EFFECTS OF TWO RECOVERY METHODS ON THE LEG MUSCLE FATIGUE OF OCEANAUTS IN A MANNED SUBMERSIBLE

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ABSTRACT

Background: The cabin of the manned submersible is a narrow and sealed space. The long-time work of oceanauts is easy to cause muscle fatigue and stiffness, which reduces efficiency. This paper explored the relative more effective way to relieve leg muscle fatigue of the oceanauts in the manned submersible. **Material and Methods:** Twenty healthy young people with an average age of 24 years were selected as the participants, while the usual natural relaxation and the stretching method proposed by the surveys were selected as the relieve method for muscle fatigue. This study compared the effects of the 2 recovery ways using the electromyography data from the quadriceps femoris and biceps femoris, and the subjective scales. **Results:** With the support of data of integral electromyogram (iEMG), root-mean-square (RMS), subjective scales, authors finally found that the 2 muscles of the leg are fatigued significantly, and biceps femoris has more accumulation of fatigue. Although the 2 recovery ways have a significant relief effect on muscle fatigue, the stretching method can reduce more muscle fatigue in a short period of time, especially for biceps femoris. The stretching method is advocated for the oceanauts. **Conclusions:** The findings suggested that the stretching method was optimal for relieving the muscle fatigue of the oceanauts during the operation. Med Pr. 2022;73(2):95–107

Key words: EMG, muscle fatigue, stretching, manned submersible, oceanauts, recovery methods

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INTRODUCTION

Effects of narrow and sealed cabins on oceanauts

Manned submersibles can carry scientists and equipment into the deep sea to perform missions such as scientific investigations, prospecting, topographic surveying, detection and capturing of suspicious objects. The cabin of a manned submersible is quite limited [1] but it includes numerous subsystems, such as a power control system, a communication system, a mechanical arm system, etc. [2]. During the operation, the oceanauts need to keep knees bent and back leaning forward to control the systems, with only the upper limbs able to move within a small range [3]. However, as the depth of the dive increases, the working time of the oceanauts (i.e., the time that the oceanaut stays in a sitting posture) becomes longer and longer.

For example, the operating hours of Nautile is about 5 h, while the maximum operating times of Jiaolong and Rainbow fish manned submersibles exceed 80 h.

Lurati [4] pointed out that prolonged sitting in the workplace can promote early muscle fatigue in both the whole body and local muscle fatigue. During prolonged sitting there is typically minimal leg muscle activity, compared to during more active work positions such as walking or cycling, which may impact vascular return [5] causing leg swelling. Further, there is a passive load on tissues particularly at the buttock but also the thigh [6]. Meanwhile, several research have revealed the relationship between the sitting time and human fatigue. Prolonged sitting has been proved could cause lumbar muscle fatigue and increase intradiscal loads [7], and discomfort in the lower extremities is a common complaint among them [8]. Bao and Lin [9] found that

in all sit/stand schedules, the longer standing schedule leading to less muscle fatigue. Chambers indicated that prolonged static postures, sitting or standing, can cause muscle fatigue for leg muscle, and frequent alternating between posture may reduce muscle fatigue both in physiological signals and self-reported fatigue [8]. In this way, the oceanauts would suffer from the muscle fatigue in the course of deep-diving operation. Muscle fatigue has been recognized as a factor in the decline of alertness, mental concentration, and motivation [10], which causes the oceanauts' declining efficiency.

Li et al. [11] found that the rectus femoris muscles of oceanauts were more fatigued during work than during rest in full ocean depth manned submersible of China. At the same time, authors have also interviewed relevant staff from the China Ship Scientific Research Center about the lower limb muscle fatigue during the work. Four of the 5 oceanauts said that they would feel fatigued in the lower limbs during the operation. This may be due to the small range of movement of the lower limbs, and they need to maintain the same posture for a long time. Although muscle fatigue is an essential factor affecting the performance of oceanauts, no research has been conducted on measures of helping them relieve fatigue.

Research on muscle fatigue

In the medical literature, fatigue is composed of fatigue experienced by the patient and physiological fatigue. In physiology, fatigue is usually defined as the loss of the ability to generate strength at will during exercise [12]. And muscle fatigue is a kind of physiological fatigue. As the accuracy and efficiency of completing work are reduced under fatigue, there has been extensive research on human muscle fatigue. Lurati [4] outlined the muscle fatigue may also lead to ligament and tendon injuries. Zhang and Li [13] performed experiments to build the muscle fatigue model based on the surface electromyogram (sEMG) signals. Kim et al. [14] compared individual shoulder muscle fatigue in various external conditions. Choi and Lee [15] studied the effect of the application direction of the kinesiology tape on the fatigued quadriceps muscles of athletes. Jebelli et al. [16] explored the dynamic characteristic of muscle fatigue in construction workers. Therefore, it can be seen that muscle fatigue exists in a wide range of work areas.

Fatigue relief problem

Traditionally, stretching, massage, acupuncture, and some professional device are used to eliminate muscle fatigue and relieve pain. Due to massage and acupuncture

have high professional requirements on the operators, they cannot be effectively implemented by the oceanauts during the diving. As for the professional device for the lower limb, such as Power Plate, Lower limb active and passive training system, they are all large in size. Due to the oceanauts have carried many instruments and equipment in the dive process and the inside of the manned submersible is very narrow, the placement of loosening aids such as foam rollers should be carefully designed. However, this aspect is obviously not included in the consideration of the existing manned submersible. As for the percussive therapy devices, it is necessary to consider the layout of its power supply, sensors and other components, so it is difficult to implement in the existing manned submersible. In this way, it is not possible to carry a professional device that relieves muscle fatigue in a submersible due to the narrow space.

