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Relationships between Force Curves and Muscle Oxygenation Kinetics during Repeated Handgrip

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Abstract The purpose of this study was to clarify the kinetics of muscle oxygenation by near infrared spectroscopy (NIRS) in the phase of the decreasing force, especially the pre- and post-phases of the inflection point, during repeated rhythmic grip (RRG) of 30 grips/min^{-1} for 6 minutes. The inflection point was the time at which the decreasing speed of the grip force changed markedly. It was calculated statistically from two regression lines fitted to each decreasing phase by applying a two-phase regression model. Ten healthy males performed the RRG for 6 minutes. Total Hb and Oxy-Hb decreased rapidly about 10 sec (7.0±5.9 sec, 9.8±5.4 sec, respectively) corresponding to the value decreasing by 90% MVC after the onset of gripping. Deoxy-Hb was maintained at a high value for 76.2±27.9 sec, corresponding to the value decreasing by 70–80% MVC. These phases are considered to be the states where oxygen was not satisfactorily supplied to the active muscles because of the obstruction of blood flow caused by an increase in the intra-muscular pressure. Deoxy-Hb decreased for 120±21.3 sec after reaching the highest value, and then reached an almost steady state at a higher level than the rest. After this phase, muscle oxygenation kinetics enters the state where oxygen is satisfactorily supplied to active muscles. We considered that the relationship between oxygen supply and demand differs during the initial and the latter phases in RRG. The changing phase in the decreasing speed of the grip force, namely the inflection point of the decreasing force, significantly correlated with the changing phase of the Oxy-Hb and Deoxy-Hb kinetics. The inflection point of the decreasing force seems to correspond to the phase where oxygen supply cannot meet oxygen demand and the increase of Deoxy-Hb. We infer that the pre- and post-phases of the inflection point depend on different physiological factors. *J Physiol Anthropol Appl Human Sci 23(6): 191–196, 2004* http://www.jstage.jst.go.jp/browse/jpa

Keywords: muscle endurance, sustained force parameter, near infrared spectroscopy, inflection point

Introduction

In general, muscle endurance has been quantitatively evaluated by time series digital data during repeated rhythmic muscle contraction of specific body segments, performed with relative load intensities based on an individual's maximal strength. However, the findings regarding muscle endurance reported by previous studies cannot be easily compared. The measurement conditions, such as intensity or muscle contraction frequency and measurement time, are considerably different. Furthermore, the contribution of physiological factors (e.g. muscle oxygenation, recruitment of muscle fibre, excitation-contraction coupling, energy supply to muscle) involving repeated rhythmic muscle contraction changes over time (Hermansen et al., 1967; Humphreys and Lind, 1963; Nielson and Ingvar, 1967). The evaluation or interpretation of muscle endurance in an analysis of the sustained force curve can, therefore, be different, depending on the evaluated phase (Yamaji et al., 2000).

The force value during maximal repeated rhythmic grip (RRG) decreases markedly during the initial phase, mainly reflecting fatigue of fast twitch fibre (Yamaji et al., 2000). The oxygen transport capacity to the active muscle decreases in the initial phase during the maximal sustained muscle contraction because of the blood flow obstruction caused by an increase in intra-muscular pressure (Kimura et al., 1999). Following the decrease of the gripping force, the resumption of blood flow occurs with a decrease of the intra-muscular pressure (Yamaji et al., 2000). The force value then decreases gradually and reaches an almost steady state. Furthermore, it has been clarified that the mean power spectrum density of EMG during RRG, shifts to a low frequency band with continuing work. Namely, the firing frequency of efferent impulses decreases with muscle fatigue and muscle fibre recruitment mobilizes changes at every moment. The contribution of physiological factor-related muscle contraction, such as muscle recruitment or muscle oxygenation kinetics, is considered to change with the working time under a high-level load close to maximal voluntary contraction (MVC). Therefore, we suggest that the above-stated two phases (marked decrease and gradual and slow decrease) during the RRG, are not only happened differently with the decreasing speed of the force, but also dependent on the different physiological factors. The contribution of physiological differences before and after the changing point of decreasing force during the sustained muscle contraction may explain a viewpoint of muscle oxygenation kinetics. There are many studies measuring oxygenation kinetics during the sustained muscle contraction (Boushel et al., 1998; De Blasi et al., 1993; Kahan et al., 1998; Kimura et al., 1999). However, few have examined the relationships between the oxygenation kinetics and sustained muscle contraction, and the correspondence of both parameters is not well known. De Blasi et al. (1993) reported that the oxygen consumption in the forearm in the initial phase (one minute) during the sustained static maximal forearm flexion, measured by NIR, was very similar irrespective of the presence or absence of blood flow limitations. They indicated that the sustained maximal muscle contraction restricts muscle blood flow in the initial phase. However, how long does the influence of the obstruction of blood flow continue? How does the relationship between the muscle oxygenation and sustained muscle contraction change after the resumption of the blood flow? These issues are not clear from previous studies. Many researchers (Kurpad et al., 2001; Lee et al., 1990; Soler et al., 1989) proposed some methods for examining the inflection point (break point) statistically by applying a two-phase regression model to time series data in two phases.

