Dynamical model of muscle fatigue and recovery considering the behavior of slow- and fast-twitch muscles and the roles of antagonistic muscles

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Abstract
The present paper proposes a model of muscle fatigue and recovery considering both the behavior of slow- and fast-twitch muscle fibers and the role of antagonistic muscles. The proposed model can be used to predict the degree of muscle fatigue of each muscle in the upper arm when the muscle activation pattern of the muscles changes because of the variation of the output force direction at the distal extremity. Furthermore, it can predict the variation in the muscle fatigue not only under maximum voluntary construction but also under any constant applied force or alternating periods of constant output force and rest. To validate the proposed model, case studies were conducted. The parameters necessary to predict the degree of fatigue of each muscle can be determined from a few preliminary experiments in which a participant outputs force in only four directions. The prediction results from the case studies showed good agreement with the measurement results. Therefore, the proposed model can be applied in cases where the output force direction changes with any force magnitude or alternates with periods rest, which is not the case for existing models.

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

1. Introduction

As the aging of the workforce increases the burden on individual workers in such fields as nursing care and manufacturing, it will become necessary to develop personalized working environments based on the physical characteristics of each worker in order to help relieve this burden. To respond to this demand, digital human models that mimic the properties and functions of the human body have been developed. Existing digital human models can evaluate the operational performance of an individual by setting the human shape and posture using a database of human geometric parameters (Adachi, 1999). These digital human models contribute to reducing the need for actual physical mockups in the design phase (Chaffin, 2001; Porter et al., 1993), improve usability evaluations (Bowman, 2001), and ultimately yield better working environments (Blome et al., 2003). It is considered necessary to predict not only the net forces or torques but also the degree of muscle fatigue during work performed over a long duration (Armstrong et al., 1993). There have been a number of previous studies in which muscle fatigue was considered (Liu et al., 2002; Laura et al., 2012). Liu et al. (2002) proposed a dynamical model considering muscle fatigue to evaluate the physical load during work performed over a long duration. In this model, the muscles can be in one of three states, and the progression of the muscle fatigue and recovery is mathematically represented. However, human muscle fibers are commonly classified into two types, slow- and fast-twitch (ST and FT) fibers, and this previous model did not consider...
the different behaviors of these two types. ST fibers are characterized by fatigue resistance and a low rate of contraction, whereas FT fibers show fatigable and rapid contraction. In our previous study, we proposed a model considering the roles of ST and FT fibers to evaluate muscle fatigue and recovery (Miura et al., 2019).

Although our previous model considers the different roles of ST and FT fibers, it can predict only the variation in the output force at the distal extremity and gives no indication of the degree of muscle fatigue of each muscle in the upper arm. However, it is necessary to predict the degree of muscle fatigue of each muscle. The human body has a unique system of muscles consisting of antagonistic pairs of synchronously acting mono- and bi-articular muscles (Hogan, 1984, 1985a, 1985b; McIntyre and Bizzi, 1993). In an antagonistic pair of muscles, the agonist muscle is the prime mover, and the antagonist muscle works in opposition to the agonist. Additionally, mono- and bi-articular muscles work respectively on a single joint and simultaneously on two joints. The present study refers to the musculoskeletal model developed by Oshima et al. (1999) considering the roles of antagonistic and bi-articular muscles. Then, the present study proposes a method of predicting the degree of muscle fatigue of each muscle considering both the different functions of ST and FT fibers and the roles of antagonist muscles. To validate the proposed method, experiments were conducted, and the predictions of the proposed model were compared with the experimental results.

2. Model of muscle fatigue and recovery considering the roles of antagonistic muscles

To predict the degree of fatigue of each muscle in the arm when performing an exercise in which the activity state of each muscle changes over time, the force produced by each muscle was predicted from the output force at the distal extremity of the upper limb using a previously developed musculoskeletal model considering the role of antagonistic muscle pairs (Oshima et al., 1999). The present paper proposes a method of predicting the degree of fatigue of each muscle considering the roles of ST and FT fibers. When the magnitude and direction of the output force at the distal extremity of the upper limb change, the proposed method makes it possible to predict the degree of fatigue of each muscle in the upper arm. In the present chapter, the musculoskeletal model considering the role of antagonistic muscle pairs proposed by Oshima et al. (1999) is first explained. The muscle fatigue and recovery model considering the different behaviors of ST and FT fibers previously proposed by our research group (Miura et al., 2019) is then explained in section 2.2. Finally, the method of predicting the degree of fatigue of each muscle in the arm proposed in the present study is described in section 2.3.

