Dynamic model of muscle fatigue and recovery considering the roles of slow-twitch and fast-twitch muscles (Validation with a pulling motion)

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Abstract
The present paper proposes a new model of muscle fatigue and recovery considering the roles of slow twitch (ST) and fast twitch (FT) muscle fibers. The proposed model can predict the variation in the degree of muscle fatigue because it considers the properties of muscle fatigue and recovery, which have been neglected in previous models. The aim of the present study was to predict not only the progression of muscle fatigue under maximum voluntary contraction (MVC) but also the endurance time for a force maintenance task and the variation in the output force achieved during MVC with regular intervals of rest. To validate the proposed model, a case study was conducted. The parameters of the proposed model, which depend on the anatomical properties of the individual, were determined from the measured variation in the output force under MVC. The endurance time for a force maintenance task with an arbitrary output force and the variation of the output force during MVC with intervals of rest were measured in the case study and compared with those predicted using the proposed model and a previously developed model that does not consider the roles of ST and FT fibers. In the case study, the proposed model showed good agreement with the measurement results and achieved better accuracy than the previous model. Therefore, the proposed model can be applied in cases with a low output force or intervals of rest, which are beyond the scope of the previous model.

Keywords: Muscle fatigue, Muscle recovery, Slow-twitch and fast-twitch muscles

1. Introduction

In the welfare field, the recent increased burden on workers has highlighted the need for working environments to be designed to place less of a burden on workers’ individual anatomy and physiology taken into consideration. To respond to these demands, digital human models that can mimic the properties and functions of the human body have been developed. These existing digital human models can evaluate operational performance by representing various human physiques and postures with a database of human geometric parameters (Adachi, 1999). These digital human models contribute to reducing the development period and cost of designing working environments. Specifically, such models reduce the need to create mockups during the design phase (Chaffin, 2001; Porter et al., 1993), simplify usability evaluation (Bowman, 2001), and improve the working environment (Blome et al., 2003). These models can predict the net forces or net torques from the trajectories of the joints during motion.

It is considered to be necessary to predict not only the net forces or net torques but also the degree of muscle fatigue during work performed over a long time period (Armstrong et al., 1993). A few previous studies have considered muscle fatigue in their models. Liu et al. (2002) proposed a dynamical model considering muscle fatigue to evaluate the physical load during long-duration work. In this model, the muscles are represented as being in one of three states, and the time progression of the fatigue and recovery of the muscles is mathematically represented. Then, this model can
predict the variation in the output force of the muscle under maximum voluntary contraction (MVC).

However, this previous model did not consider the roles of the slow-twitch (ST) and fast-twitch (FT) muscle fibers, which are the two classes of human muscle fibers. ST fibers are characterized by a slow rate of contraction and slow fatigue, whereas FT fibers show a fast rate of contraction and fast fatigue. The proportion of these types of muscle fibers affects the characteristics of the muscles and varies from individual to individual. Therefore, the previous model cannot accurately predict the progression of muscle fatigue under the condition of a low output muscle force; that is, the previous model can be applied only to cases in which the FT fibers are the main contributors of the output force.

The present paper proposes a new model considering the roles of both ST and FT fibers to evaluate muscle fatigue and recovery with reference to the muscle fatigue model proposed by Liu et al. (2002). Furthermore, methods of predicting the endurance time for a force maintenance task and the variation in the output force under MVC with regular intervals of rest were developed in this study. To validate the proposed model, experiments were conducted, and the results predicted by the proposed model were compared with those measured in the experiment and were further assessed in comparison with the results obtained using the previous model.

2. Muscle fatigue and recovery model considering the role of slow-twitch and fast-twitch muscles

2.1 Slow-twitch and fast-twitch muscles

Human muscle fibers can be classified into two types: ST and FT fibers. ST fibers are characterized by a slow rate of contraction and slow fatigue, whereas FT fibers show a fast rate of contraction and fast fatigue. The proportion of these types of muscle fibers affects the characteristics of the muscles and varies from individual to individual. If a muscle fatigue model that does not distinguish between these two types of muscle fibers is used, the prediction accuracy of the fatigue differs depending on the output muscle force. For example, if a muscle fatigue model considering only FT fibers is used, the model overestimates the degree of muscle fatigue during a period of low output muscle force. Generally, when the muscle outputs a low force, the ST fibers, which have a low motor nerve activity threshold, activate first, and the FT fibers, which have a high motor nerve activity threshold, activate later. This phenomenon is called the “size principle” (Hennema, 1957). Therefore, it is necessary to consider the role of ST fibers when predicting the muscle fatigue under low force conditions.

