the Borg scale to evaluate local muscle fatigue in the upper limb after isometric muscle action. Thirteen young males performed isometric actions with the upper limb at different force levels. sEMG activities of the biceps brachii were recorded during the actions. Borg scales were used to evaluate the subjective sensation of local fatigue of the biceps brachii after the actions. sEMG activities were analyzed using the one-third band octave method, and an equation to determine the degree of fatigue was derived based on the relationship between the variable and the Borg scale. The results showed that the relationship could be expressed by a conic curve, and could be used to evaluate muscle fatigue during machine operation.

isometric muscle activity, muscle fatigue, one-third band octave method, evaluation model for muscle fatigue

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With the development of science and technology, human-centered design has become an increasingly important feature of manual operating systems. The degree of fatigue of machine operators is a key contributory factor in occupational injuries. It is generally agreed that fatigue resulting from poor posture and long working times are the main reasons for system down time, occupational diseases and low work efficiency. It is therefore important to develop methods of assessing fatigue during machine operation, which may produce valuable results in terms of designing controls, planning rational working systems and programs, preventing occupational injuries, and monitoring human body functioning.

Fatigue includes both local and systemic fatigue. Local fatigue is caused by long working time or by poor posture whilst working. Systemic fatigue is caused by excessive physical work, as well as by mental factors and disease [1]. There is no current consensus on how fatigue develops. The main theories include the power-source consumption theory, the accumulation of fatigue substances theory, the physiological and biochemical change theory, and the local blood stop theory [2,3]. Based on these theories, fatigue assessment is an important part of ergonomic analysis and design of human-machine systems. Although assessments comprise objective and subjective methods, the results should always be objective, independent of the subjective explanation. Four methods are currently used [4–7]. Firstly, subjective scales, such as the Borg scale, are designed to grade fatigue

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*Corresponding author (email: zqxg@buaa.edu.cn) according to the subjective sensation of the operator. Secondly, biomechanical analysis of joint parts can be carried out under mechanically constrained conditions. Thirdly, fatigue can be assessed by measuring physiological signals, e.g., by cardiography, electroencephalography and surface electromyography (sEMG). Lastly, oxygen consumption and breath rate during operation can be measured to evaluate the subject's degree of fatigue. These methods suggest that both physiological signals and subjective scales can be used to build a useful fatigue assessment model.

sEMG measures the bioelectric phenomenon that occurs on the surface of the skin in association with muscle activity. It produces muscle activity information on fatigue degree, muscle force, and excitation conduction velocity, which reflect the muscle activity state [8]. Analysis and evaluation of sEMG activity represents an important method of studying muscle fatigue, because change in sEMG correlates with muscle functional state [9,10]. For example, Ye *et al.* [10] studied fatigue-related changes in the biceps brachii and changes in sEMG during convalescence at 100% and 50% maximal voluntary contraction (MVC), and discussed the possible reasons for and mechanisms of sEMG activity during muscle fatigue. They concluded that sEMG could be used to evaluate the recovery of muscle function. Ge *et al.* [11] carried out sEMG tests on the brachioradialis, biceps brachii, deltoid and trapezius muscles in 14 male university students in three different postures: uplift, abduction and extension of the right arm. Borg scales were also used to grade subjective fatigue in the different postures. The results showed a significant correlation between the percent of maximal voluntary electrical activation and Borg scales for subjective fatigue.

Many studies [7,12,13] have investigated muscle fatigue using mean power frequency (MPF), median frequency (MF) and root mean square (RMS) of sEMG. MF and RMS decrease continuously during muscle fatigue, and MPF, MF and RMS can be used to characterize the physiological indicators of muscle charge. However, only whole signal band analysis can be performed using MPF and MF, which is not easily utilized. In this study, we used the one-third band octave method to analyze measurements of sEMG obtained in the experiments. The current experiments measured fatigue in the biceps brachii during pulling/extension operations, because these represent common activities during manual machine operation. An assessment model for muscle fatigue was constructed based on objective and subjective data from the experiment. This model will be valuable for monitoring and analyzing fatigue-related changes in the upper limb, for planning work schedules and for developing ergonomic manual operating systems.