The current manned submersibles use automatic control systems during diving and floating [17], which allow the oceanauts a few minutes of rest. Through interviews with and documentaries about Chinese oceanauts, authors learned that they can change their posture, as standing up with doing nothing to relieve fatigue during breaks, and the average amount relieve time do not exceeds 15 min in 2-hour working. However, because of the limited rest time, the effectiveness of relieving fatigue through this method is insufficient. Thus, it is of considerable significance to investigate the means of quickly reliving leg muscle fatigue.

Nicol et al. [18] demonstrated that muscle strength would change during dynamic stretching, and take the lower-limb extensor muscles as examples. Laur et al. [19] found that although acute stretching of the hamstring muscle produced transient muscle power, it did not affect normal movement. Park et al. [20] determined the optimal time and frequency for static stretching to recover from hamstring muscle fatigue. Macadam et al. [21] studied the spinal muscles in stretch-shortening cycles, which are widely used in athletic training. Previous studies have revealed that when the muscles exert strength continuously and contract for extended periods, they become stiff. Stretching the muscles momentarily produces large strength, and muscle fatigue can be reduced quickly. However, there is little work on identifying the most effective means of relieving fatigue in narrow, sealed environments.

Quantification of muscle fatigue

In the 1980s, surface electromyography (sEMG) began to be widely used to quantitatively measure muscle

fatigue. During continuous muscle exertion, the action potential (AP) conduction rate decreases [22], which causes the frequency spectrum of the sEMG to change. Aminoff et al. [23] used sEMG to track the electromyography (EMG) changes in muscle fatigue. Areeudomwong et al. [24] used sEMG to observe the muscle activity of the lower neck to identify whether the shoulder taping reduces neck discomfort. Naik and Khan [25] proposed ergonomic mediations for lessening the risk of musculoskeletal injuries in professional cleaners based on EMG.

In this study, authors examined 2 approaches of recovering from muscle fatigue during work, natural relaxation and stretching, to determine the most effective means of relieving the leg muscle fatigue of oceanauts in narrow, sealed cabins of manned submersibles. Towards this end, this study analyzed and compared the results of experiments based on sEMG and subjective scales for both recovery methods.

MATERIAL AND METHODS

Experimental design

This study acquired the sEMG signals of the quadriceps femoris and biceps femoris of the study participants >20 min, followed by the sEMG signals of the 2 muscles after 8-minute recovery. Each participant performed 2 tests, one with a defined sitting posture and natural relaxation recovery and the other with the defined sitting posture and stretching recovery.

The defined sitting posture acquired by the interview with the relevant staff from the China Ship Scientific Research Centerwas designed to simulate the postures of working oceanauts: the back leaned forward at 15° to observe the front control panel, the knees were bent at 100°, and the feet were placed on the ground, as shown in Figure 1a. The first recovery method was natural relaxation, which is the most common technique used by oceanauts, as shown in Figure 1b. Actually, it is the relaxation behavior that participants do not take the initiative to perform any action, but only stop performing work. The recovery time was 8 min. The second recovery method was stretching. The stretching exercise consisted of 2 sets of stretching for the front thigh and 2 for the back thigh, as shown in Figures 1c–f. In total, 8 sets of stretching were completed, each of which lasted for 30 s, with alternation between the legs. Thus, the total stretching time was 4 min. Then, the participants were allowed to relax for 4 min in the position shown in Figure 1b, yielding a total recovery time of 8 min. In order

to demonstrate the effectiveness of author proposed stretching exercise can be operated in the manned submersible cabin, this study drew a schematic diagram as shown in Figures 1g–l.

Experimental preparation

This study used flexible wood strips to build a 2-meter diameter spherical cabin to define the participants' motion ranges. The carpet was used to represent the floor area, panels and portholes were constructed with cardboard to simulate the working postures of oceanauts. Authors also provided a cushion with a height of 250 mm according to the JiaoLong manned submersible, as shown in Figure 1.

Authors used the Biopac EMG signal acquisition system. The collected data were transferred to AcqKnowledge 4.2, which was compatible with the hardware for processing. Twenty healthy young people with an average age of 24 years were selected as the participants, including 13 males and 7 females (the characteristics of them as shown the Table 1). None of the participants had any symptoms of muscle pain or skeletal pain or were overly obese or thin. Before the experiment began, all the participants signed an informed consent form, and the study was approved by Northwestern Polytechnical University, and complied with the Declaration of Helsinki.

Experimental process

The measured muscles in this experiment were the quadriceps femoris and biceps femoris. This study used AgCl electrode sheets with an electrical contact area of 1 cm². The positive and negative electrodes were spaced 20 mm apart. In Figure 2, × indicated the position of the positive electrode, and • represented the assist points. The bipolar sEMG electrodes were placed around the recommended sensor location and were oriented parallel to the muscle fibers.