2.2 Muscle fatigue prediction method under maximum voluntary contraction

Liu et al. (2002) suggested a muscle fatigue model including the states of activity, fatigue, and recovery of a muscle. As shown in Fig. 1, this model includes three groups of muscular motor units: the standby group with $M_{sc}$ units, the active group with $M_A$ units, and the fatigued group with $M_F$ units. The total number of motor units existing in a muscle is represented by $M_0$. The parameters $B$, $F$, and $R$ represent the rates at which standby units in $M_{sc}$ are changed to active units in $M_A$, active units in $M_A$ to fatigued units in $M_F$, and fatigued units in $M_F$ to active units in $M_A$, respectively. This model then defines the progression among the muscle states based on a physiological mechanism.

![Fig. 1 Dynamic relationship among the three groups of muscular motor units in the standby, active, and fatigued states](image-url)
Because the previous model did not consider the roles of ST and FT fibers, it could be applied only to evaluation under conditions of high output muscle force. The present study considers the roles of ST and FT fibers and proposes a new method of predicting the degree of muscle fatigue, as shown in Fig. 2. As in the previous model, the total number of motor units existing in a muscle is represented by $M_0$. The proportions of ST and FT fibers contained in the muscle are represented by $\%ST$ and $\%FT$. Then, the numbers of motor units representing ST and FT fibers are denoted $M_0^s$ and $M_0^f$, respectively. The numbers of standby ST and FT units, active ST and FT units, and fatigued ST and FT units are represented by $M_{ucs}$, $M_{ucf}$, $M_{As}$, $M_{Af}$, $M_{Fs}$, and $M_{Ff}$, respectively. The active units in $M_{As}$ and $M_{Af}$ contribute to the output of the muscle, whereas the standby units in $M_{ucs}$ and $M_{ucf}$ or the fatigued units in $M_{Fs}$ and $M_{Ff}$ do not. Each unit progresses to different states over time. In the initial state ($t = 0$), all units are in the standby state. Therefore, the state of each unit at $t = 0$ is represented as

$$M_{Ai} = 0 \ (i = s, f)$$

$$M_{Fi} = 0 \ (i = s, f)$$

(1)

$$M_{ucs} + M_{ucf} = M_0.$$  

The parameters $F_s$ and $F_f$ represent the rates at which active units are changed to fatigued units for the ST and FT fibers, respectively. The parameters $R_s$ and $R_f$ represent the rates at which fatigued units are changed to active units for the ST and FT fibers, respectively. However, the parameter that represents the rate at which standby units are changed to an active units is the same for both ST and FT fibers and is represented by $B$. Fig. 2 shows the direction of the unit state change produced by each parameter. From the unit state change, the output force of the ST and FT fibers can be predicted. In the case of MVC, the ST and FT fibers are simultaneously activated because the maximum output force is quickly reached. The resulting temporal variation in the forces of the ST and FT fibers and the total force is as shown in Fig. 3. The change in the number of units in each state is represented as

$$\frac{dM_{As}(t)}{dt} = B \cdot M_{ucs}(t) - F_s \cdot M_{As}(t) + R_s \cdot M_{Fs}(t)$$ \hspace{1cm} (2)

$$\frac{dM_{Fs}(t)}{dt} = F_s \cdot M_{As}(t) - R_s \cdot M_{Fs}(t)$$ \hspace{1cm} (3)

$$M_{ucs}(t) = M_{0s} - M_{As}(t) - M_{Fs}(t)$$ \hspace{1cm} (4)

$$\frac{dM_{Af}(t)}{dt} = B \cdot M_{uaf}(t) - F_f \cdot M_{Af}(t) + R_f \cdot M_{Ff}(t)$$ \hspace{1cm} (5)

$$\frac{dM_{Ff}(t)}{dt} = F_f \cdot M_{Af}(t) - R_f \cdot M_{Ff}(t)$$ \hspace{1cm} (6)

$$M_{uaf}(t) = M_{0f} - M_{Af}(t) - M_{Ff}(t).$$ \hspace{1cm} (7)