1 sEMG energy calculation of muscle fatigue

sEMG can record sequential signals from muscles during the fatigue process, thus sEMG signals should be monitored throughout the experiment, and changes in their characteristics in the operator's muscles should be analyzed over time. Although this represents a relatively straightforward monitoring method, its use is restricted because of the specialist knowledge and experience required. We therefore developed a novel method in which the sEMG activity was measured before (at the beginning of the operation) and during fatigue, and the energy was calculated using a signal-processing method. After energy normalization, it is possible to calculate the point of fatigue and assess the results of fatigue. The calculation process is as follows:

(i) To avoid the effects of power frequency noise, the sEMG data were initially subjected to digital trapped wave and filtering pretreatment (Figure 1).

(ii) Fatigue energy was calculated using the one-third band octave method. The octave is a relative scale for frequency, which is formed by a series of frequency points and average crest values for signals corresponding to these frequency points. Spectrum analysis is conducted by graded frequency, and involves many band-pass filters connected in parallel. Octave analysis is a kind of frequency domain analysis, with fewer spectrum lines and a boarder frequency band. Because of the frequency domain of the sEMG signals, the frequency domain analysis approach was chosen to calculate the sEMG energy spectrum (Figure 2), which is an octave spectrum, after pretreatment or Fourier transformation. According to the pertinent regulations of the International Electrotechnical Commission (IEC) International

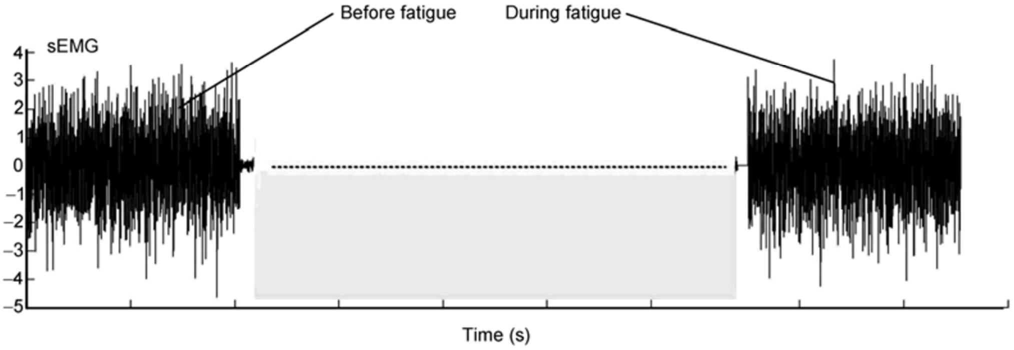

Figure 1 sEMG signals before and during fatigue.

Electrochemical Commission, the center, upper and lower frequency limits of one-third band octave spectrum analysis were decided as in Table 1. The formula for calculating the energy $F(f_i)$ is

$$F(f_i) = \int_{\text{lower limit}}^{\text{upper limit}} F(f)df. \quad (1)$$

In this formula, f_i is the centre frequency; f is the frequency of sEMG activity switched by Fourier transformation; $F(f)$ is the fatigue energy value of sEMG activity after Fourier transformation.

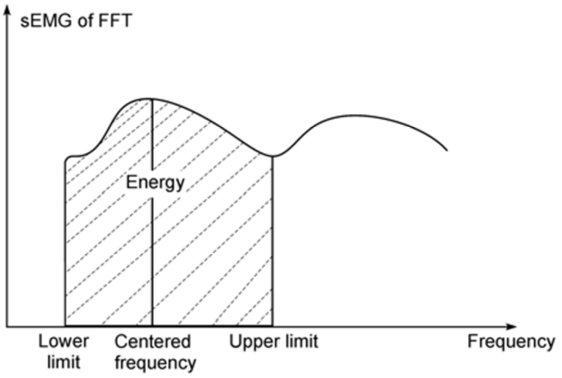

Figure 2 Energy of one center frequency by one-third band octave analysis.

The octave spectrum of energy after one-third band octave analysis of the signal in Figure 1 is shown in Figure 3.

(iii) The maximum octave spectrum before fatigue is divided by the octave spectrum during fatigue and the relevant one-third band octave spectrum $F'(f_i)$ is obtained.