During the experiment, the participants were required to maintain the defined sitting position for 20 min and try to avoid changing the posture. The sEMG signal was recorded simultaneously. The experiment is conducted as shown in Figures 1m and 1n. Each participant performed 2 tests: one in which the defined sitting posture was followed by natural relaxation and another in which the defined sitting posture was followed by stretching. The participants were allowed to recover for 8 min using the different recovery methods, and the sEMG signal was recorded for 1 min after recovery. After each experiment, the participant rested for 60 min until returning to the initial state and then begin the next experiment. Authors also invited
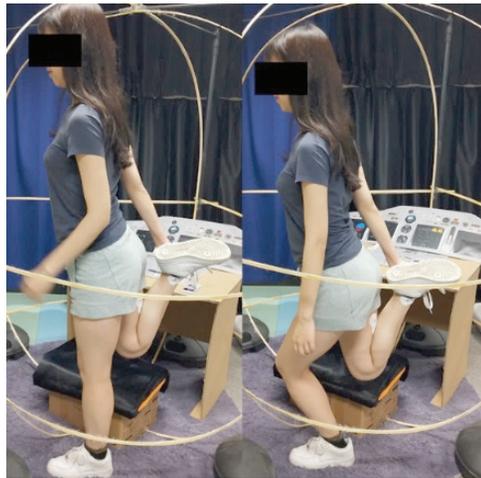
a)

b)

c)

d)

One leg is bent at right angle. The other knee is placed on the ground, and the hand grabs the ankle and pulls up. The front knee cannot extend beyond the toe.

One leg is straight. The other leg is bent, and the instep of this leg is grasped with the hand. Then the supporting leg is bent to lower the body.

e)

f)

While seated, one foot is placed on the floor and the other is raised with the leg straight. The upper body is kept straight. The hands are extended forward slowly, and the back of the raised leg is pulled.

While standing, the upper body is bent forward and the legs are clasped with the hands, with the head kept close to the calves.
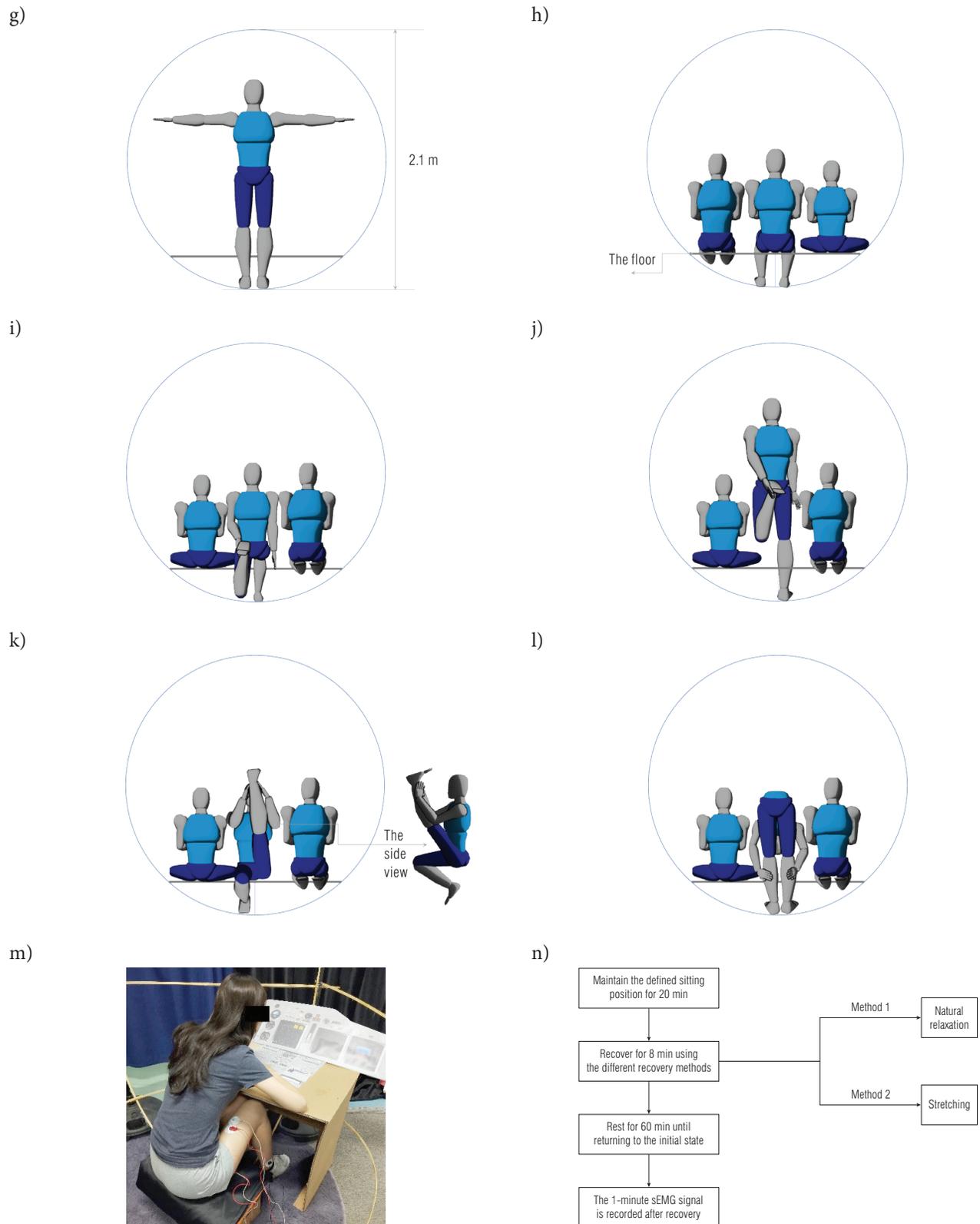
g)

2.1 m

h)

The floor

i)

j)

k)

The side view

l)

m)

n)