The variation of the numbers of each unit can be discretely calculated by using a finite difference method as following according to the differential equations described above.

$$M_{ij}(t + 1) = M_{ij}(t) + \frac{dM_{ij}(t)}{dt} \cdot \Delta t \hspace{1cm} (i = A, F, uc: j = s, f)$$ \hspace{1cm} (8)
2.3 Prediction of muscle fatigue during a force maintenance task

As stated previously, when the muscle outputs a low force, the ST fibers generally activate first and the FT fibers activate later in a phenomenon called the "size principle" (Hennema, 1957). According to this principle, the ST fibers are the primary actors, and the FT fibers activate to aid the ST fibers. Therefore, the state change of the units is classified into two patterns according to the magnitude of the target output force. The first pattern is the case in which the target output force cannot be achieved by only ST fibers, and the second pattern is the case in which the target output force can be achieved by only ST fibers. The unit state progression in each case is as follows.

(A) The target output force cannot be achieved by only ST fibers

In the first pattern, the target output force is larger than the maximum output force of the ST fiber units in $M_{A_{\text{max}}}$. Fig. 4 shows the progression of the number of units in each group over time. In the initial state (Fig. 4(a)), only standby units exit in both the ST and FT fibers (Fig. 4(a)). After the muscle begins to output a force, the standby ST units in $M_{\text{us}}$ become activated and change to active units, contributing to $M_{A}$. Simultaneously, the standby FT units in $M_{\text{uf}}$ change to active units in $M_{Af}$ to provide the necessary force to reach the target output force (Fig. 4(b)). Subsequently, the active ST and FT units in $M_{A}$ and $M_{Af}$ change to fatigued units in $M_{Fs}$ and $M_{Ff}$. However, additional standby FT units in $M_{\text{uf}}$ must be changed to active units in $M_{Af}$ to continue to maintain the target output force (Fig. 4(c)). In this way, the number $M_{\text{uf}}$ of standby FT units gradually decreases. When all standby FT units have changed to active FT units in $M_{Af}$ ($M_{\text{uf}} = 0$), the FT fibers can no longer cover the gap between the force generated by the ST fibers and the target output force, thus causing the output force to decrease (Fig. 4(d)). After that, the active units in $M_{A}$ and $M_{Af}$ change to fatigued units $M_{Fs}$ and $M_{Ff}$ and the system reaches a steady state. The temporal variation in the forces output by the ST and FT fibers and the total output force is shown in Fig. 5. The ratio of the target output force to the MVC is represented by $X \%$. Then, the change in the number of units in each state can be calculated using Eqs. (2)–(7) for the
case shown in Fig. 4(d) and using the following equations for the case in the period between the states shown in Fig. 4(b) and (c):

\[
\frac{dM_{As}(t)}{dt} = B \cdot M_{ucx}(t) - F_x \cdot M_{As}(t) + R_x \cdot M_{Fs}(t)
\]

(9)

\[
\frac{dM_{Fs}(t)}{dt} = F_x \cdot M_{As}(t) - R_x \cdot M_{Fs}(t)
\]

(10)

\[
M_{ucx}(t) = M_{0s} - M_{As}(t) - M_{Fs}(t)
\]

(11)

\[
M_{Af}(t) = M_0 \cdot \frac{X}{100} - M_{As}(t)
\]

(12)

\[
\frac{dM_{Ef}(t)}{dt} = F_f \cdot M_{Af}(t) - R_f \cdot M_{Ef}(t)
\]

(13)

\[
M_{ucf}(t) = M_{0f} - M_{Af}(t) - M_{Ef}(t)
\]

(14)

Fig. 4   Muscle fatigue progress of ST and FT fibers under the condition of a constant output force \((M_{Asmax} < M_0X/100)\)
Fig. 5  Variation of the normalized forces under the condition of a constant output force  
\((M_{\text{Asmax}} < M_{X}/100)\)