We studied the kinetics of muscle oxygenation in the sustained force curve, especially the pre- and post-phases of the inflection point during RRG.

Materials and Methods

Subjects

Subjects were 10 males, aged 20–26 years (height 173.9 ± 7.3 cm, body mass 71.5 ± 11.2 kg). All subjects were healthy without upper extremity impairments. Their physical characteristics approximated the standard values for Japanese males of the same age (Lab Physical Edu in Tokyo Met Univ, 2000). The research protocol was approved by the Human Subjects Committee at Kanazawa University. The written informed consent was obtained from all subjects after a full explanation of the experimental purpose and protocol.

Materials

Grip strength was measured using a digital hand dynamometer with a load-cell sensor (EG-100, Sakai, Japan). Each signal during RRG was sampled at 20 Hz with an analogue-to-digital interface, and then relayed to a personal computer. To increase the motivation of the subjects during RRG, the recorded digital data was immediately displayed on a screen as a sustained force curve to give feedbacks.

Near infrared (NIR) spectroscopic measurements evaluated muscle oxygenation by the forearm during RRG. The NIR instrument (PSA-IIIN, Biomedical Science, Japan) consisted of a probe and a computerized control system. The probe contained a light source that was filtered at 700, 750, and 830 nm. The two optical detectors were placed at 15 mm and 25 mm, respectively, from the light source. The transmitted light from the probe was then either absorbed or scattered within the tissue. The scattered light was delivered via two fibre-optic light detectors of the same size to a photomultiplier every 0.1 sec. The probe was engineered for a photon depth penetration of 15–25 mm. It is generally assumed that the pattern of the light path detected from input to output follows a banana-shape in which the penetration depth into the tissue is approximately equal to half the distance between the light and the detector (Hamaoka et al., 1992) .The validity of this assumption has been verified only with a mathematical model and an *in vitro*, but not *in vivo*, experiment (Hamaoka et al., 1992). If the mean optical path length coefficient is 4.3, this assumption is valid. However, the coefficient in the body has been reported in previous studies to be approximately 3–10 (Sakai and Saito, 1995). The pattern of the light path, therefore, does not always follow a banana-shape, and is semi-circular due to the distribution of light intensity in the tissue (Sakai and Saito, 1995). The PSA-IIIN used three-wavelengths and two optical detectors analysed absorbance of the three wave-lengths based on the Lambert–Beer law, and measured tissue oxygen saturation (StO_2) and total tissue haemoglobin (Total Hb). Total absorbance of light incident on the tissue is explained by the sum of the absorbance by the oxygenated haemoglobin (Oxy-Hb) and deoxygenated haemoglobin (Deoxy-Hb) in the blood and tissue, excluding the blood. Moreover, it is assumed that the difference of the absorbance of tissue excluding the blood is very small and can be neglected, because of a very narrow range of three wavelengths (700–830 nm) on a NIR spectroscope. The following equation comes from this assumption. StO_2 is measurable even if the mean optical path length cannot be calculated.

$$StO_2 = Ca \cdot \bar{d} / (Ca + Cb) \cdot \bar{d} \cdot 100 = Ca/Hb \cdot 100$$

Ca: mass of Oxy-Hb, Cb: mass of Deoxy-Hb, $\bar{d}$: mean optical path length, Hb: total Hb volume

