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The Properties and Interrelationships of Various Force-time Parameters during Maximal Repeated Rhythmic Grip

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Abstract The purpose of this study was to examine the properties and interrelationships of various force-time parameters including the inflection point for the rate of decline in force during a maximal repeated rhythmic grip. Fifteen healthy males (age M=21.5, SD=2.1 yr, height M=172.4, SD=5.7 cm, body mass M=68.2, SD=9.2 kg) participated in this study. Subjects performed a maximal repeated rhythmic grip with maximal effort with a target frequency of 30 grip$\cdot$min^{-1} for 6 min. The force value decreased linearly and markedly until about 70% of maximal strength for about 55 s after the onset of a maximal repeated rhythmic grip, and then decreased moderately. Because all parameters showed fair or good correlations between 3 min and 6 min, they are considered to be able to sufficiently evaluate muscle endurance for 3 min instead of 6 min. However, there were significant differences between 3 min and 6 min in the integrated area, the final force, the rate of the decrement constant (k) fitting the force decreasing data to $y=ae^{-kx}+b$ and the force of maximal difference between the force and a straight line from peak force to the final force. Their parameters may vary generally by the length of a steady state, namely, a measurement time. The final force value before finishing and the rate of the decrement constant (k) reflect the latter phase during a maximal repeated rhythmic grip. Although many parameters show relatively high mutual relationships, the rate constant (k) shows relatively low correlations with other parameters. We inferred that decreasing the time until 80% of maximal strength and the amount of the decrement force for the first 1 min reflect a linear decrease in the initial phase. *J Physiol Anthropol 26(1): 15–21, 2007*
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Introduction

Muscle endurance generally has been evaluated by achievement times of repeated exercises such as sit-ups, push-ups, or pull-ups. However, these methods have the shortcoming that individual differences in strength and physique affect the measurement value. Many researchers have, therefore, used methods with relative load intensities based on individual maximal strength (Maughan et al., 1986; Milner-Brown et al., 1986; Walamies and Turjanmaa, 1993; Capodaglio et al., 1997; Yamaji et al., 2000; Yamaji et al., 2002). Because of the ease of controlling the performance measurement, motions such as handgrip, knee extension/flexion, forearm flexion, or plantar/dorsal flexion have been used in laboratory tests. These methods evaluate muscle endurance from force-time parameters such as the time to reach a certain force level, integrated area under the force-time curve, decreasing contraction rate, or the final force value before finishing. These parameters are calculated from time series data of repeated rhythmic muscle contraction. The parameters are based on the definition of muscle endurance, and evaluate the decreasing speed or the decrement in force production during repeated rhythmic muscle contraction. However, each parameter evaluates respectively different decreasing phases, such as the marked decreasing phase, the steady state phase, or the final phase before finishing.

In the case of repeated rhythmic muscle contraction with near maximal strength, muscle blood flow differs greatly in the initial and the latter phases. In the initial phase, there is a blood flow obstruction caused by an increase in intra-muscular pressure, and in the latter phase, there is a resumption of blood flow (Hermansen et al., 1967; Nielson and Ingvar 1967). The force-time curve during this contraction, therefore, can be divided into two phases of a marked decrease (the initial phase) and an almost steady state (the latter phase). These two phases depend on different physiological factors (Yamaji et al., 2000). Nakada et al. (2004) and Yamaji et al. (2004) proposed the inflection point, which statistically divides the initial phase and the latter phase by applying a two-phase regression model to the force-time curve. They suggested that the inflection point relates to the oxygenation kinetics during sustained muscle contraction with high intensity, and is a good indicator of the blood reflow after the blood flow obstruction. The inflection point may be a useful parameter to clarify the properties of force-time parameters for muscle endurance considering physiological factors. Although previous studies have proposed many force-time parameters as measures of endurance, their properties and interrelationships have not been clarified. That is, the parameters useful for evaluating muscle endurance have not been selected by considering the properties of the phases measured by each parameter sufficiently. This may be one of the important reasons for different findings regarding gender differences in muscle endurance (Bowie and Cumming, 1972). It is, therefore, necessary to clarify the phase evaluated by each parameter. In addition, because the measurement time differed in previous studies, it is also necessary to examine whether the evaluation of muscle endurance is influenced by measurement time.