2.1 Musculoskeletal model considering the role of antagonistic muscle pairs

Oshima et al. (1999) proposed a musculoskeletal model that considers the roles of antagonistic pairs of mono- and bi-articular muscles. This model includes three pairs of antagonistic muscles in the upper limb, as shown in Fig. 1a. The maximum force that each of these muscles can produce at the distal extremity are defined as $F_{m1}$, $F_{m2}$, $F_{m3}$, $F_{mf1}$, $F_{mf2}$, and $F_{mf3}$, as shown in Fig. 1a (Oshima et al., 1999; Fujikawa et al., 1997). Then, the maximum output force distribution at the distal extremity can be geometrically represented as a hexagon based on maximum force of each muscle. Oshima et al. (1999) also experimentally verified that the maximum output force distribution on the distal extremity is a hexagon, and the vector of the output force at the distal extremity was found to relate to the muscle activation pattern as shown in Fig. 1b (Oshima et al.; 1999, Fujikawa et al., 1997). For example, when the output force has the maximum magnitude in the direction labeled a in Fig. 1a, the activation level, which is defined as the ratio of the forces produced by each muscle to its corresponding maximum muscle force, is 100% for muscles $e1$, $e2$, and $e3$ and 0% for muscles $f1$, $f2$, and $f3$. This case is represented by the circles at the center of the muscle activation level plots in Fig. 1b. On the basis of this result, the pattern of activation of each muscle can be determined from the vector of the output force at the distal extremity and the muscle activation pattern, as shown in Fig. 1b. The vector of the output force at the distal extremity must be calculated to estimate the distribution of the force of each muscle using this musculoskeletal model. The vector of the output force at the distal extremity can be measured by a three-component dynamometer.
(a) Muscles of the upper limb. f1: anterior deltoid (Da), e1: posterior deltoid (Dp), f2: brachialis (Br), e2: lateral head of triceps brachii (Tla), f3: long head of biceps (Blo), e3: long head of triceps brachii (Tlo)

(b) Muscle activation level plotted against the output force as labeled in Fig. 1a

Fig. 1 Musculoskeletal model considering the role of antagonistic muscle pairs in the arm

2.2 Muscle fatigue and recovery model considering slow- and fast-twitch muscles

Liu et al. (2002) proposed a muscular fatigue model including states of activity representing the fatigue and recovery of a muscle. As shown in Fig. 2, the muscle is composed of a total of $M_0$ discrete muscular motor units, and these are each classified into one of three groups representing the possible activation states: the standby group with $M_{st}$ units, the active group with $M_A$ units, and the fatigued group with $M_F$ units. Units can then change their state over time, and the rates at which units change from one state to another are represented by a set of parameters, as defined in Fig. 2. Motor muscular units in the standby state become activated with rate $B$, active units become fatigued with rate $F$, and fatigued units recover with rate $R$. The variation of the state of each unit is defined in this manner based on the actual physiological mechanisms of fatigue and recovery. Because this model does not consider the different behaviors of ST and FT fibers, it can be applied only when there is a high muscle output force.

As stated previously, human muscle fibers can be classified as ST and FT fibers, where ST fibers show a low rate of contraction and high fatigue resistance and FT fibers show rapid contraction and fatigable. The proportions of these types of muscle fibers, which vary from individual to individual, affect the characteristics of the muscles. The use of a muscle fatigue model that does not distinguish between these two types of muscle fibers affects the accuracy of fatigue prediction in a manner dependent on the output muscle force. For example, if a muscle fatigue model considering only FT fibers is used, the degree of muscle fatigue predicted is overestimated when the output muscle force is low.
Generally, when the muscle outputs a low force, ST fibers, which have a low motor nerve activity threshold, activate first, and FT fibers, which have a high motor nerve activity threshold, activate later. This feature is called the size principle (Henneman, 1957). Therefore, the role of ST fibers must be considered for the accurate prediction of muscle fatigue under the condition of a low output force.