(iv) Fatigue energy p is calculated using the following formula, based on the relative octave spectrum during fatigue.

$$p = \sum_i g(f_i)F'(f_i). \quad (2)$$

In this formula, $F'(f_i)$ is the relative one-third band octave spectrum; f_i is the center frequency (Table 1); $g(f_i)$ is the coefficient of frequency spectrum, whose value is calculated using the Blackman window:

$$g(f_i) = \begin{cases} 0.42 + 0.5\cos(\pi f_i / f_0) + 0.08\cos(2\pi f_i / f_0) \\ \qquad (0 < f_i \leqslant f_0), \\ 0 \quad (f_i \geqslant f_0). \end{cases} \quad (3)$$

f_0 is the virtual cut-off frequency. Because the frequency domain of sEMG activity in local activities of the neuromuscular system is 0–400 Hz, f_0=400 Hz is usually chosen.

2 Methods

2.1 Subjects

Thirteen healthy young male volunteers (mean age (23.4±2.45) years, mean weight (64.7±5.43) kg, mean height (171.7±5.41) cm) were involved in this study and gave their informed, written consent to participate. All the subjects were right handed and all were in good condition at the start of the experiments, having had no recent strenuous exercises and with no accumulated fatigue.

2.2 Devices

An impact trainer FM8220 (IMPACT Corp., China) was used to record hand-force curves of the subjects. An sEMG signal collecting system (Biovision, Wertheim, German) was used to measure sEMG curves for the biceps.

2.3 Experimental procedure

The experimental process is shown in Figure 4. The main steps were as follows:

(i) Each subject was familiarized with the purpose, process and regulation of this experiment through experimental

Table 1 Center, upper and lower frequency limits after one-third band octave spectrum analysis

Center frequency (Hz)	Lower limit frequency	Upper limit frequency	Center frequency (Hz)	Lower limit frequency	Upper limit frequency
1	0.89	1.12	25	22.27	28.06
1.25	1.11	1.40	31.5	28.06	35.36
1.6	1.43	1.80	40	35.64	44.90
2	1.78	2.24	50	44.54	56.12
2.5	2.23	2.81	63	56.13	70.72
3.15	2.81	3.54	80	71.27	89.80
4	3.56	4.49	100	89.09	112.25
5	4.45	5.61	125	111.36	140.31
6.3	5.61	7.07	160	142.54	179.59
8	7.13	8.98	200	178.18	224.49
10	8.91	11.22	250	222.72	280.62
12.5	11.14	14.03	315	280.63	353.58
16	14.25	17.96	400	356.36	448.98
20	17.82	22.45	500	445.45	561.23

instruction. Before the experiment, all subjects relaxed and learnt the outline of the experiment. The subjects were ordered to keep quiet for 10–15 min, and the sEMG activity of the biceps brachii was recorded under these conditions for 1–2 min using a biomedical signal collecting system.

(ii) Each subject was asked to drag the impact trainer using their right hand with the palm inward. At the same time, the sEMG activity of the biceps brachii was recorded. The sEMG sampling frequency was 1000 Hz and the action frequency of the trainer was 1 Hz.

Care was taken to ensure that the location of the electrode plane was the apophysis of the muscle belly of the biceps brachii, and the two recording electrodes were parallel to the direct axis of the muscle fiber. A third electrode made equilateral triangle with the two recording electrodes, 2–3 cm apart. The relevant areas of skin were shaved and cleaned before electrode placement.

Keeping a normal standing posture on the platform, each subject kept their body straight and gripped the impact trainer using their right hand, with the palm inwards and the left arm adhering to the body. Firstly, the 100% MVC was tested, and the result was set as force standard of isotonic muscle actions. The subjects were then requested to perform isotonic muscle actions with different force levels (10%, 30%, 50% and 80% MVC) until fatigue. The MVC was defined following the investigation of Scott Chadwick, who considered MVC to be the maximal voluntary contraction lasting 5 s [14]. There was about 3–20 min rest between each test.

(iii) After every test, the level of effort was subjectively assessed using the Borg scale (Table 2), by asking the subjects to provide a score from 0 to 10.

3 Results and discussion

3.1 One-third band octave analysis of sEMG activity and subjective sensation after fatigue

sEMG activities were recorded and analyzed using one-third band octave analysis during every test at 10%, 30%, 50% and 80% MVC, based on the maximum one-third band octave sEMG activity before fatigue. At the same time, Borg scales were recorded after each test. The results are shown in Table 3.