Maintain the defined sitting position for 20 min

Recover for 8 min using the different recovery methods

Method 1 → Natural relaxation

Method 2 → Stretching

Rest for 60 min until returning to the initial state

The 1-minute sEMG signal is recorded after recovery

Figure 1. Schematic diagram of experimental design: a) defined sitting posture, b) natural relaxation, c) the first step of stretching the front thigh, d) the second step of stretching the front thigh, e) the first step of stretching the back thigh, f) the second step of stretching the back thigh, g) space of manned submersible cabin, h) diagram of oceanauts' common operating postures, i) diagram of the first step of oceanauts' stretching the front thigh during the operation, j) diagram of the second step of oceanauts' stretching the front thigh during the operation, k) diagram of the first step of oceanauts' stretching the back thigh during the operation, l) diagram of the second step of oceanauts' stretching the back thigh during the operation, m) participant experimenting, n) the experiment process

a)

b)

c)

d)
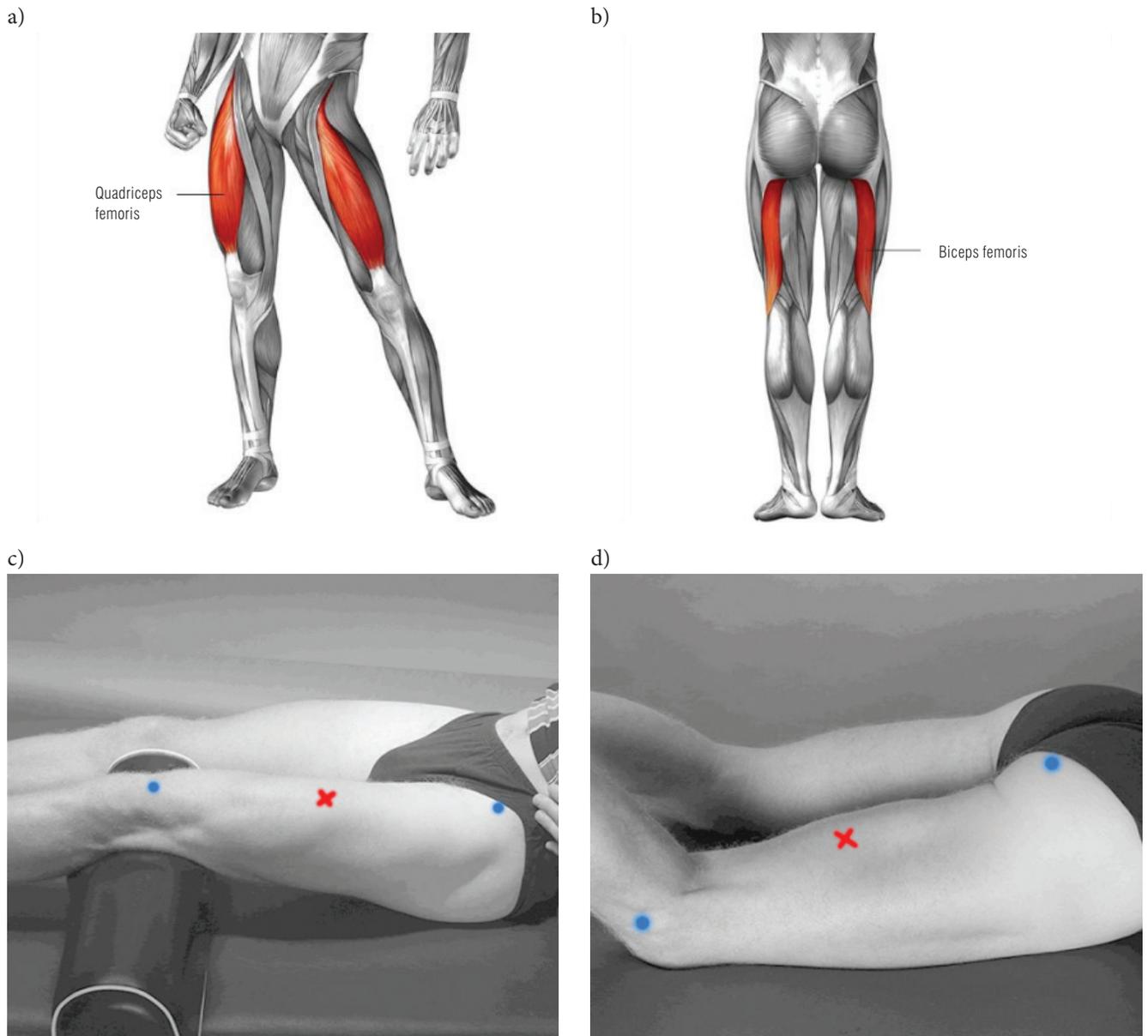
x position of the positive electrode   ● assist point

Figure 2. The measured muscles and position of the electrode: a) quadriceps femoris, b) biceps femoris, c) position of the electrodes in quadriceps femoris, d) position of the electrodes in biceps femoris

Table 1. Characteristics of the study participants conducted in Northwestern Polytechnical University, Xi'an, China, in November, 2019–February, 2020

Variable	Participants (N = 20)		
	men (N = 13) (M)	women (N = 7) (M)	total (M±SD)
Age [years]	24.23	23.57	24±2.20
Height [cm]	176.00	161.57	170.95±8.50
Weight [kg]	73.76	50.28	65.55±13.53
Body mass index [kg/m²]	23.80	23.57	22.21±3.05

the participants to fill out subjective assessments to record their fatigue levels every 6.5 min during the experiment. This study divided the degree of fatigue into 6 levels:

- level 0: no fatigue feeling,
- level 1: weak fatigue feeling,
- level 2: slightly feeling of fatigue,
- level 3: strong feeling of fatigue,
- level 4: very strong feeling of fatigue, and
- level 5: extremely strong feeling of fatigue.