The purpose of this study was to examine the properties and the interrelationships of various parameters from analysis of the force-time curve during a maximal repeated rhythmic grip.

Method

Subjects

Subjects were 15 healthy males without upper extremity impairments [age M=21.5, SD=2.1 yr, height M=172.4, SD=5.7 cm, body mass M=68.2, SD=9.2 kg]. Their physiques approximated standard values for Japanese males of the same age-group. Written informed consent was obtained from all subjects after a full explanation of the experimental purpose and protocol was given to them.

Materials

Grip strength was measured using a digital hand dynamometer with a load-cell sensor (EG-100, Sakai, Japan). Each signal during a maximal repeated rhythmic grip 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 a maximal repeated rhythmic grip, the input digital data was immediately displayed on a screen as a force-time curve to give feedback.

Experimental procedure

Each subject's dominant hand was judged using Oldfield's Handedness Inventory (Oldfield, 1971). All subjects performed the handgrip test with the dominant hand while seated in an adjustable chair. The arm was in a sagittal and horizontal position and was supported by an armrest with the forearm vertical and the hand in a semi-prone position, and grip width was individually adjusted to achieve a 90-degree angle with the proximal-middle phalanges. Maximal grip was measured two times in a sitting position, and the higher value (MVC: Maximal voluntary contraction) was used as a target value for a maximal repeated rhythmic grip test. Each subject performed the test with a target frequency of 30 grips$\cdot$min^{-1} for 6 min. No verbal encouragement was given during the test. The numbers of repeated contractions and the measurement time were based on the method of Huczel and Clarke (1992).

Force-time parameters

Drawing from previous studies (Walamies and Turjanmaa, 1993; Yamaji et al., 2000, 2002), five points of view were used to select the force-time parameters for this study: (1) time to decay to specific values, (2) integrated area, (3) final force values before finishing, (4) decreasing rate, and (5) inflection time. Figure 1 shows the nine force-time parameters selected. The force-time curve was obtained by plotting the peak force from every maximal repeated rhythmic grip, namely, 180 grips=30 grips$\cdot$min$^{-1}\times$6 min. Decreasing time is the time when the force value decreased to 60, 70, and 80% MVC. The integrated area under the force-time curve is the average of all force values during a maximal repeated rhythmic grip. The final force value is the average rate of forces in the final 30 s. The parameters evaluating the decrease are (a) the amount of