Our research group proposed the model shown in Fig. 3 for the prediction of muscle fatigue and recovery considering the roles of ST and FT fibers (Miura et al., 2019). As before, the muscle is considered to consist of $M_0$ total motor units. 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 represented by $M_{0s}$ and $M_{0f}$, respectively. The ST and FT fiber units are then divided into three groups representing the activity state, in the same manner as in the previous model. The numbers of ST fiber units in the standby, active, and fatigued states are given by $M_{ucs}$, $M_{As}$, and $M_{Fs}$, respectively, and those of the FT fiber units are $M_{ucf}$, $M_{Af}$, and $M_{Ff}$, respectively. The active units $M_{As}$ and $M_{Af}$ contribute to the output of the muscle, whereas the standby units $M_{ucs}$ and $M_{ucf}$ and fatigued units $M_{Fs}$ and $M_{Ff}$ do not. The state of each unit may change over time, and thus the number of units in each state changes over time. In the initial state ($t = 0$), all units are in the standby group, as described by

$$M_{Mi} = 0 \ (i = s, f)$$
$$M_{Fi} = 0 \ (i = s, f)$$
$$M_{ucf} + M_{uf} = M_0.$$  \hspace{1cm} (1)

Fig. 3 shows a schematic describing how the ST and FT fiber units traverse the different states. The rates at which active ST and FT fibers become fatigued are given by $F_s$ and $F_f$, respectively, and the rates at which fatigued ST and FT fiber units recover are given by $R_s$ and $R_f$, respectively. However, ST and FT fiber units are considered to change from the standby state to the active state at the same rate, given as $B$. The variation in the number of units in each state is then 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)

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

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

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

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

$$M_{ucf}(t) = M_{Af} - M_{Af}(t) - M_{Ff}(t)$$  \hspace{1cm} (7)

From the progression of the number of units in each state obtained in this way, the output force of the ST and FT fibers can be predicted. In the case of maximum voluntary contraction (MVC), ST and FT fibers are activated simultaneously and the maximum output force is quickly reached. The forces output by the ST and FT fibers and the total force are plotted over time in Fig. 4. In the present study, a muscular motor unit is assumed to be 1 N in the ST and FT fibers.
2.3 Prediction of muscle fatigue considering the roles of antagonistic muscle pairs

The analytical approach developed in the present study makes it possible to predict the degree of muscle fatigue of each muscle in the arm when applying a force at the distal extremity. In this approach, the muscle fatigue and recovery model considering the roles of ST and FT fibers described in section 2.2 is applied to the musculoskeletal model considering the role of antagonistic muscle pairs described in section 2.1 to produce a more complete and realistic model of the muscle behavior. In the present study, the parameters $F_s$, $F_f$, $R_s$, and $R_f$, which describe the muscle fatigue and recovery rates, and the parameter $B$, which corresponds to the command intensity from the brain, were assumed to be common to all of the muscles in the model. The total numbers of motor units existing in the different muscles in the arm are represented by $M_{0f1}$, $M_{0f2}$, $M_{0f3}$, $M_{0e1}$, $M_{0e2}$, and $M_{0e3}$, and it can be determined from the maximum output force distribution on the distal extremity by the musculoskeletal model described in section 2.1. The numbers of ST and FT fiber motor units of in the different muscles are represented by $M_{0f1s}$, $M_{0f1f}$, $M_{0f2s}$, $M_{0f2f}$, $M_{0f3s}$, $M_{0f3f}$, $M_{0e1s}$, $M_{0e1f}$, $M_{0e2s}$, $M_{0e2f}$, $M_{0e3s}$, and $M_{0e3f}$, and their values can be determined from the proportions of ST and FT fibers contained in the muscle. Then, it is possible to predict changes in the state of the motor units in each muscle during muscle activation.