(B) The target output force can be achieved by only ST fibers

In the second pattern, the target output force is smaller than the maximum output force achievable by the ST fibers when all units are in the active state \((M_{\text{As}} = M_{\text{Asmax}})\). Fig. 6 shows the progression of the number of units in each group over time. In the initial state, only standby units exit in both the ST and FT fibers (Fig. 6(a)). After the muscle begins to output a force, the standby ST units in \(M_{\text{ucs}}\) become activated and change to active units in \(M_{\text{As}}\) until the number of active units can generate a force equal to the target output force. In this case, the standby FT units do not change to active units because the target output force can be achieved by only ST fibers (Fig. 6(b)). The active ST units in \(M_{\text{As}}\) gradually change to fatigued units in \(M_{\text{Fs}}\) and more standby ST units in \(M_{\text{ucs}}\) change to active units to maintain the target output force (Fig. 6(c)). After all standby ST units have changed to active units and the number of fatigued units continues to increase, the target output force can no longer be achieved. Then, the standby FT units begin to activate to compensate for the difference between the target output force and the force achieved by the ST units (Fig. 6(d)). After that, the active units in \(M_{\text{As}}\) and \(M_{\text{Af}}\) change to fatigued units in \(M_{\text{Fs}}\) and \(M_{\text{Ff}}\). The target output force is maintained by standby FT units in \(M_{\text{ufc}}\) changing to active units as needed (Fig. 6(e)). After all of the standby FT units in \(M_{\text{ufc}}\) have changed to active units, the output force decreases because no units are available to compensate for the discrepancy with the target output force (Fig. 6(f)). The temporal variation in the forces output by the ST and FT fibers and the total output force is shown in Fig. 7. The change in the number of units in each state can be calculated using Eqs. (2)–(7) and (9)–(14) for the case shown in Fig. 6(f) and for the period between the cases shown in Fig. 6(d) and (e), respectively. For the period between the states shown in Fig. 6(b) and (c), the state progression can be calculated using the following equations:

\[
M_{\text{As}}(t) = M_0 \cdot \frac{X}{100} \quad \text{(15)}
\]

\[
\frac{dM_{\text{Fs}}(t)}{dt} = F_s \cdot M_{\text{As}}(t) - R_s \cdot M_{\text{Fs}}(t) \quad \text{(16)}
\]

\[
M_{\text{ucs}}(t) = M_{0s} - M_{\text{As}}(t) - M_{\text{Fs}}(t) \quad \text{(17)}
\]

\[
M_{\text{Af}}(t) = M_{\text{Ff}}(t) = 0 \quad \text{(18)}
\]
Fig. 6  Muscle fatigue progress of ST fiber and FT fiber under the condition of a constant output force

\( M_{\text{Asmax}} > M_0 \times X/100 \)

Fig. 7  Variation of the normalized forces under the condition of a constant output force

\( M_{\text{Asmax}} > M_0 X/100 \)
2.4 Prediction of muscle fatigue and recovery with rest

A model to evaluate the degree of the muscle recovery with rest considering the roles of ST and FT fibers is proposed. Fig. 8 shows the progression of the number of units in each state over time when the muscle periodically alternates between MVC and rest. In this case, after the muscle begins to output a force, standby ST and FT units in $M_{ucs}$ and $M_{ucf}$ become activated and change to active units in $M_{As}$ and $M_{Af}$. Then, the active ST and FT units in $M_{As}$ and $M_{Af}$ gradually change to fatigued units in $M_{Fs}$ and $M_{Ff}$ as a result of muscle fatigue (Fig. 8(a)). When the muscle begins to rest, all active units in $M_{As}$ and $M_{Af}$ change to standby units in $M_{ucs}$ and $M_{ucf}$ (Fig. 8(b)). During rest, only the muscle recovery effect is at play, and the fatigued units in $M_{Fs}$ and $M_{Ff}$ change to standby units in $M_{ucs}$ and $M_{ucf}$. When the muscle begins to output a force again after resting, the standby units in $M_{ucs}$ and $M_{ucf}$ are activated, and any fatigued units in $M_{Fs}$ and $M_{Ff}$ remain in the fatigued state (Fig. 8(a)). If the duration of rest is not sufficient for the recovery of all of the fatigued units, the numbers $M_{Fs}$ and $M_{Ff}$ of fatigued units gradually increase, and the output force achieved during MVC decreases. The temporal variation in the forces output by the ST and FT fibers and the total output force is shown in Fig. 9. The change in the number of units in each state during the rest period (Fig. 8(b)) can be calculated as

\[
M_{Ai}(t) = 0 \quad (i = s, f) 
\]  
\[
\frac{dM_{Fi}(t)}{dt} = R_i \cdot M_{Fi}(t) \quad (i = s, f) 
\]  
\[
M_{ucs}(t) = M_{0i} - M_{Ai}(t) - M_{Fi}(t) \quad (i = s, f). 
\]  

