

## Relationships between Force and Muscle Oxygenation Kinetics during Sustained Static Gripping using a Progressive Workload

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**Abstract** This study aimed to examine the relationships between force and subjective muscle-fatigue sensation (SMS), and muscle oxygenation kinetics during sustained static gripping using a progressive workload. Subjects consisted of 10 males (height  $173.2 \pm 7.1$  cm, body weight  $70.3 \pm 15.1$  kg, and age  $21.1 \pm 1.5$  years). They performed sustained static gripping with 7 gradually increasing relative demand values of 20% to 80% maximal voluntary contraction (MVC). The staging of the progressive workload was 10 s for 20% MVC, 20 s each for 30, 40, 50, 60, and 70% MVC, and 10 s for 80% MVC. Borg's SMS was used to measure the fatigue sensation of the antebrachial region in a pre-test and every 10 s during the test. The time to reach minimum Oxy-Hb/Mb appeared at about 50 s ( $52.6 \pm 25.2$  s) after the onset of sustained static gripping, and the time to reach maximum Deoxy-Hb/Mb occurred later at 90 s. Significant and high correlations ( $r=0.632-0.721$ ) were found between the time to reach maximum Deoxy-Hb/Mb, and Peak Force Time and Average Force. Even though the demand values caused a workload increase and reached 50% MVC, the change of Total Hb/Mb and Oxy-Hb/Mb kinetics was relatively small. Therefore, the effect caused by an obstruction of blood volume may not occur during the progressive workload. It was determined that the contraction time after the peak of SMS is relatively short and an individual difference in force value expands in the phase where SMS reaches its peak. *J Physiol Anthropol* 28(3): 109–114, 2009 <http://www.jstage.jst.go.jp/browse/jpa2> [DOI: 10.2114/jpa2.28.109]

**Keywords:** muscle oxygenation kinetics, sustained static gripping, progressive workload

### Introduction

Muscle endurance has been evaluated by sustaining time or decreasing rate, using fixed relative load intensities (Maughan et al., 1986; Laforest et al., 1990; Clarke et al., 1992; Huczel et al., 1992; Larsson et al., 2003). And, it has been reported that

forces exerted in muscle endurance measurements largely differ by workload, measurement time, and patterns of exertion (Nakada et al., 2004; Yamaji et al., 2004). Therefore, under differing measurement conditions, the evaluated muscle endurance is not the same. For example, the sustained force exertion with over 50% maximum voluntary contraction (MVC) can be sustain for a short period of time and produces a marked force decrease by the effect of blood volume obstruction after the onset of force exertion (Yoshimura et al., 1996; Nagasawa et al., 2000). In addition, the force value in any workload reaches a steady state at 15–20% MVC and then decreases little (Yoshimura et al., 1996; Nagasawa et al., 2000; Yamaji et al., 2000; Yamaji et al., 2004). Muscle blood volume obstruction increases blood pressure and heart rate, and produces muscle fatigue and pain sensation (Petrofsky and Hendershot, 1984). When this pain sensation occurs in an early phase, sustained force exertion becomes very difficult. Hence, considering the above-mentioned problem, a proper measurement method for muscle endurance should be developed.

A progressive workload has been used to measure maximal oxygen uptake (Fitchett, 1985; Okura et al., 1998), and Fitchett (1985) reported that it can obtain exact values because of its safety and short measurement time, more so than a steady workload using the fixed loads. The progressive workload gradually increases relative loads, considering physiological responses, and is safe because it can prevent a rapid increase of heart rate and blood pressure (Petrofsky and Hendershot, 1984), thus reducing the subject's physical burden (Fitchett, 1985). Hence, when using this method to evaluate muscle endurance, the above-stated problem may be resolved.

There are many reports on muscle oxygenation kinetics during exercise with a constant workload method (De Blasi et al., 1993; Kahn et al., 1998; Hick et al., 2001; Yamaji et al., 2002). Although muscle oxygenation kinetics do not evaluate strictly the increase and decrease of blood volume, they give an indication of the relative change in oxygen delivery and consumption by muscle blood volume (Kuwamori et al., 1995). Yamaji et al. (2002) clarified that in a constant workload

method, Oxy-Hb/Mb decreased markedly about 20 s (about 60–70% MVC) after the onset of sustained force exertion, due to the obstruction of the blood flow caused by an increase in intramuscular pressure. In addition, Nakada et al. (2004) reported that the properties of grip force in the initial phase during maximal repeated gripping were similar to those of sustained force exertion in a constant workload. It is clear that either method produces blood volume obstruction in the initial phase, and in this phase, subjective muscle fatigue sensation increases markedly (Nagasawa et al., 2000). Therefore, also in the progressive workload newly proposed, it will be necessary to confirm how muscle oxygenation kinetics and subjective muscle fatigue sensation change.