Sakai and Saito (1995) discussed in detail the principle of PSA-IIIN. They reported that PSA-IIIN can be used to calculate the absolute value of StO_2 and Total Hb from a mathematical model. However, a broader study of the validity of the absolute value lies outside the scope of the present paper. This study, therefore, used the relative change value based on the value during rest as well as the other NIR device. Kawasuji et al. (1997) examined the oxygenation kinetics of myocardial blood measured using PSA-IIIN, and confirmed the validity of StO_2. Moreover, Yamaji et al. (2004) examined a change of forearm blood flow measured by NIR (PSA-IIIN) and strain gauge plethysmograph (EC5R, HOKANSON) using the venous occlusion method (Kagaya, 1992) during the sustained static gripping at 20–60% MVC (target value) for 60 sec. They reported that the change by both measurement devices with an increasing target value was in proportion, and that the validity of the relative change of StO_2 and Total Hb by PSA-IIIN was high.

Experimental procedure

The dominant hand of each subject was judged using Oldfield's handedness inventory (1997). All subjects performed the handgrip test with the dominant hand, and the grip width was individually adjusted to achieve a 90-degree angle with the proximal-middle phalanges. Each subject performed handgrip measurements while seated in an adjustable ergometric chair. The arm, supported by an armrest, was in a sagittal and horizontal position, with the forearm vertical and the hand in a semi-prone position. After measuring the maximal grip strength, each subject performed the RRG test using maximal grip strength as a target value with a target frequency of 30 grips/min^{-1} for 6 minutes. No verbal encouragement was given during the test. The NIR probe was positioned over the surface of the flexor digitorum superficialis of the dominant hand, and the muscle oxygenation kinetics was continuously monitored during two minutes rest and the RRG test.

Sustained force parameters

A sustained force curve was obtained by plotting the peak force from every RRG, namely 180 grips$=$30 grips/min$^{-1}\times$ 6 minutes. The inflection point was the time at which the decreasing speed of the grip force changed markedly (see Fig. 1), and was calculated statistically from two regression lines fitted to each decreasing phase by applying the two-phase regression model (Kurpad et al., 2001; Lee et al., 1990; Soler et al., 1989). The grip force in the pre-inflection phase was markedly decreased, while in the post-inflection phase it was a gradual and slow decrease. The inflection point (time) was determined by the following conditions:

1) The time series sustained force data (180 data) divided into the former and latter phases at all combinations (e.g. the former: the latter, 3 : 177, 4 : 176, ..., 176 : 4, 177 : 3), and respective regression lines were calculated.

2) The best-fit regression lines determined by the regression coefficients (a1) in the pre-inflection phase were significant and greater than those determined by the regression coefficients (a2) in any other post-inflection phase. And the sum of the determination coefficients of both regression equations was highest.

3) The inflection point was determined at the time from the best-fit regression lines in the combination of time series data.

The parameters used to evaluate the sustained force curve were selected from decreasing time to reach 60, 70, and 80% MVC, the mean peak force value, the decreasing force during 1 minute, the rate of decrement constant (k) in the exponential function ($y=a^{e^{-kt}}+b$), and the regression coefficients (a1 and a2) in the pre- and post-phases.

Muscle oxygenation kinetics

The muscle oxygenation kinetics during RRG, with oxygenated, deoxygenated and total haemoglobins (Oxy-Hb, Deoxy-Hb, and Total Hb, respectively) as parameters, were examined using the following equations;

$$\text{Oxy-Hb} = \text{Total Hb} \times StO_2 \quad (\%)$$

$$\text{Deoxy-Hb} = \text{Total Hb} - \text{Oxy-Hb} \quad (\%)$$

Data obtained by NIR spectroscopy were normalized to the resting value for each individual. The parameters for the change of Oxy-Hb used the time to reach the lowest value during the RRG and the regression coefficient in the markedly increasing phase after reaching the lowest value. The parameters for the change of Deoxy-Hb used the time to reach the highest value during the RRG and the regression coefficient in the markedly decreasing phase after reaching the highest value. The regression coefficient during the change of Oxy-Hb and Deoxy-Hb was the value when the coefficient of regression estimation was determined to be the highest.

Data analysis

Pearson's correlation coefficient was used to examine the relationship among all parameters. The probability level of 0.05 was taken as an indication of the statistical significance.