3.2 Evaluation model for fatigue based on sEMG activity

Numerous studies [1,13,14] have suggested that sEMG can reflect local muscle fatigue, as supported by the data in Ta-

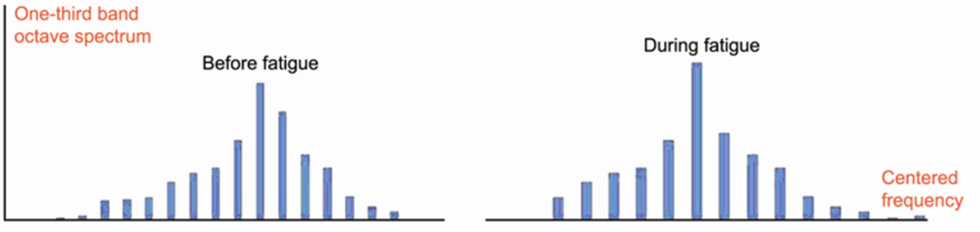

Figure 3 Calculation result of one-third band octave before and in the fatigue.

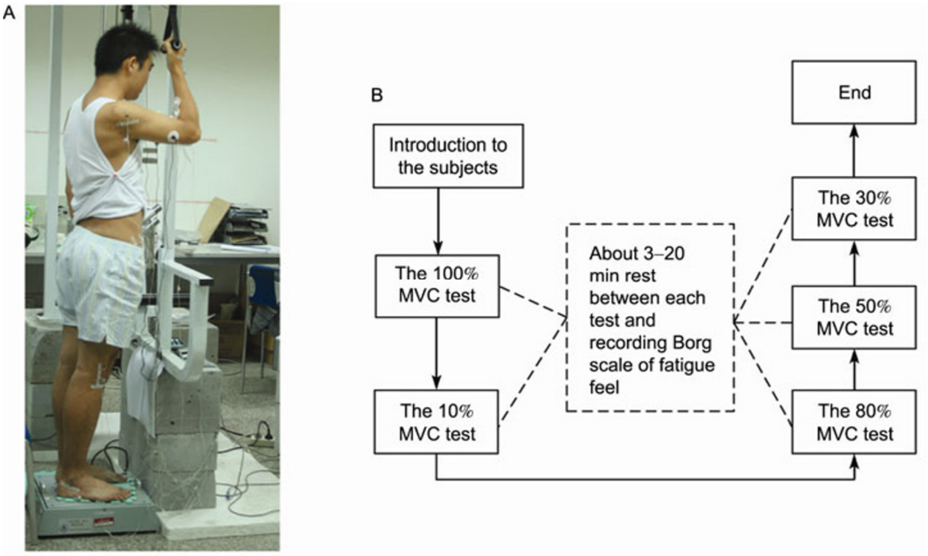

Figure 4 Experimental process. A, Electrodes on biceps muscle of arms. B, The experimental procedure.

Table 2 Borg scale

Score	Verbal description	MVC (%)
0	Nothing at all	0
0.5	Extremely weak (just noticeable)	5
1	Very weak	10
2	Weak (light)	20
3	Moderate	30
4[a)]		40
5	Strong (heavy)	50
6		60
7	Very strong	70
8[b)]		80
9[b)]		90
10	Extremely strong (almost maximal)	100

a) A score of 4 represents an effort between 3 and 5. b) A score of 8 or 9 represents an effort between 7 and 10, and the change is linear.

ble 3. As shown in Table 3, Borg scale values increased with increasing fatigue energy, demonstrating a functional relationship between these factors. sEMG measures muscle action potentials, and increasing muscle charge is associated with increased sEMG amplitude. A rise in sEMG for the same charge denotes local muscle fatigue [15].

In Table 3, the fatigue energy of subjects A7 and A13 deviated from the Borg scale values. The reason was that the subjects reported inaccurate fatigue sensations. These data were subsequently treated as singular points. Individual differences could be counteracted using sEMG signal energy during fatigue. The relationship coefficient reflects the degree of correlation between these measures.

Three kinds of curves were tested to describe the relationship between the variable p and the Borg scale: quadratic, quintic and exponential curves. The results were as follows:

Model I, quadratic curve:

$$y=-0.0599x^2+1.295x+1.096, \tag{4}$$

with a correlation coefficient R of 0.856, and an F value of 53.582.

Model II, quintic curve:

$$y=-0.0032x^5+0.0717x^4-0.562x^3 +1.778x^2-0.928x+1.865, \tag{5}$$

with a correlation coefficient R of 0.785, and an F value of 13.492.