Statistical and analytical methods

In this study, the initial sEMG signals were obtained through the sEMG sensor at a sampling rate of 1000 Hz. Next, the sEMG signals were preprocessed using a filter with a pass range of 10–600 Hz. Then, they were amplified and post-filtered using a second order Butterworth filter of 10–500 Hz to cancel noise. Finally, the filtered sEMG signals were full wave rectified.

Thus far, the time-frequency sEMG analysis method has been considered to be suitable for non-stationary signals [26]. In this way, the integral electromyogram (iEMG) and root-mean-square (RMS) are approved parameters for responding to the EMG signal. As muscle fatigue builds up, the value of iEMG and RMS increase. This study converted the raw data into iEMG, taking 2.5 s as the integration time unit. Thus, 480 iEMG values were obtained for each muscle of each person in 20 min, and 24 iEMG values were acquired within 1 min after recovery. Also, 504 RMS values were obtained for each muscle of each person. Finally, authors imported the obtained values into the SPSS (Statistical Product and Service Solutions) for analysis.

To facilitate statistical analysis, this study selected the 3 typical task stages: the first minute in maintaining the sitting posture period as the first stage, the last minute in maintaining posture period as the second stage, and 1 min after the recovery as the third stage.

This study intercepted 24 values from each of the 3 stages in turn. One-way repeated measures ANOVAs and *post hoc* multiple tests on were conducted on iEMG values of both quadriceps femoris and biceps femoris muscles across the selected 3 stages. It was found that, the iEMG values of quadriceps femoris and biceps femoris obtained from the natural relaxation were significantly lower than that in the last minute in the posture maintaining period. In the same way, the iEMG values acquired from the strengthening were significantly different from that in the last minute during the sitting.

RESULTS

Fatigue changes in muscles

Firstly, this study applied a regression analysis to the iEMG with 20 min of accumulated fatigue. Authors imported 500 values from these 20 subjects into the SPSS for regression fitting. The SPSS could report the R-squared (R^2) of the fitted curve. The R^2 is also called the coefficient of determination of the equation, which can range 0–1. The closer it is to 1, the closer the association of the independent variable with the dependent variable, and the more successful the equation fitting.

Figure 3a and 3b presented the fitting curves for the average iEMG of the quadriceps femoris and biceps femoris before using the 2 different recovery methods. The R^2 values of both lines are close to 1, which means that the linear fit is good. The positive values of these slopes indicated that the muscle fatigue accumulated >20 min. The cubic curves shown here also revealed the changes in the muscles. Before x = 200, the curves changed slowly and there was no obvious upward trend. After x = 200, the curves of both 2 muscles continued growing and the rising speed increases. Thus, beginning at the eighth minute, the force output of 2 muscles both increased significantly, and the muscles began to accumulate fatigue.

Compared to the quadriceps femoris, the biceps femoris function had a smaller intercept and a higher slope, which meant that the biceps femoris accumulates fatigue faster.

Authors analyzed the RMS in the same manner, as shown in Figures 3c and 3d. The slope of the fitted RMS result is positive, indicating that the muscle fatigue of the participants accumulated. The curve grow faster after x = 200, indicating rapid fatigue accumulation from the eighth minute. Comparing the intercepts and slopes of the functions, it was evident that the output of biceps femoris is less than that of the quadriceps femoris, but the rate of fatigue growth of the biceps femoris was greater than that of the quadriceps femoris.