Results

Relationships between the grip force value and muscle oxygenation kinetics during RRG

Figure 1 shows the average curves of the changes for the changes Oxy-Hb, Deoxy-Hb, Total Hb and grip force during the RRG of 30 grip/min^{-1}. The discrete data for these average curves was used to calculate the average for each sampling time (20 Hz and 10 Hz) of each subject. All subjects in this study showed trends similar to Fig. 1. Total Hb and Oxy-Hb decreased linearly from the resting value for about 10 sec (7.0$\pm$5.9 sec and 9.8$\pm$5.4 sec, respectively) after the onset of the RRG test, and then increased markedly by until about 100 sec (104.0$\pm$19.9 sec and 95.7$\pm$25.5 sec, respectively). After that, they reached an almost steady state with a higher level than at rest (about 115.8$\pm$13.4% and 114.7$\pm$14.4%, respectively). Deoxy-Hb increased markedly for about 34.8$\pm$13.0 sec, and was maintained for about 76.2$\pm$27.9 sec after the onset of the RRG test. After this increase, it decreased

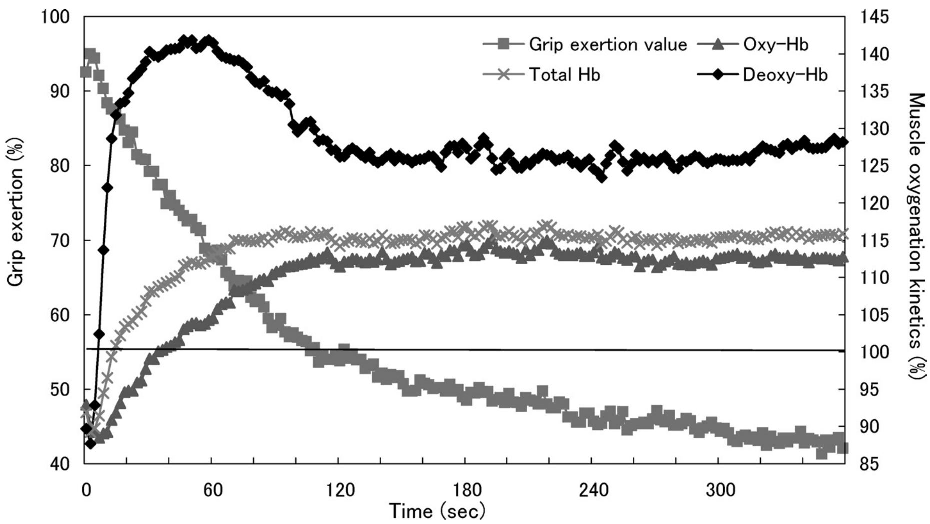

Fig. 1 Average curves of the muscle oxygenation kinetics (Total Hb, Oxy-Hb, and Deoxy-Hb) and relative grip force over 6-minutes repeated rhythmic gripping.

Table 1 Correlations between the sustained force parameters and muscle oxygenation parameters during repeated rhthmic gripping

	Mean	SD	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Force-time parameters														
(1) Time to 80% MVC (sec)	32.2	15.0												
(2) Time to 70% MVC (sec)	58.2	19.7	**.86**											
(3) Time to 60% MVC (sec)	105.6	47.2	.27	.22										
(4) Average integrated area ($\% \cdot sec^{-1}$)	54.6	7.3	.45	.57	**.70**									
(5) Rate of decrease for 0–1 min ($\% \cdot sec^{-1}$)	18.7	4.5	**−.94**	**−.88**	−.24	−.49								
(6) RC of pre-inflection	−396.9	123.4	.23	.59	-.18	.35	−.24							
(7) RC of post-inflection	−160.0	90.3	.20	.21	.38	**.68**	−.28	.19						
(8) Exponential rate of decrement (*k*)	−2.6	1.6	.19	.35	.51	**.79**	−.33	.08	.60					
(9) Time at an inflection point (sec)	68.6	14.7	−.42	−.50	−.30	−.49	.60	−.04	−.52	−.77				
Muscle oxygenation parameters														
(10) Time at lowest Oxy-Hb value (sec)	9.8	5.4	−.03	.04	−.30	−.26	−.01	.06	**−.73**	−.34	.44			
(11) Time at highest Deoxy-Hb value (sec)	34.8	13.0	−.59	**−.72**	−.26	−.46	**.71**	−.14	−.11	**−.65**	**.84**	.03		
(12) RC in the decreasing phase of Deoxy-Hb	−0.27	0.26	−.15	.03	−.01	.32	.23	.50	.06	−.04	.52	.24	.34	
(13) RC in the increasing phase of Oxy-Hb	161.20	41.29	.28	.14	.06	−.17	−.05	.16	−.40	**−.68**	**.63**	.28	.33	.37