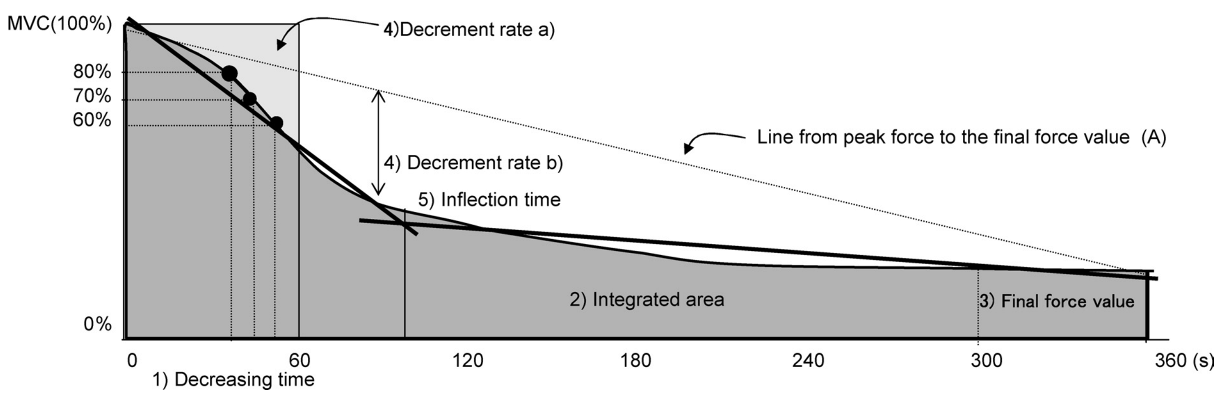

Fig. 1 Force-time parameters during maximal repeated rhythmic gripping (RRG). Parameters: 1) Decreasing time; the time until the force value decreased to 60, 70, and 80% of MVC. 2) Integrated area; average of all force values during RRG. 3) Final force value; average of the force at 300, 330, and 360 s. 4) Decreasing rate: a) amount of decrement in force over the first 1 min, b) maximal difference between the force and the linear line (A), c) rate of decrement constant (k). 5) Inflection time: time at which the decreasing speed of force exertion changed markedly. Data sampling of RRG was 20 Hz. MAX: Maximal grip strength before RRG (target force: 100%).

the decrement force for the first 1 min, (b) the maximal difference between the force and a line joining the peak force to the final force value (the force of maximal difference), and (c) the rate of the decrement constant (k), which were then calculated by fitting the force decreasing data to the equation $y=ae^{-kx}+b$, where y is force value at time x, and k is the rate constant in min^{-1}. In this study, the inflection point of the decreasing speed in the force-time curve was calculated statistically to distinguish between a marked decreasing phase and an almost steady state phase.

Many researchers (Soler et al., 1989; Lee et al., 1990; Kurpad et al., 2001) have proposed a method to calculate the inflection point (break point) statistically by applying a two-phase regression model to time series data that can assume two phases. The inflection point in this study was the time at which the decreasing speed of the force exertion markedly changed, and was calculated statistically from two regression lines fitted to each decreasing phase by applying this model. There was a marked decrease of the force value in the pre-inflection phase, while in the post-inflection phase it was almost at a steady state.

The inflection point (time) was determined by the following conditions:

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

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

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

Data analysis

The inflection time and force-time parameters for 3 min and 6 min were calculated from time series force values by maximal repeated gripping in each subject. The mean differences in the parameters between 3 min and 6 min were examined using a paired t test. Pearson's correlation coefficients were calculated to examine the relationship between all parameters for both measurement times. The probability level of .05 was considered statistically significant.

Results

Decreasing pattern time during repeated rhythmic grip exertion for individuals

The trial-to-trial reliability of maximal grip strength (MVC) was very high (ICC: .927, $p<.05$). Figure 2 shows the average force-time curve during a maximal repeated rhythmic grip for 6 min. All subjects in this study showed almost the same pattern as shown in Figure 2. The force value decreased linearly and markedly until about 70% MVC for about 55 s after the onset of a maximal repeated rhythmic grip, and then decreased moderately. Furthermore, all subjects' force values exceeded 45% MVC for 6 min.