Comparison of the effects of the 2 recovery methods: iEMG and RMS analysis

Firstly, 2-tailed t-test was performed to compare the 2 recovery methods. The result of iEMG indicated that both recovery methods have positive effects on muscle recovery. Meanwhile, the 2-tailed t-test of biceps femoris RMS indicated that for biceps femoris, the natural relaxation way cannot achieve the purpose of relieving the fatigue (p > 0.05).
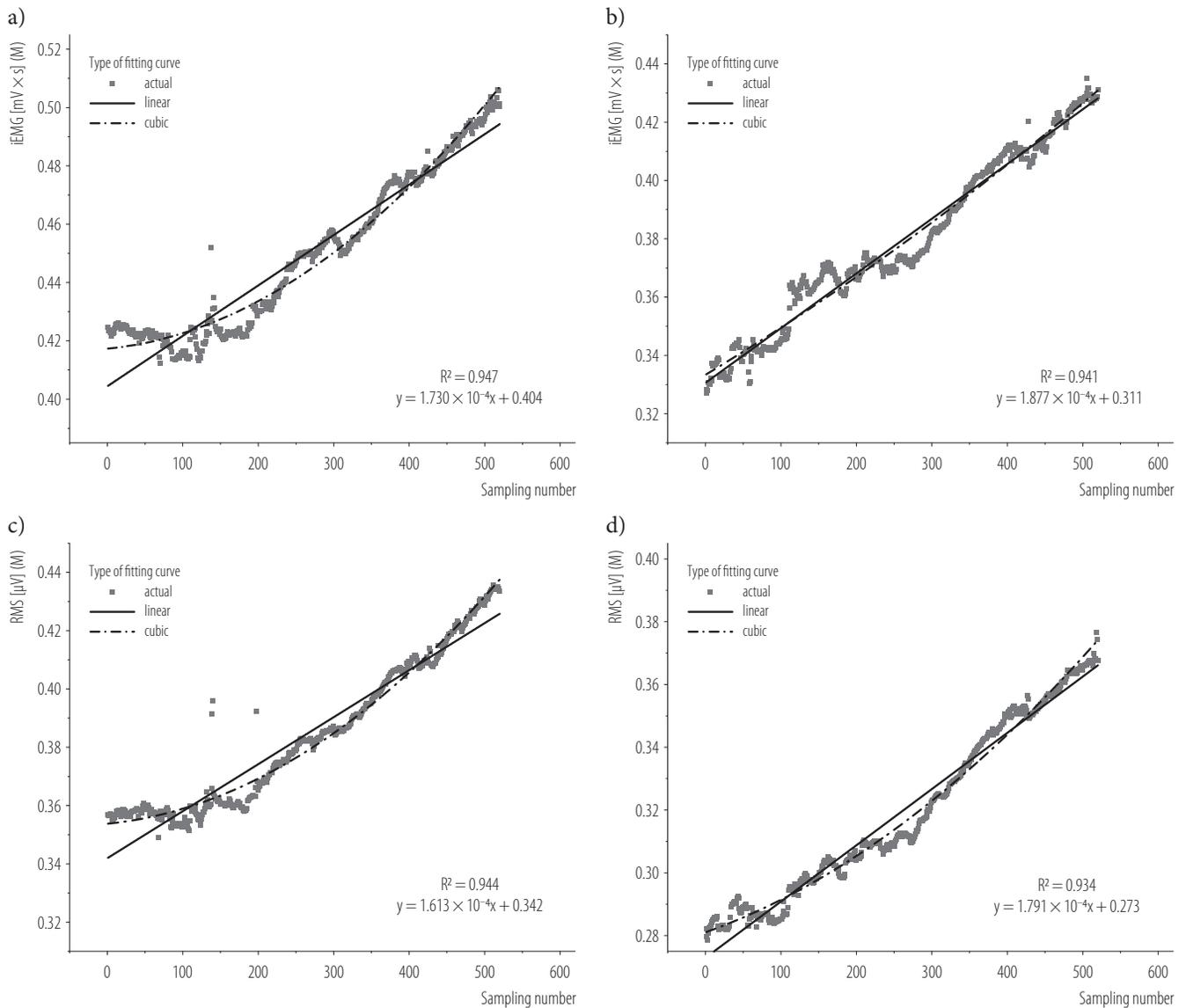
Figure 3. Fitting curves: a) the integral electromyogram (iEMG) of the quadriceps femoris, b) the iEMG of the biceps femoris >20 min, c) the root-mean-square (RMS) of the quadriceps femoris, d) the RMS of the biceps femoris >20 min; the study conducted in Northwestern Polytechnical University, Xi'an, China, in November, 2019–February, 2020

Next, this study performed a covariance analysis on the iEMG and RMS values. Covariance analysis can eliminate the effects of artificial and uncontrollable co-variates on the variance of the different recovery methods. The results obtained for the quadriceps femoris are shown in Table 2. The significance levels of the iEMG and RMS with the modified approach are both <0.05, indicating that the 2 recovery methods have significantly different effects on the relief of the quadriceps femoris. The results for the biceps femoris are also shown in Table 2. The 2 recovery methods have significantly different effects on the relief of the biceps femoris. The significance level of gender is >0.05, indicating that gender does not affect muscle recovery.

Then, this study compared the differences between the effects of the 2 recovery methods. To represent the percentages of iEMG recovery of the quadriceps femoris authors used equation (1) and to represent the iEMG recovery of biceps femoris muscles respectively after recovery, as shown in Figure 4a, authors used equation (2).

$$QF_{iEMG} = 1 - R_1/BR_1 \qquad (1)$$

$$BF_{iEMG} = 1 - R_2/BR_2 \qquad (2)$$

where:
R_1 and R_2 – the iEMG of the 2 muscles after recovery,
BR_1 and BR_2 – the iEMG of the 2 muscles before recovery.

Table 2. Covariance analysis-effect test for iEMG of quadriceps femoris after recovery; the study conducted in Northwestern Polytechnical University, Xi'an, China, in November, 2019–February, 2020

Variable	SS	df	MSE	F	p
Quadriceps femoris					
iEMG					
modified model	2.218[a]	4	0.555	84.454	0.000
quadriceps femoris 20 min	1.713	1	1.713	260.836	0.000
2 different recovery methods	0.035	1	0.035	5.352	0.028
gender	0.019	1	0.019	2.954	0.096
deviation	0.190	29	0.007		
RMS					
modified model	1.810[b]	2	0.905	170.125	0.000
quadriceps femoris 20 min	1.789	1	1.789	336.208	0.000
2 different recovery methods	0.028	1	0.028	5.331	0.027
deviation	0.176	33	0.005		
Biceps femoris					
iEMG					
modified model	2.079[c]	4	0.520	49.033	0.000
biceps femoris 20 min	1.287	1	1.287	121.416	0.000
2 different recovery methods	0.051	1	0.051	4.767	0.037
gender	0.009	1	0.009	0.847	0.365
deviation	2.079[a]	4	0.003		
RMS					
modified model	0.944[d]	2	0.472	59.760	0.000
biceps femoris 20 min	0.832	1	0.832	105.308	0.000
2 different recovery methods	0.057	1	0.057	7.256	0.011
deviation	0.261	33	0.008		

MSE – mean square error, SS – squared sum of dispersion.
[a] $R^2 = 0.921$ (adjusted $R^2 = 0.893$), [b] $R^2 = 0.912$ (adjusted $R^2 = 0.905$), [c] $R^2 = 0.871$ (adjusted $R^2 = 0.832$), [d] $R^2 = 0.784$ (adjusted $R^2 = 0.781$).