Note: Significant correlations ($p<.05$) were shading portion and bold-faced type ; RC=regression coefficient

rapidly for about 128±21.3 sec, and reached an almost steady state with a higher level than at rest (about 122.0±23.7%). Oxy-Hb reached its lowest value after the onset of the RRG test (about 9.8±5.4 sec) at which time the grip force decreased by about 90% MVC. When the Deoxy-Hb reached its highest value, the grip force decreased until about 70–80% MVC. After that, the Deoxy-Hb decreased until the grip force decreased to about 60% MVC (for about 105.6±47.2 sec). When Oxy-Hb reached an almost steady state, the decrease of grip force became gradual and slow.

Relationships between the sustained force parameters and muscle oxygenation kinetics

Table 1 shows the correlation coefficients between the parameters of sustained force and muscle oxygenation kinetics. There was a significant correlation between the time to reach the lowest Oxy-Hb and the regression coefficient (a2) of the post-inflection phase in the sustained force curve. The time to reach the highest Deoxy-Hb value (mean 34.8±13.0 sec) approximately corresponded to the time when the grip force decreased by 70–80% MVC (mean 32.2±15.0 sec and mean 58.2±12.7 sec, respectively), and correlated significantly with the time when the grip force decreased by about 70% MVC ($r=-.72$, $p<.05$). The time to reach the highest Deoxy-Hb value and the regression coefficient of Oxy-Hb in the marked increasing phase significantly correlated with the inflection time and the rate of decrement constant (*k*) in the exponential function. The regression coefficient of Deoxy-Hb in the marked decreasing phase did not show a significant correlation with any sustained force parameter.

Discussion

In the sustained static maximal grip test, Oxy-Hb markedly decreased for 20 sec, at which time the grip force decreased by 60–70% MVC, after the onset of maximal grip because a blood flow obstruction was caused by an increase in intra-muscular pressure (Yamaji et al., 2000). However, the marked decrease of Total Hb and Oxy-Hb during the RRG of 30 grips/min^{-1} in this study, was found for about 10 sec from the onset of the grip. Within this time, the grip force also decreased to about 90% MVC. De Blasi et al. (1993) reported that oxygen consumption in the forearm in the initial phase (one minute) during the sustained static maximal forearm flexion, measured by NIR, was very similar, irrespective of the presence or absence of blood flow limitations. They indicated that the sustained maximal forearm flexion restricts muscle blood flow in the initial phase. A temporary blood flow obstruction was caused by an increase in intra-muscular pressure at the beginning phase of exhibiting large strength (above about 90% MVC) in the case of RRG of 30 grips/min^{-1} as well as the sustained static grip (Bonde-Petersen et al., 1975; Gaffney et al., 1990; Kahn et al., 1998; Kimura et al., 1999; Nielson and Ingvar, 1967; Royce, 1958). It is thought that in the alternating muscle contraction and relaxation in the RRG, blood obstruction and perfusion of blood flow alternated with each other. That is because an increase and a decrease of intra-muscular pressure occurred intermittently, and resumption of blood flow occurred from a relatively high muscle contraction (about 90% MVC). Deoxy-Hb continued to increase for about 60 sec from the onset of the grip. The increase of Deoxy-Hb in the initial phase of RRG of 30 grips/min^{-1} may be explained, in part, by the obstruction of blood flow as discussed above. Kimura et al. (1999) reported that the obstruction of muscle blood flow caused by an increase in intra-muscular pressure in the initial phase would restrict the oxygen supply to the active muscle. Then, oxygen stored in muscles or blood may be consumed and Deoxy-Hb might remain without being eliminated. That is, the Deoxy-Hb increase in the initial phase depends on the obstruction of blood flow, and oxygen demand by RRG remains high, being the state where oxygen cannot be satisfactorily supplied to active muscles.