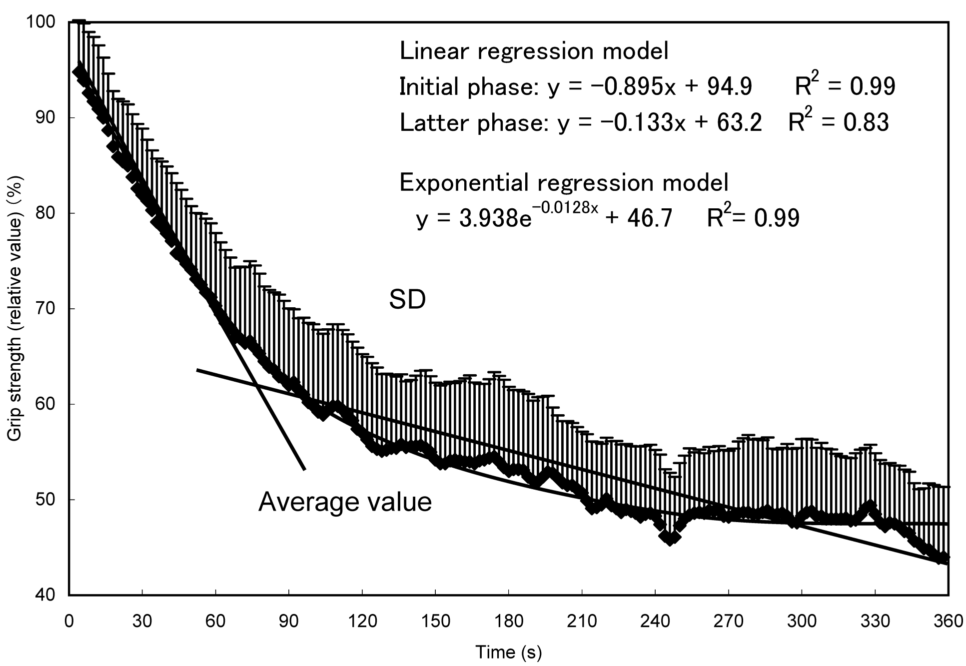

Fig. 2 Average force-time curve during RRG for 6 min. Dots indicate the average force value for all subjects in each data sampling. Upper bars indicate standard deviations.

Relationship of the force-time parameters between 3 min and 6 min, and interrelationship among parameters

Table 1 shows correlation coefficients between parameters for 3 min and 6 min. The decreasing time until 60% and 70% MVC, and integrated area for both measurement times correlated highly (r=.97–.99). The other parameters correlated fairly well (r=.62–.77). The inflection time showed a similar value, and correlated fairly well (r=.62). The decreasing times until 80% and the amount of decrement force for the first 1 min were the same values between 3 min and 6 min for all subjects.

Table 2 shows correlation coefficients between all parameters for 3 min and 6 min. Their values tended to be similar. The decreasing time until 80% MVC was reached correlated highly with that required until 70% MVC was reached, the integrated area, and the amount of decrement force for the first 1 min in both evaluation times (3 min; r=.96, .91, −.92: 6 min; r=.95, .88, −.92, respectively). The decreasing time until 60% MVC was reached correlated highly with the time until 70% MVC was reached, the integrated area, and the force of maximal difference (3 min; r=.91, .92, −.86: 6 min; r=.94, .90, −.94, respectively). The final force value correlated highly with the integrated area (3 min; r=.96: 6min; r=.81) and the decreasing time until 60% MVC was reached for 3 min (r=.89). The rate of the decrement constant (k)

Table 1 Correlation Coefficients between Measurements Taken for 3 min and 6 min

Parameter		Unit	3 min M	3 min SD	6 min M	6 min SD	t	r
Time	until 80% of MVC	(sec)	35.1	19.13	35.1	19.13		
	until 70% of MVC	(sec)	63.5	32.52	64.7	35.79	0.09	0.99*
	until 60% of MVC	(sec)	102.3	37.40	108.1	50.68	0.35	0.98*
Integrated area		(%)	64.8	6.52	56.8	6.26	3.33*	0.97*
Final force value		(%)	54.7	8.00	47.0	6.67	2.76*	0.71*
Decrement in force for the first 1 min		(%)	17.9	5.94	17.9	5.94		
Force of maximal difference		(%)	19.1	5.56	29.1	6.91	4.23*	0.77*
Constant k (thousand-fold value)			14.3	1.21	12.8	0.76	5.46 *	0.72*
Inflection time		(sec)	43.5	13.67	54.5	20.62	1.67	0.62*