This study aimed to examine relationships among force, subjective muscle-fatigue sensation, and muscle oxygenation kinetics during sustained static gripping using a progressive workload.

## Methods

### Subjects

Subjects were 10 young male adults (height  $173.2 \pm 7.1$  cm, body weight  $70.3 \pm 15.1$  kg, and age  $21.1 \pm 1.5$  years). Written informed consent was obtained from all subjects after a full explanation of the experimental purpose and protocol. The experimental protocol obtained the approval of Kanazawa University Ethics Committee.

### Materials

Grip strength was measured using a digital hand dynamometer with a load-cell sensor (EG-100, Sakai, Japan). Each signal was sampled at 20 Hz through an analog-to-digital interface, and then relayed to a personal computer. The changes in force values on the computer display were shown on a time-series graph on a horizontal scale and relative values were shown on a vertical scale. The scale marker was drawn such that with increasing load, the subjects could exert the best gripping and grasp the demand value visually.

Near infrared spectroscopic (NIRS) measurements (PSA-IIIN, Biomedical Science, Japan) evaluated muscle oxygenation of the forearm. A PSA-IIIN using three wavelengths and two optical detectors analyzed absorbance at three wavelengths (700 nm, 750 nm, and 830 nm) based on the Lambert-Beer Law, and measured tissue oxygen saturation ( $StO_2$ ) and total tissue haemoglobin (Total Hb) (Sakai and Saito, 1995). In this study, the normal value was a predetermined muscle oxygenation level in a resting state, and the muscle oxygenation kinetics measured by NIRS was only examined as a relative change compared to the resting state. Each signal of the muscle oxygenation kinetics measured by NIRS was sampled at 10 Hz through an analog-to-digital interface, and then relayed to a personal computer.

### Subjective Muscle-fatigue Sensation

A Category-Ratio Scale based on Borg's RPE was used to

evaluate Subjective Muscle-fatigue Sensation (SMS) (Saito and Mano, 1989). This scale consists of 12 points ("Nothing at all" (0) to "Maximal (limit)" (10)). The SMS was measured from fatigue sensation in the antebraial region.

### Setting of progressive workloads and measurement time

Sustained force exertion with over 75% maximum voluntary contraction (MVC) cannot be sustained as a target force for long (West et al., 1995; Nagasawa et al., 2000). In addition, the force exertion value in a case of less load than 20% MVC decreases little (Nagasawa et al., 2000). Hence, this study selected a measurement time of 2 min with progressive workloads of 20–80% MVC.

### Experimental procedure

The subject's dominant hand was based on Oldfield's handedness inventory (1971). After measuring maximal grip force, each subject performed the sustained static gripping by progressive workload with 7 relative demand values (20–80% MVC) to MVC. Each persistence time of demand values was 20% MVC for 10 sec, 30–70% MVC for 20 sec, and 80% MVC for 10 sec. The SMS of the antebraial region was measured at a pre-experimental test and every 10 sec (a total of 13 times) during sustained static gripping for 120 sec (Fig. 1).

### Parameters

Referring to previous studies (Yamaji et al., 2000), the following force-time parameters were selected: (1) peak of force value (peak force), (2) time of PF (peak time), (3) final force value (final force), (4) the integrated area under the force-time curve as the average of all force values during the sustained static gripping using a progressive workload for 2 min (average force). The final force value was the force exerted at 120 sec. The average SMS and final SMS were selected as SMS-parameters.