Deoxy-Hb began to decrease after reaching the highest Deoxy-Hb value (about 60 sec after the onset of the grip), and then attained a steady state at about 120 sec after the onset of grip. The times when Total Hb and Oxy-Hb changed from a marked increase to a steady state were about 70 and 100 sec, respectively. The change time of Deoxy-Hb was about 120 sec. We assumed that all parameters reached an almost steady state after these change points. The Deoxy-Hb decreased after reaching its highest value. From this point in time, the Oxy-Hb exceeded the rest level (about 105%), and the Total Hb also reached an almost steady state. Muscle oxygenation kinetics in the phase after reaching the maximal Deoxy-Hb value imply that Deoxy-Hb began to be eliminated because of the relief of the obstruction of blood flow caused by the decreasing force, and accompanying that, an increase of oxygen supply caused by resumption of blood flow. Thus, the change in this phase indicates that oxygen was satisfactorily supplied to the active muscles. Boushel et al. (1998) reported that venous oxygen saturation was in a constant state during 30% MVC repeated rhythmic grips for two minutes. Oxy-Hb and Deoxy-Hb reached an almost steady state, because the oxygenation supply and consumption in active muscles were suitable in the phase when the grip force decreased below about 50% MVC. The inflection time of the decreasing force (68.6 ± 14.7 sec) occurred from the time of reaching the highest Deoxy-Hb value (34.8 ± 13.0 sec) to the time when the Deoxy-Hb value (76.2 ± 27.9 sec) started to decrease.

This inflection time corresponded to an increasing phase of Oxy-Hb and correlated significantly to parameters evaluating this phase. The changing phase of the decreasing speed of grip force corresponds approximately to that of Oxy-Hb and Deoxy-Hb. The inflection time calculated statistically from the sustained force curve is considered to reflect the changing point of physiological parameters. Moreover, Yamaji et al. (2000) reported that the inflection times were similar during 3 minutes and 6 minutes in static maximal hand gripping (65.0 ± 22.8 sec, 74.9 ± 27.9 sec). The inflection times in this study would be a useful method with two phases. The time to reach the lowest Oxy-Hb value preceded the time to reach the highest Deoxy-Hb value. Deoxy-Hb during this period increased even though Oxy-Hb began to increase with the resumption of blood flow because of high oxygen demand caused by RRG. This disagreement in the change time of Oxy-Hb and Deoxy-Hb may be explained by an increase in oxygen demand with RRG. Thus, the inflection point of the decreasing sustained force curve corresponds to the phase in which the oxygen supply to oxygen demand is not in balance and Deoxy-Hb increases.

On the other hand, the grip force decreases gradually and slowly in the post-inflection phase, in which Deoxy-Hb decreased markedly, followed by a steady state. The marked decrease of Deoxy-Hb occurred after the inflection point of the grip force, and the regression coefficient in the decreasing phase of Deoxy-Hb did not correlate significantly with any sustained force parameter. Although the parameters regarding the oxygenation kinetics reached an almost steady state in this phase, the grip force still decreased gradually. Therefore, the alternative physiological mechanisms (i.e. muscle fiber recruitment and fire frequency of the impulse etc.) may contribute to the decreasing grip force. Thus, the physiological mechanisms of skeletal muscles in this phase differ from that in the initial phase, showing a marked decrease of the grip force.

The time to reach the highest Deoxy-Hb value and the regression coefficient of Oxy-Hb in the marked increasing phase significantly correlated with the rate of decrement constant (k) in the exponential function. The exponential function k indicates the total decrease ratio from the onset of grip to the end. This parameter is also thought to reflect muscle oxygenation kinetics.

In summary, Oxy-Hb decreased for 10 sec (decreasing by about 90% MVC), and Deoxy-Hb increased for about 60 sec (decreasing by about 70–80% MVC) after the onset of RRG of 30 grips/min^{-1}. In these phases, the oxygen supply to oxygen demand is not in balance. On the other hand, Deoxy-Hb, after reaching the highest value, decreases for about 120 sec (decreasing by about 50% MVC), and reaches an almost steady state. In this phase, oxygen would be satisfactorily supplied to active muscles. Both phases, showing a marked decreasing force and a gradual and slow decreasing force, depend on respectively different physiological factors. It is suggested, therefore, that the inflection point of the decreasing force can divide the sustained force curve into the above-stated phases. Muscle endurance should be evaluated by distinguishing pre- and post-phases of the inflection point, because the inflection point of the grip force reflects the oxygenation kinetics as stated above and both phases depend on different physiological factors. In the future, it would be valid to examine useful parameters to evaluate muscle endurance based on the inflection time of the decreasing force and the exponential function *k*.

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