![Diagram](image)

**Fig. 8** Muscle fatigue and recovery progress of ST and FT fibers during alternating periods of MVC and rest

![Graph](image)

**Fig. 9** Variation of the normalized forces during alternating periods of MVC and rest
3. Validation experiment

To validate the proposed muscle fatigue and recovery model considering the role of ST and FT fibers, a validation experiment was conducted. After giving informed consent, one university student (height: 168.0 cm, mass: 67 kg) participated in this experiment. This experiment was approved by the ethics committee of the Graduate School of Engineering, Kobe University. First, the variation in the output force achieved by a pulling motion under MVC was measured using a dynamometer. The electrical activity of the muscle of the upper limb was also measured by surface electromyography (sEMG). Furthermore, the endurance time was measured under the condition of maintaining a constant target output force. The parameters for the proposed model were obtained from these measurement results. After the determination of the parameters, the endurance time for a force maintenance task was predicted. An experiment on the variation of the output force during MVC with intervals rest was also conducted.

3.1 Output force of maximum voluntary contraction for determination of parameters

In this experiment, sEMG was performed using a myoelectric pad (BlueSensor P, Ambu) and a myoelectric amplifier (EMG-021/025, Harada Industry Co., Ltd.) with a sampling rate of 1 kHz. The position of the myoelectric pad was specified by an anatomical map (Osti, 2016). A ground myoelectric pad was affixed in a position distant from the measurement pad. Simultaneously, the variation in the output force was measured using a three-component dynamometer (LSM-B-SAI, Kyowa Corp.) with a sampling rate of 20 Hz. A handgrip attached to an aluminum frame on the three-component dynamometer was used to measure the output force, as shown in Fig. 10. The posture of the upper limb was such that the angle between the line from the shoulder to the elbow and the line from the elbow to the wrist was 90°, the shoulder abduction was 90° and the wrist supination was 0°, as shown in Fig. 11. The present study focused on the isometric flexing motion. The participant applied a force by pulling the handgrip with maximum effort and continued to apply a force until the measured output force leveled off due to fatigue. The variation in the output force and the electromyogram was measured. Since the present study cannot estimate muscle force of each muscle at the moment, the validation was conducted by using the output force at the tip. When the posture of the upper limb and the direction of the output force is constant, the activated muscles are considered constant. Then, this experiment is considered to measure the variation of the same muscle group. Although the behaviors of gripping fingers and wrist fixing might affect the measurement accuracy, these differences are ignored due to the limitations of the experimental instrument.

The measured output force is shown in Fig. 12. In this experiment, three measurement trials were conducted, and the parameters of the proposed model were determined from the average of the measurement results.

Fig. 10 Equipment to measure the output force (side view)  Fig. 11 Equipment to measure the output force (top view)
3.2 Measurement of endurance time for force maintenance

The endurance time for a force maintenance task was measured. The participant was instructed to hold a weight to ensure the load to the participant was constant. A wire was attached to the wrist of the participant, and a weight corresponding to the target output force was attached to the end of the wire via a pulley, as shown in Fig. 13. The reason why the posture of the upper limb is different from the posture as the experiment in Fig. 10 is due to the limitations of the experimental instrument. When the posture as the experiment in Fig. 10 is the same, there was a risk of harming the wrist of the participant. Although the posture might affect the measurement accuracy, these differences are ignored because the same muscle group is activated as the experiment in Fig. 10 on the isometric flexing motion. The participant continued to maintain the output force by holding his wrist in a constant position until the displacement of the weight exceeded the displacement tolerance, given in Table 1, due to fatigue, and the endurance time was measured as the time at which this occurred. The conditions of this experiment are also given in Table 1, in which the force maintenance task with output forces equal to 20% (Cases E1), 30% (Cases E2) and 40% (Cases E3) of the MVC of the participant. The target output force could be changed by changing the number of attached modular weights, as shown in Fig. 14.