Muscle oxygenation kinetics during sustained static gripping using a progressive workload, with oxygenated, deoxygenated, and total haemoglobins-myoglobins (Oxy-Hb/Mb, Deoxy-

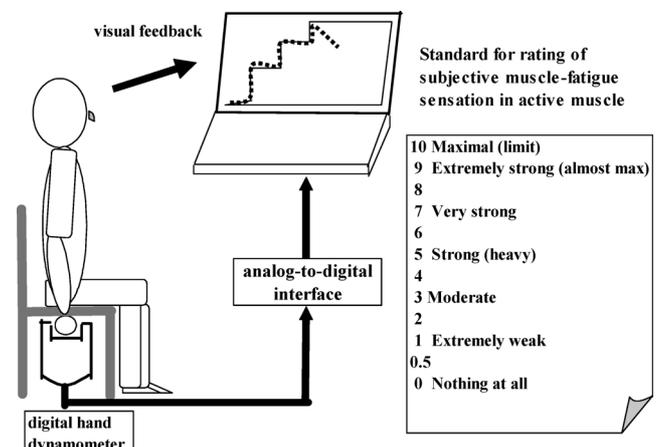


Fig. 1 Experimental system and standard for rating SMS.

Hb/Mb, and Total Hb/Mb, respectively) as parameters, were calculated using the following equations:

- 1) Oxy-Hb/Mb (oxygenated haemoglobin-myoglobin)  
= Total Hb/Mb (total haemoglobin-myoglobin) × StO<sub>2</sub> (%)
- 2) Deoxy-Hb/Mb (deoxygenated haemoglobin-myoglobin)  
= Total Hb/Mb – Oxy-Hb/Mb (%)

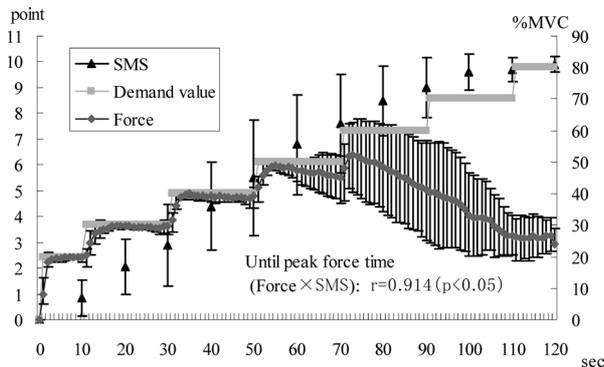
The parameters for a change in Total Hb/Mb and Oxy-Hb/Mb were used until the time at which they reached their lowest values during sustained static gripping using a progressive workload. Similarly, the parameters for a change in Deoxy-Hb/Mb were used until the time at which they reached their highest values.

### Data analysis

Pearson's correlation coefficient was used to examine the relationships among force-parameter, SMS-parameter, and muscle oxygenation kinetics. A probability level of 0.05 was used as indicative of statistical significance.

## Results

Figure 2 shows average curves of changes in time-series forces and SMS during sustained static gripping using the progressive workload. The peak force appeared at 75 s after the



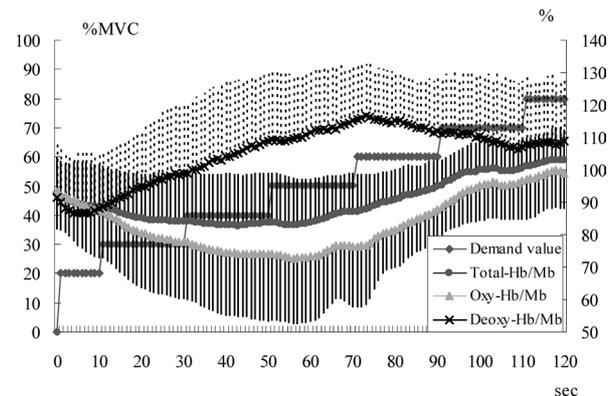
**Fig. 2** Average curves of force and subjective muscle-fatigue sensation during sustained static gripping using a progressive workload.

onset of gripping, corresponding to 60% MVC. Then, the force decreased until the end of the 2 min measurement, and the final force was about 40% MVC. The individual difference in force values increased from 60 s (demand value: 50% MVC) to 90 s (demand value: 70% MVC) after the onset of sustained static gripping, and was reduced until the end of the measurement.

The SMS increased linearly and slowly with the increase in demand value until 90 s after the onset of sustained static gripping and then reached 9 points (extremely strong) at about 100 s. The time to reach strong SMS (5) was at about 50 s (demand value: 60% MVC) after the onset of the sustained static gripping. This time agreed with the dropout time of a demand value.