Model III, exponent curve:

$$y=2.6924e^{0.151x}, \tag{6}$$

with a correlation coefficient R of 0.721, and a standard deviation (SD) value of 2.692.

All three models are shown in Figure 5.

According to statistical theory, curve fitting is considered

Table 3 sEMG and Borg scale results

Subject	10% MVC		30% MVC		50% MVC		80% MVC	
	Fatigue energy	Borg scale	Fatigue energy	Borg scale	Fatigue energy	Borg scale	Fatigue energy	Borg scale
A1	0.4278	1	1.403	2.5	5.609	5.5	4.1523	9.2
A2	0.5897	2	2.4347	4.5	5.0997	7	7.0781	9.3
A3	0.5788	0.7	2.0997	2.2	4.8763	5.5	6.6743	8
A4	0.3132	2	2.7039	4	4.9859	5.5	5.7407	9.5
A5	0.2682	1	2.5355	3	5.4144	6	5.8772	9
A6	0.3941	1	2.9672	3	5.3373	5	9.0778	8
A7	1.1829	4	3.6064	7.8	6.0081	6.5	16.5172	8
A8	0.681	2	2.8388	4	6.0515	4.6	20.3261	6
A9	0.7789	2	2.1803	4.5	5.7876	6.5	6.721	8.5
A10	0.886	1.5	3.1459	2.4	6.0918	3	19.6576	7
A11	0.0751	2	2.7744	6	5.053	7.9	7.3459	7
A12	1.2425	1	4.2549	3	5.5925	6	5.4701	7
A13	0.5218	5	2.2996	8.5	5.6191	7	3.9515	8

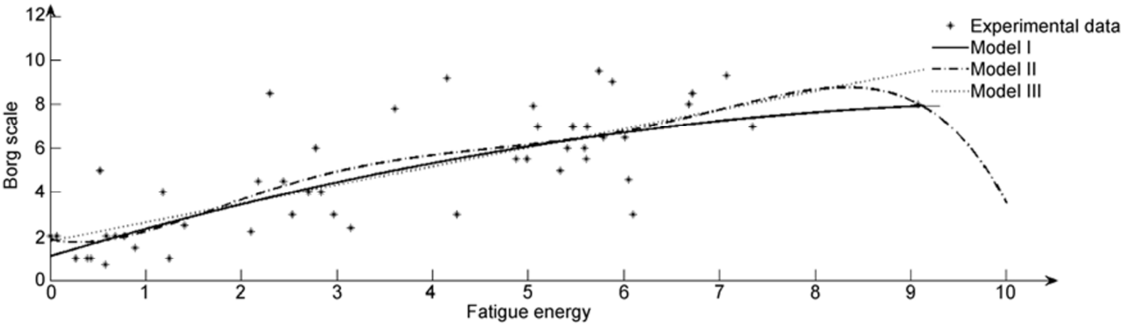

Figure 5 Curve of evaluation model for fatigue.

to be good if the correlation coefficient R>0.85. Thus model I represents a reasonable fatigue evaluation model based on sEMG activity.

During the experiments, several factors, such as individual volunteer, electromagnetic interference and recovery after fatigue, were accounted for and therefore did not influence the overall results. Consecutive measurements of sEMG activity can therefore be used as a relatively straightforward method of evaluating fatigue, after calculation with the proposed algorithm. This represents a more convenient and practical method than time domain analysis based on sEMG activity.

4 Conclusion

This study evaluated muscle fatigue during isotonic muscle action at different force levels. The model used for evaluating muscle fatigue was based on fatigue energy and Borg scale, and was able to reflect the effects of many factors, including operation time, posture, and operation mode and frequency, on muscle fatigue of the upper limb. sEMG is a time domain signal related to the above factors, while the Borg scale provides a subjective value for muscle fatigue. The model developed in this study thus provides a good reflection of the situation in reality.

The results demonstrated that a quadratic curve reflected the relationship between fatigue energy and fatigue sensation, which suggests that fatigue energy can be calculated using collected sEMG activity recordings, and that fatigue sensation can be determined using this evaluation model. This model therefore provides a suitable basis for developing fatigue-monitoring equipment based on sEMG activity, as well as providing a theoretical and design basis for monitoring the fatigue levels of operators, and designing and planning jobs to make them more ergonomic and intuitive.

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