In the case of MVC, when the direction of the output force at the distal extremity is known, the muscle activation level of each muscle can be predicted using the musculoskeletal model described in section 2.1. A muscle with an activation level of 100% is in MVC, and a muscle with an activation level of 0% is in recovery. A muscle with an activation level between 0% and 100% produces a constant output force. For example, when the output force at the distal extremity is the vector $P$ shown in Fig. 5, the activation levels of muscles $e1$ and $e3$ are 100%, those of muscles $f1$ and $f3$ are 0%, that of muscle $f2$ is 70%, and that of muscle $e2$ is 30%. The state distribution of the motor units in each muscle immediately after the force is output is shown in Fig. 6. As shown in Fig. 6, in muscles $e1$ and $e3$, which are under MVC, all of the motor units in both the ST and FT fibers were activated from the standby condition. In
muscles f1 and f3, which were at a 0% activation level, the ST and FT fiber motor units all remained in the standby state. In muscles f2 and e2, which were at an intermediate activation level and producing a constant output force, the response of the motor units was a bit more complex. The number of ST fiber units in the standby state for muscle f2 became zero because of Henneman’s size principle (Henneman, 1957), whereas only a portion of the FT fiber motor units in muscle f2 were activated. In muscle e2, only ST fiber motor units were activated, and the FT fiber motor units remained in the standby state because of the small output force.

When a constant output force is produced at the distal extremity, the activation level of each muscle can be also predicted from the vector of the output force at the distal extremity using the musculoskeletal model described in section 2.1. In this case, the magnitude of the output force can be maintained for a short time. The states of the motor units of each muscle immediately after the force was output are shown in Fig. 7. According to Fig. 7, in muscles e1 and e3, which are under an intermediate activation level, no ST fiber motor units remain in the standby state because of Henneman’s size principle (Henneman, 1957), and a portion of the FT fiber motor units is activated. In muscles f1 and f3, which are at a 0% activation level, both the ST and FT fiber motor units remain in the standby state. In muscle f2, which is also at an intermediate activation level, none of the ST fiber units remain in the standby state because of Henneman’s size principle (Henneman, 1957), whereas all of the FT fiber units of remain in the standby state because of the small output force. In muscle e2, which is also at an intermediate activation level, only the ST fiber motor units are activated, and a fraction of the ST fiber units remain in the standby state because of the small output force.

Fig. 5 Distribution of the output force distribution at the distal extremity of the arm according to the activation level of each muscle

Fig. 6 Dynamical relationship among the three groups of muscular motor units in ST and FT fibers of each muscle in the arm immediately after MVC with the force P (Fig. 5) output at the distal extremity
3. Validation experiment

To validate the proposed muscle fatigue and recovery model considering the roles of antagonistic muscle pairs, a validation experiment was conducted. One university student (height: 177.0 cm, mass: 65 kg), after informed consent, participated in this experiment. This experiment was approved by the ethics committee of the Graduate School of Engineering, Kobe University.

3.1 Identification of parameters for the prediction of muscle forces using the musculoskeletal model

To predict the muscle forces as described in section 2.1, it is necessary to identify the maximum muscle force of each muscle, which can be obtained from the distribution of the maximum output force at the distal extremity. The participant was instructed to apply a force in each possible direction with the maximum possible magnitude to measure the maximum output force distribution. As shown in Fig. 8, a hexagon can be described from four measurement points that do not overlap with edges or vertices (Oshima et al., 2001). The four measurement points correspond to forces applied in four directions: to the front ($F_1$), rear ($F_3$), left ($F_2$), and right ($F_4$), which are directions in which the participant can easily output a force. To obtain a hexagon from the measurement points, point $F_1$ is defined as vertex A of the hexagon, point $F_2$ lies on edge BC, and point $F_4$ lies on edge EF. Finally, the hexagon is described to include point $F_3$ on one of the remaining edges (Fig. 8).