Total-Hb/Mb and Oxy-Hb/Mb decreased slowly for  $27.9 \pm 16.9$  s and  $52.6 \pm 25.2$  s (demand value: 30–50% MVC), respectively, and then increased until the end (Fig. 3). Deoxy-Hb/Mb increased for  $90.8 \pm 24.1$  s (demand value: 60–70% MVC), and then decreased slowly until about 110 s, and reached an almost steady state until the end.

Table 1 shows correlations between force parameters, SMS parameters, and muscle oxygenation kinetic parameters. SMS parameters showed insignificant correlations with time to reach a minimum in Total-Hb/Mb and Oxy-Hb/Mb, which are an



**Fig. 3** Average curves of muscle oxygenation kinetics during sustained static gripping using a progressive workload.

**Table 1** Relationships between force, SMS, and muscle oxygenation kinetics during sustained static gripping using a progressive workload

Parameters	Unit	Mean	SD	Total-Hb/Mb Min	Oxy-Hb/Mb Min	Deoxy-Hb/Mb Max
Peak force	%MVC	57.4	7.4	-0.177	0.109	0.603
Peak force time	sec	71.8	14.5	-0.078	0.171	0.632*
Final Force	%MVC	24.1	5.0	-0.393	-0.290	0.203
Average Force	%MVC	35.9	5.2	0.102	0.359	0.721*
Mean SMS	point	5.9	1.0	0.267	0.245	0.035
Final SMS	point	9.9	0.3	0.102	0.399	0.390
Total-Hb/Mb Min	sec	27.9	16.9			
Oxy-Hb/Mb Min	sec	52.6	25.2			
Deoxy-Hb/Mb Max	sec	90.8	24.1			

Note: \* ( $p < 0.05$ )

index of the blood volume obstruction. Also, the time to reach a minimum in Total-Hb/Mb and Oxy-Hb/Mb showed insignificant correlations with force parameters. Significant and moderate correlations ( $r=0.632-0.721$ ,  $p<0.05$ ) were found between peak force time, average force, and time to reach maximum in Deoxy-Hb/Mb.

## Discussion

In the case of muscle endurance measurements using a constant workload with large loads, the exertion force is strongly affected by muscle blood volume obstruction with an increase in intramuscular pressure (Bonde-Peterson et al., 1975; Clarke et al., 1992; Kahn et al., 1998). Also, blood pressure and heart rate, or pain sensation in the muscles increases (Petrofsky and Hendershot, 1984). Muscle oxygenation kinetics during local muscle exercise give an indication of the relative change in oxygen delivery and consumption by muscle blood volume (Kuwamori et al., 1995). Also, in sustained static gripping using a progressive workload, it is very important to clarify changes of relationships between force and muscle oxygenation kinetics with the gradual progressive workload.

Yamaji et al. (2002) reported that Total-Hb/Mb and Oxy-Hb/Mb decreased markedly about 10 s and 20 s, respectively, after the onset of maximal sustained static grip due to the obstruction of the blood flow caused by an increase of intramuscular pressure. In addition, Nakada et al. (2004) reported that the time to reach the lowest value of Oxy-Hb/Mb was seen about 10 s after the onset of maximal repeated gripping. In the present sustained static gripping using a progressive workload, the time to reach a minimum Total-Hb/Mb and Oxy-Hb/Mb appeared at about  $27.9\pm 16.9$  s and  $52.6\pm 25.2$  s, respectively. These decreases were moderate and slower than those in previous studies (Yamaji et al., 2002; Nakada et al., 2004). In addition, Yamaji et al. (2004) suggested that there is a relationship between the time to reach minimum Oxy-Hb/Mb and the rate of decrease of force exertion for 0–1 min, and the marked decrease of initial force exertion is affected by Oxy-Hb/Mb kinetics. However, Kimura et al. (1998) reported that the muscular blood volume obstruction by an increase of intramuscular pressure occurred markedly above 50% MVC. Therefore, the following is considered: there is little muscular blood volume obstruction during the onset of a light workload (20% MVC) of sustained static gripping using a progressive workload. In addition, even though the workload increased at 50% MVC, the changes in Total-Hb/Mb and Oxy-Hb/Mb kinetics are relatively small, and the effect of blood volume obstruction occurs infrequently.