The results showed that for the quadriceps femoris, the iEMG recovery with stretching is >30%, while the iEMG recovery with natural relaxation is <20%. For biceps femoris, the iEMG recovery with stretching is >30%, while the iEMG recovery with natural relaxation is <15%. In this way, muscle fatigue is significantly reduced after stretching, and stretching is more effective for the quadriceps femoris.

To represent the percentage of RMS recovery of the 2 muscles respectively after recovery, as shown in Figure 4b, authors used:

$$QF_{RMS} = 1 - R_3/BR_3 \qquad (3)$$

$$BF_{RMS} = 1 - R_4/BR_4 \qquad (4)$$

where:
R_3 and R_4 – the RMS values of the 2 muscles after recovery,
BR_3 and BR_4 – the RMS values of the 2 muscles before recovery.

The results showed that for the quadriceps femoris, the RMS recovery with stretching was about 30%, while that with natural relaxation was about 22%. For the biceps femoris, the RMS recovery with stretching was >25%, while that with natural relaxation was <10%. Again, stretching resulted in more effective muscle recovery.

Finally, this study used the mean values of all participants at each sample point to evaluate the changes of the 2 recovery methods over time as shown in Figures 4c–f. Meanwhile, authors predicted the value in
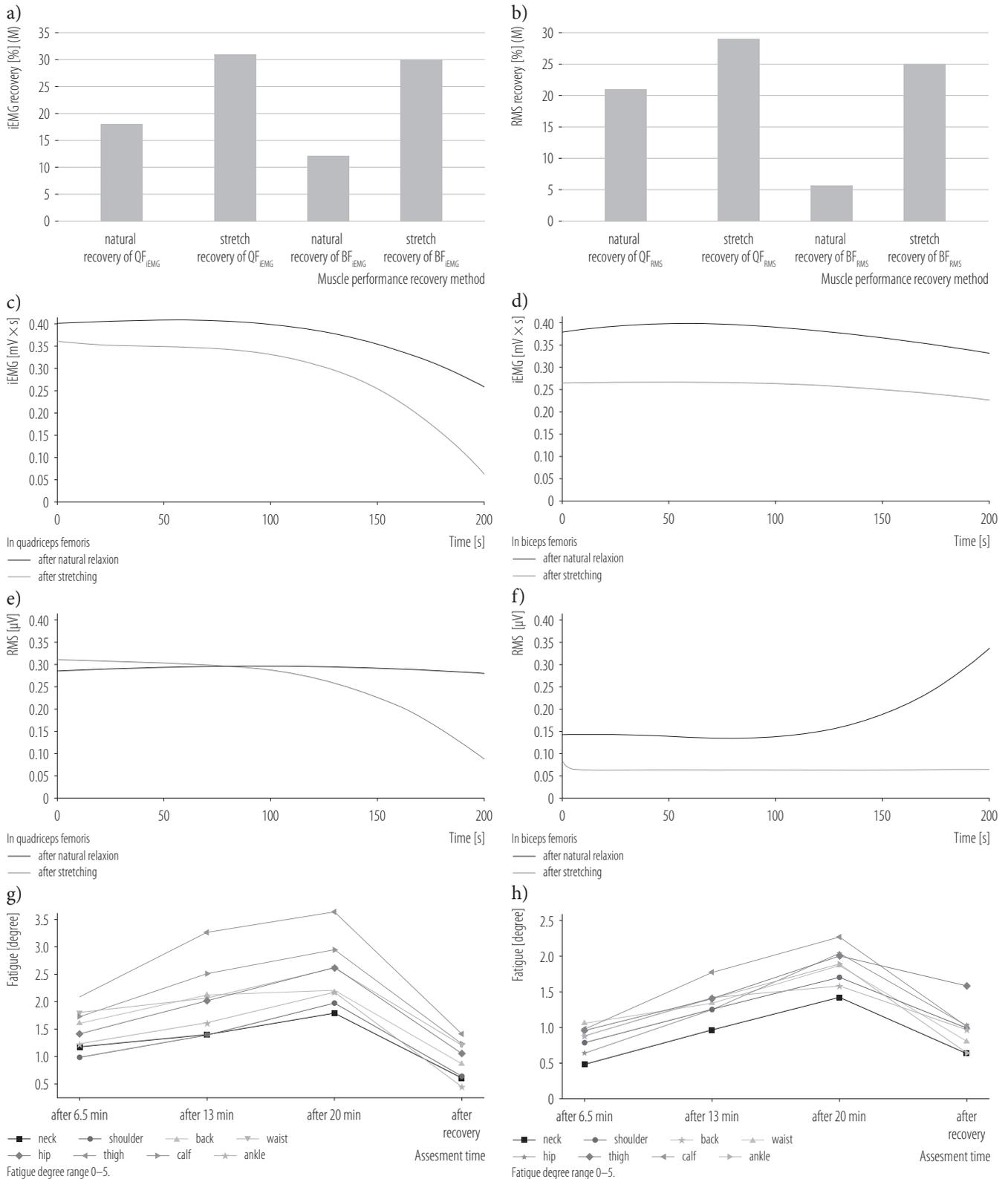
Figure 4. Comparison of 2 recovery methods: a) comparison of iEMG recovery with the 2 recovery methods, b) comparison of RMS recovery with the 2 recovery methods, c) the rule of iEMG variation in quadriceps femoris of 2 recovery method with time, d) the rule of iEMG variation in biceps femoris of 2 recovery method with time, e) the rule of RMS variation in quadriceps femoris of 2 recovery method with time, f) the rule of RMS variation in biceps femoris of 2 recovery method with time, g) subjective scores >20 min of working and recovery of natural relaxation, h) subjective scores >20 min of working and recovery of stretching; the study conducted in Northwestern Polytechnical University, Xi'an, China, in November, 2019–February, 2020

the following time according to the rule of value change by the time they obtained within 1 min. The Figures 4c–f clearly showed that stretching have a better restorative effect than natural recovery for both muscles. In the comparison of the 2 muscles, obviously stretching was more effective for the recovery of quadriceps femoris fatigue, which was consistent with the previous analysis. However, there was a big difference between the recovery effect of the natural relaxation and the stretching on biceps femoris. According to the analysis of Figure 4f, natural recovery cannot achieve effective recovery, which verified the conclusion of 2-tail test above.