* $p<.05$

Table 2 Correlation Coefficients between All Parameters

	Parameter		1	2	3	4	5	6	7	8
	3 min									
1	Time	until 80% of MVC								
2		until 70% of MVC	0.96							
3		until 60% of MVC	0.85	0.91						
4	Integrated area		0.91	0.92	0.92					
5	Final force value		0.80	0.86	0.89	0.96				
6	Decrement in force for the first 1 min		−0.92	−0.83	−0.69	−0.83	−0.66			
7	Force of maximal difference		−0.80	−0.82	−0.86	−0.78	−0.63	0.72		
8	Constant k		0.42	0.54	0.70	0.73	0.67	−0.23	−0.32	
9	Inflection time		0.06	0.12	0.00	0.00	−0.06	−0.08	−0.17	0.45
	6 min									
1	Time	until 80% of MVC								
2		until 70% of MVC	0.95							
3		until 60% of MVC	0.85	0.94						
4	Integrated area		0.88	0.89	0.90					
5	Final force value		0.73	0.73	0.69	0.81				
6	Decrement in force for the first 1 min		−0.92	−0.80	−0.67	−0.75	−0.59			
7	Force of maximal difference		−0.83	−0.87	−0.94	−0.91	−0.57	0.69		
8	Constant k		0.32	0.53	0.67	0.72	0.43	−0.24	−0.54	
9	Inflection time		0.37	0.39	0.32	0.32	0.08	−0.40	−0.35	0.43

fitting the equation $y=ae^{-kx}+b$, and the inflection time did not correlate highly with any parameter.

Discussion

Properties of the force decreasing curve during a maximal repeated rhythmic grip

It is known that sustained muscle contraction, regardless of continual or intermittent force exertions, decreases markedly in the initial phase, and then reaches an almost steady state (Caffier et al., 1992; Clarke et al., 1992; Nagasawa et al., 2000). Clarke et al. (1992) examined the force value during repeated rhythmic forearm flexion with the same measurement condition (target force, contraction frequency, and time) as this study, reporting that it decreased to 82–85% MVC for the initial 1 min, and then decreased to about 50% MVC for 6 min. This decreasing tendency was similar to that in this study (Fig. 2). In the case of repeated rhythmic muscle contraction, the force value is considered to show a similar decreasing pattern regardless of muscle region, although the relative force value during the steady state phase is different. The endurance test of repeated or sustained muscle contraction is affected by the subject's psychological response to pain during the test (Nagasawa et al., 2000).

We will need to examine the possibility of evaluating muscle endurance in a shorter time, because 6 min imposes a high level of pain on the subjects and it may be not a useful evaluation time for practical use. Walamies and Turjanmaa (1993) used a shorter measurement time, 1 min, because the decrease in motivation caused by the long measurement time may affect the force exertion value. All subjects' force values decreased moderately about 55 s after the onset of a maximal repeated rhythmic grip, and reached an almost steady state for 180 s. Therefore, the force-time parameters in this study were calculated from the force-time curve for 3 min and 6 min. In addition, the inflection time was calculated using a two-phase regression model, because the existence of two phases (a markedly decreasing phase and an almost steady state phase) was confirmed in the force-time curve for both times. The inflection time occurred for nearly the first 1 min, and was similar to that of the previous study calculated from the force-time curve during maximal sustained static (holding) grip for 3 min and 6 min (Yamaji et al., 2000). The tendency of the marked decreasing phase during a maximal repeated rhythmic grip with a target frequency of 30 grips$\cdot$min^{-1} can be very similar to that during maximal sustained static grip. Bowie and Cumming (1972) suggested that the marked decreasing force in the initial phase related closely to the fatigue of fast twitch fibres. In repeated rhythmic muscle contraction with a high load, muscle blood flow kinetics differ in the initial and latter phases. In the former phase, a blood flow obstruction occurs by an increase in intra-muscular pressure, and in the latter phase, there is a resumption of blood flow (Hermansen et al. 1967; Nielson and Ingvar, 1967). The two phases, which show a marked force decrease and an almost steady state, are considered to depend on respectively different physiological factors. Therefore, the parameters useful for evaluating muscle endurance should be selected by considering the characteristics of both phases.