Nagasawa et al. (2000) examined relationships between endurance time and the SMS during sustained static gripping with a constant workload method, and reported that the SMS reached over “5: strong” at about 35 s (demand value: 50% MVC). In this study, the SMS slowly increased from the onset workload (20% MVC) of sustained static gripping, and reached a similar point (5: strong) at about 50 s (demand value:

60% MVC). Because peak force was  $57.4\pm 7.4\%$  MVC, the exertion force may begin to decrease before reaching the large workloads that strongly affect blood volume obstruction. With a strong muscle blood volume obstruction, blood pressure and heart rate enhance, and muscle fatigue and pain sensation increase marked (Petrofsky and Hendershot, 1984). Because the sustained static gripping of 50% MVC restricts oxygen supply, because of muscle blood volume obstruction by the above-stated intramuscular pressure (Kimura et al., 1998), the intramuscular oxygen and the oxygen in the blood are consumed and the muscle becomes congested with reduced circulation of Deoxy-Hb/Mb. Therefore, the progressive workload method is considered to be safe and reduces the subject’s physical burden.

Yamaji et al. (2002) reported that the time to reach the maximum Deoxy-Hb/Mb value appeared about 40 s after the onset of sustained static maximal gripping. Nakada et al. (2004) reported that the time to reach maximum Deoxy-Hb/Mb appears about 35 s after the onset of the gripping in repeated maximal gripping. The time in this study was about twice that of the above (about 90 s). In this phase, Deoxy-Hb/Mb increases, even though Oxy-Hb/Mb began to increase with the resumption of blood flow because of the high oxygen demand caused by sustained force exertion (Kahn et al., 1998; Nakada et al., 2004). The delay time to reach maximum Deoxy-Hb/Mb during sustained static gripping using a progressive workload is considered to be linked to the delay time to reach minimum Oxy-Hb/Mb. The individual difference in force exertion increased after about 60 s (demand value: 50–80% MVC) from the onset of the sustained gripping, and then the SMS was about 6.8 (7: very strong). Because the Total-Hb/Mb began to increase from 60 s, this time may correspond to the onset time of an increase of blood volume. In the above-stated study of Nagasawa et al. (2000), the peak of SMS in 50% MVC appeared in  $95.0\pm 36.3$  s. That is, it is considered that SMS reaches a peak earlier than that for sustained static gripping using a progressive workload, and after reaching the peak, the individual differences in force increase until the allowed time. In the present sustained static gripping using progressive workloads, the contraction time after the peak of the SMS is relatively short, and an individual difference in force values increased when the SMS reached a peak. That is, it is possible to evaluate individual differences in force before reaching the peak of the muscle-fatigue sensation or all-out exertion.

The progressive workload method is not strongly affected by blood volume obstruction as is a constant method with high workloads. However, it appeared that in the increasing phase of individual differences in force, Deoxy-Hb/Mb increases, due to high demand value, and there was insufficient oxygen due to an imbalance between oxygen supply and demand. In the case of the constant workload method (Nagasawa et al., 2000), the effect of the blood volume obstruction is very small in light workloads under 30% MVC, but the measurement time becomes long. In contrast, the muscle endurance reflecting

individual differences of oxygen-carrying capacity can be evaluated due to the occurrence of the blood volume obstruction in large workloads over 50% MVC, but there remains problem that the subject's feeling of pain is very considerable. The progressive workload in this study may be effective due to a reduction of the above-stated problems. However, individual differences in the muscle oxygenation kinetics parameters of this study were particularly large. The validity of this study should be examined in the future by using blood flow volume and EMG.

## Summary

In summary, the time to reach a minimum in Oxy-Hb/Mb appears at about 50 s ( $52.6 \pm 25.2$  s) after the onset of sustained static gripping using a progressive workload, and the time to reach a maximum in Deoxy-Hb/Mb (about 90 s) is late. Significant and high correlations ( $r=0.632-0.721$ ) are found between the time to reach maximum Deoxy-Hb/Mb and the Peak Force Time and Average Force. Even though the progressive workload reached 50% MVC, changes in Total Hb/Mb and Oxy-Hb/Mb kinetics are relatively small and an effect due to blood volume obstruction during the gripping was not found. The contraction time after the peak of SMS is relatively short, and an individual difference in force value increases in the phase during which the SMS reaches a peak. The progressive workload in this study is judged to minimize the subject's physical pain, and is able to evaluate muscle endurance with safety and in a short period of time.

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