The endurance times for the force maintenance task with output forces equal to 20%, 30%, and 40% of the MVC of the participant were measured. In this experiment, three measurement trials were conducted. The results of the experiment are given in Table 2.
Table 1  Experimental conditions (weights and allowable moving distances)

|                | Cases E1 | Cases E2 | Cases E3 |
|----------------|----------|----------|----------|
| %MVC [%] (Weight [N]) | 20 (76)  | 30 (105) | 40 (135) |
| Displacement tolerance [mm] | 5        | 10       | 15       |

Table 2  Measured endurance times for the force maintenance task

| Measured time [s] | Cases E1 | Cases E2 | Cases E3 |
|-------------------|----------|----------|----------|
| 1st               | 418      | 138      | 75       |
| 2nd               | 387      | 129      | 69       |
| 3rd               | 428      | 159      | 76       |
| Average           | 411      | 142      | 73       |

3.3 Measurement of the variation in the output force during maximum voluntary contraction with intervals of rest

The variation of the output force during MVC with periodic intervals of rest was measured. The output force was measured using a three-component dynamometer on an aluminum frame with a handgrip, as shown in Fig. 10. The posture of the upper limb was as shown in Fig. 11. The participant alternated between regular periods of MVC and rest. The durations of the MVC and rest periods are given in Table 3. In cases R1, MVC duration is 30 sec and rest duration is 10 sec. In cases R2, MVC duration is 30 sec and rest duration is 30 sec. In cases R3, MVC duration is 40 sec and rest duration is 20 sec. In this experiment, three measurement trials were conducted for each duration condition. The results for each of the three conditions are respectively shown in Figs. 15–17.

Table 3  Durations of MVC and rest periods in each considered case

|                | Cases R1 | Cases R2 | Cases R3 |
|----------------|----------|----------|----------|
| MVC duration [s] | 30       | 30       | 40       |
| Rest duration [s] | 10       | 30       | 20       |

Fig. 15  Measured output force under alternating periods of MVC and rest  
(Case R1 - MVC: 30 s, rest: 10 s)
4. Discussion

4.1 Determination of parameters

To predict muscle fatigue using the proposed model, it is necessary to determine the following parameters: the total number of muscular motor units $M_0$, which is proportional to the maximum output force; the rate coefficient $B$ for units changing from the standby state to the active state; the rate coefficients $F_s$ and $F_f$ for units changing from the active state to the fatigued state; and the rate coefficients $R_s$ and $R_f$ for units changing from the fatigued state to the active state; and the proportions $\%ST$ and $\%FT$ of ST and FT fibers contained in the muscle. The parameter $M_0$ can be determined from the measured output force $M_{A\text{max}}$ under MVC using the relationship between $M_{A\text{max}}$ and $M_0$ (Liu et al., 2002):

\[
M_{A\text{max}} = M_0 \times \frac{97}{100}
\]  

(22)

The parameter $B$ was set to 5 following Liu et al. (2002). The parameters $\%ST$ and $\%FT$ can be determined as (Gerdle et al., 1988)

\[
\%ST = 87.1 - (0.55 \times MPF)
\]  

(23)

\[
\%FT = 100 - \%ST
\]  

(24)

where the mean power frequency $MPF$ can be obtained from the power spectrum obtained as the fast Fourier transform (FFT) of the measured electromyograph at MVC.
The parameters $F_s$, $F_f$, $R_s$, and $R_f$ were obtained by first fitting the measured output force curve with that of the proposed model by minimizing the residual sum of squares and then minimizing the difference between the measured and predicted endurance times at 20% MVC (Case E1 in the endurance test). The parameters determined from the experimental results are given in Table 4.

### Table 4 Parameters of the proposed model determined from the experimental results

|   | $M_0$ | $B$ | $F_s$ | $F_f$ | $R_s$ | $R_f$ | %ST | %FT |
|---|-------|-----|-------|-------|-------|-------|-----|-----|
| Participant | 338   | 5   | 0.0374 | 0.0374 | 0.0107 | 0.0107 | 45  | 55  |

#### 4.2 Comparison of measured and predicted endurance times for the force maintenance task

The endurance time for the force maintenance task under each considered load condition was predicted using the proposed model with the determined parameters. The measured and predicted endurance times under 20%, 30%, and 40% MVC are given in Table 5. These results demonstrate the validity of the proposed model, as the predicted endurance time is in agreement with the measured endurance time.