Relationship of the parameters for 3 min and 6 min

The relationships between 3 min and 6 min for all force-time parameters were fair, or good. Therefore, all parameters selected in this study evaluate the same for both measurement times. Namely, they are considered to be able to sufficiently evaluate muscle endurance for 3 min instead of 6 min. However, there were significant differences between 3 min and 6 min in the integrated area, the final force, the rate of the decrement constant (k) and the force of maximal difference. Their parameters may vary generally by the length of a steady state, namely, a measurement time. Yamaji et al. (2000) inferred that the exponential function fitting the whole force-time curve with a long gradual decreasing phase cannot rightly reflect the initial decreasing phase.

Their parameters need to be interpreted carefully, because they may evaluate a different decreasing phase for a particular measurement time. The time until 80% MVC is reached and the amount of decrement in force in the first 1 min would mainly evaluate the pre-inflection phase, i.e., the marked force-decreasing phase. This marked decreasing force phase is closely related to the fatigue of fast twitch fibres, as stated above (Bowie and Cumming, 1972), and also to a fairly high state of force exertion. It is, therefore, inferred that a deficiency of oxygen supply as compared with oxygen demand occurs in activated muscles caused by a blood flow obstruction with an increase in intra-muscular pressure (Kahn and Monod, 1989). Although repeated rhythmic muscle contraction in this study repeats muscle contraction and relaxation, a previous study reports that the ischemia occurs in the repeated rhythmic muscle contraction with a target frequency of 30 exertion$\cdot$min^{-1} as well as static holding contraction. The time until 70% MVC related to time until 80% MVC and the amount of decrement in force for the first 1 min, but it showed a greater individual difference. This parameter appeared over a wide range of pre- or post-inflection points for over 3 min. It is clear that the effect of the blood flow obstruction during sustained muscle contraction occurs in the phase until 50 to 70% MVC is reached, and the individual difference of MVC affects these force exertion levels (De Blasi et al., 1993). Therefore, the time until 70% MVC may evaluate the phase related to different physiological factors in each subject. Inflection time appeared within 1 min after the onset of a maximal repeated rhythmic grip, corresponding to about 70% MVC in this study. It is suggested that the changing point of decreasing speed relates to the effect of the blood flow obstruction, and inflection time may indicate the physiological change.

The time until 60% MVC was reached and the force of maximal difference tended to appear before reaching a steady state, namely, they evaluate the phase shift from the marked force decrease to a gradual force decrease. The effect of muscle blood flow obstruction in this phase would fade, and the oxygen supply to activate muscle becomes sufficient. Moreover, force exertion is maintained by the recruitment of fast and slow twitch fibres. The final force value evaluates the phase of reaching an almost steady state. However, as noted by an individual difference of each force value in Fig. 2, the force value during a steady state phase is almost the critical force in repeated muscle contraction, and the individual difference of exertion value in the phase becomes smaller. Further study will need to examine whether this parameter is useful for evaluating muscle endurance, because the coefficient of variation (CV) for the final force value is small as compared with the other parameters (CV=14.2%).

The integrated area, which is the average of all force values, correlated highly with the parameters except for the inflection time. However, the coefficient of variation for this parameter was smaller than that for the final force value (CV=11.0%). There is a possibility that the individual difference of the integrated area became small because a steady state phase with the small individual difference was included in the evaluation interval.

This study determined the force-time curve properties and the interrelationships of parameters to establish the evaluation parameters for muscle endurance. Further study should determine whether the parameters change as a result of individual differences of muscle fiber composition.

In summary, the force value during a maximal repeated rhythmic grip with a target frequency of 30 grip$\cdot$min^{-1} decreased markedly until 70% MVC, and then decreased moderately. Furthermore, all subjects' force values reached an almost steady state for 180 s, and exceeded 45% MVC for 6 min. Most parameters evaluate the same between 3 min and 6 min. In particular, the decreasing time until 80% MVC was reached and the amount of decrement in force for the first 1 min is the same between 3 min and 6 min for all subjects, because it reflects a marked decreasing phase. Although many parameters show relatively high mutual relationships, the rate constant (k) shows relatively low correlations with other parameters. It is, therefore, necessary to examine its usefulness.

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