Subjective analysis

During the experiment, the participants completed the assessment every 6.5 min during the 20 min test period, as well as once after the recovery, for a total of 4 times. The average data for all 20 participants are shown in Figures 4g and 4h.

In 20 min, the level of muscle fatigue generally increased by 1 to 1.5 times. The thigh and calf muscles were the most fatigued, and the accumulation of fatigue in the thigh, calf, back, and waist was the most pronounced. Comparing Figures 4g and 4h, this study found that the participants could relax to the state of the 10th min by natural relaxation, but experienced relief to the initial state by stretching. Thus, the participants generally believed stretching to be a more effective means of relieving muscle fatigue.

Other factors affecting fatigue recovery

This study found that stretching is generally superior to natural relaxation for fatigue recovery, but it was not known whether this advantage varied from person to person. Thus, authors investigated the effects of the weight and height of the participants on the results using probit regression analysis, which is a non-linear regression analysis method that addresses the effects of different stimuli on variables.

As a result, the effects of the weight and height on the iEMG and RMS of the 2 muscles had significance values >0.05, indicating that weight and height have no significant effects on the recovery methods. The effects of the recovery methods were independent of the body size of the person and apply to anyone of normal size.

DISCUSSION

Studies have confirmed the correlation between EMG amplitude (including iEMG and RMS) and muscle fatigue. Yung and Wells [27] found that due to fatigue accumulation, the EMG signal was associated with an increase in RMS amplitude. Weir et al. [28] and Kamavuako et al. [29] found a significant positive correlation between the average iEMG and muscle strength respectively. Dideriksen et al. [30] found that the force capacity and the electrophysiological membrane properties of the muscle fibres can change during fatiguing contractions. They also proposed an integrative model of both surface EMG and force generation to inferring how EMG and muscle force change during different types of fatiguing contractions. In this way, authors compared the effects of 2-leg muscle recovery methods in a narrow, sealed space by EMG based on iEMG, RMS, and subjective assessment data. This study found that the fitting effects of the iEMG and RMS were consistent when indicating the muscle fatigue changes within 20 min. The fatigue accumulation was obvious. The slopes and intercepts of the curves indicated that the quadriceps femoris have a more initial output and less fatigue accumulation than the biceps femoris.

In the 2-tailed test, the iEMG results showed significant differences between before and after recovery in all experiments. However, in the RMS results, there was no significant difference for the biceps femoris between before and after natural recovery, indicating that the natural recovery of the biceps femoris was not as good as in the other groups. All sets of data exhibited greater recovery after stretching. Overall, the results indicated that stretching is more effective for reducing leg muscle fatigue. After maintaining a certain working posture for a long time, the muscles are fatigued, and stretching breaks the fatigue of the muscles, which induces relaxation and makes the muscles recover more fully. What is more, the gender, weight and height do not affect muscle recovery according to the analysis above, in this way, the stretching is suitable for everyone.

Besides, subjective evaluations effectively represented the perceived fatigue of the participants. As evidenced by the subjective assessment results, the stretching is indeed a more effective way to relieve muscle fatigue.

Even though this experiment was based on the cabin of a manned submersible, the conclusions obtained are also applicable to other narrow, sealed spaces. As future submersible cabins will have greater dive depths, longer working times, and more confined space, the proposed stretching method is advocated for oceanauts to relieve fatigue and improve work efficiency.

Of course, this study also has some limitations. This study only compared the muscle fatigue recovery results

of active stretching and natural relaxation. This study aims to form a standardized exercise method to the oceanauts in the actual diving process. However, authors have not carried out research on the effect of different stretching sequences on personnel fatigue recovery, which is this research goal in the next stage. Besides, due to Jia [7] found that compared to traditional EMG-based fatigue measurement methods, muscle stimulation methods, could provide more stable and visible results in muscle fatigue measurement. Authors would use both the EMG amplitude method and muscle stimulation method to evaluate the muscle fatigue in the future research.

CONCLUSIONS

In the present study, authors quantitatively investigated the natural recovery and stretching recovery on the relief of oceanauts' leg muscle fatigue. The study included 20 healthy young people with an average age of 24 years in a simulated environment of manned submersible to improve the reliability of results. The EMG analysis and subjective assessment were applied to compare the effect of methods. The result of the study revealed that the oceanauts' quadriceps femoris has less fatigue accumulation than the biceps femoris after keeping a defined posture during the operation, and both recovery methods significantly relieved muscle fatigue. The study strongly recommended that the stretching recovery method for it is more effective, especially for the biceps femoris, despite the genders, weights and heights of oceanauts. In addition, the iEMG, and RMS analysis corresponds well with the perceived fatigue of the participants, as evidenced by the subjective assessment results. The conclusion of the study has significant implications for oceanaut comfort as well as the efficiency and accuracy of their work, and is also applicable to workers in other narrow, sealed spaces. To improve the oceanauts' working efficiency, further research should pay attention to the fatigue relief of other parts of the oceanauts.

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