### Table 5 Measured and estimated endurance times

|               | Cases E1 | Cases E2 | Cases E3 |
|---------------|----------|----------|----------|
| Measured time [s] | 411      | 142      | 73       |
| Estimated time [s] | 384      | 136      | 73       |
| Percent error [%] | $-6.6$   | $+4.2$   | $0.0$    |

#### 4.3 Comparison of measured and predicted output force of MVC with intervals of rest

The variation of the output force during MVC with regular intervals of rest was predicted using the proposed model with the determined parameters. Fig. 18 shows the measured and predicted variation of the output force achieved during MVC under case R1, in which the durations of the MVC and rest stages were 30 and 10 s, respectively.

![Fig. 18 Measured and predicted output force during MVC with intervals of rest before modifying the FT fiber parameter that affects the muscle recovery (Case R1 – MVC: 30 s, rest: 10 s)](image-url)
As shown in Fig. 18, the difference between the measured and predicted output forces was large. The reason for this is considered to be that the rate of muscle recovery represented by $R_s$ and $R_f$ in the proposed model were not accurately expressed. A previous study (Kawahatsu et. al., 1974) has clarified that the muscles recover rapidly just after starting to rest and the rate of muscle recovery gradually decreases. Thus, it was assumed in the present study that the parameter $R_f$ describing the rate of muscle recovery for the FT fibers is proportional to the ratio of the number $M_{ff}$ of fatigued FT units to one plus the number $M_{Af}$ of active FT units based on the previous study (Kawahatsu et. al., 1974). The relationship is given by

$$R_f = \frac{M_{ff}}{1 + M_{Af}} \times R_f'. \quad (25)$$

The variation of the output force during MVC with intervals of rest was predicted by the proposed model using the new parameter of muscle recovery defined in Eq. (25). The measured and predicted variation of the output force during MVC in cases R1, R2, and R3 are shown in Fig. 19. These results show good agreement between the measured and predicted variation of the output force, thus validating the proposed model.
4.4 Comparison of previous and proposed models

Nishida et al. (2016) previously proposed a method of predicting the endurance time and the variation of the output force during MVC with intervals of rest by expanding the muscle fatigue model proposed by Liu et al. (2002). However, their model did not show good prediction accuracy under a low output force because it did not consider the roles of ST and FT fibers. In the present study, the results predicted using the model by Nishida et al. (2016) and the proposed model were compared.

The results of the endurance times obtained using the previous and proposed models are given in Table 6. Table 6 also gives the percent error of the predicted endurance times with respect to the measured endurance times for each model. As demonstrated by these results, the proposed model showed greater accuracy than the previous model in predicting the endurance time.

The variation of the output force during MVC with intervals of rest obtained using the previous and proposed models is shown in Fig. 20. As a representative, only the results for case R3 are shown. As shown by these results, the proposed model was able to predict the output force more accurately than the previous model.

| Table 6 Predicted endurance times obtained using the previous and proposed models |
|---------------------------------|-----------|-----------|-----------|
|                                 | Cases E1  | Cases E2  | Cases E3  |
| Measured time [s]              | 411       | 142       | 73        |
| Previous model [s]             | \(\infty\) | 94        | 52        |
| (Percent error [%])            | \(\infty\) | (-33.8)  | (-28.8)  |
| Proposed model [s]             | 384       | 136       | 73        |
| (Percent error [%])            | (-6.6)    | (4.2)     | (0.0)     |
5. Conclusion

The present paper proposed a new model of muscle fatigue and recovery considering the roles of ST and FT fibers. Furthermore, methods of predicting the endurance time for the force maintenance task and the variation of the output force during MVC with intervals of rest were also developed. To validate the proposed methods, validation experiments were conducted. The predicted endurance times and variation of the output force of MVC with intervals of rest were compared with those measured experimentally as well as those predicted by a previous model. The results demonstrate that the proposed model can accurately predict the degree of muscle fatigue. Furthermore, the difference between the measurement and prediction results was smaller for the proposed model than for the previous model. Future study work will involve predicting the degree of muscle fatigue of different muscles in the body, as the present study only considered muscle fatigue for a distal extremity.

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