An aluminum frame with a handgrip on a three-component dynamometer (KYOWA Corp. LSM-B-SAI) was used to measure the maximum output forces of the upper limb, as shown in Fig. 9. The posture of the upper limb of the participant can be set as desired by adjusting the three-component dynamometer and seat. The length of each link and the posture of the upper arm are given in Table 1. The participant output the maximum force to the four points and the output force was measured by the three component dynamometer. Then, the sampling frequency of the three component dynamometer was 20 Hz.
3.2 Identification of parameters for the prediction of muscle fatigue considering the roles of slow- and fast-twitch fibers

To predict the degree of muscle fatigue of each muscle with the proposed model, the parameters must be determined in a preliminary experiment. These parameters are $M_{0f1}$, $M_{0f2}$, $M_{0f3}$, $M_{0e1}$, $M_{0e2}$, and $M_{0e3}$, which are the total numbers of motor units in each muscle; $\%ST_{f1}$, $\%FT_{f1}$, $\%ST_{f2}$, $\%FT_{f2}$, $\%ST_{f3}$, $\%FT_{f3}$, $\%ST_{e1}$, $\%FT_{e1}$, $\%ST_{e2}$, $\%FT_{e2}$, $\%ST_{e3}$, and $\%FT_{e3}$, which are the proportions of ST and FT fibers contained in each muscle; $B$, which represents the rate at which units are activated from the state; $F_s$ and $F_f$, which represent the rates at which active units become fatigued; and $R_s$ and $R_f$, which represent the recovery rate of fatigued units.

With the same instrument and under the same conditions as in Fig. 9 and Table 1, the participant applied a force with maximum effort and continued to apply this force until the output force became steady due to fatigue. In this experiment, the participant applied a force in the front, rear, left, and right directions, and the variation of the output force in each direction was measured. Furthermore, to validate the prediction of the degree of the muscle fatigue even in the case that the output direction changes, which means the muscle activation pattern changes, the variation of the output force applied in the direction offset by $30^\circ$ from the front–rear direction was measured and compared with the predicted result.

Table 1 Physical characteristics and postural conditions of the participant

|   | $l_1$ [cm] | $l_2$ [cm] | $\theta_1$ [deg] | $\theta_2$ [deg] |
|---|---|---|---|---|
| Participant | 31 | 35 | 50 | 45 |
3.3 Variation of the output force under maximum voluntary contraction with alternating periods of rest

An experiment in which periods of output and rest were repeated was conducted as shown in Fig. 10 using the same instrument and posture as in Fig. 9. First, the participant applied a force under MVC in one direction (rear) for 30 s, followed by a period of rest for 10 s. Then, the participant applied a force under MVC in a different direction (left) for 30 s, again followed by 10 s of rest. This cycle of alternating MVC and rest were repeated until the output force became steady as a result of muscle fatigue.

Fig. 10 Experiment with alternating periods of output under MVC and rest (30 s MVC, 10 s rest)

3.4 Variation of the output force under a constant applied force

An experiment in which the participant was instructed to apply a constant output force was conducted as shown in Fig. 11 using the same instrument and posture as in Fig. 9. In the first pattern, the participant first applied a constant output force in the backward direction for 30 s and then again in the forward direction for 30 s, and this pattern was repeated. The magnitude of the constant applied force was 50% of that under MVC. In the second pattern, the directions were backward and to the left.

Fig. 11 Experiment in which the participant maintains a constant output force in different directions
4. Results and Discussion

4.1 Identification of parameters for the prediction of muscle forces using the musculoskeletal model

First, the maximum output force of each muscle at the distal extremity in the musculoskeletal model was experimentally determined as described in section 3.1. The four measured points of the output force and the maximum distribution of the output force on the distal extremity derived from these points are shown in Fig. 12. To determine the maximum muscle force of each muscle according to the obtained output force distribution, it is necessary to know the muscle force ratio of each antagonistic muscle pair. In the present study, the ratio of the muscle forces of muscles $f_3$ and $e_3$ was assumed to be 50:50 (Fujikawa et al., 1997). The results of the maximum output force of each muscle are given in Table 2.

![Fig. 12 Measured output forces and output force distribution](image)

| Participant | $f_1$ [N] | $f_2$ [N] | $f_3$ [N] | $e_1$ [N] | $e_2$ [N] | $e_3$ [N] |
|-------------|-----------|-----------|-----------|-----------|-----------|-----------|
|             | 246.5     | 260.9     | 67.1      | 186.2     | 103.2     | 67.1      |

Table 2 Determined maximum muscle force of each muscle at the distal extremity

4.2 Identification of parameters for the prediction of muscle fatigue considering the roles of slow- and fast-twitch fibers

The relationship between the MVC $M_{Amaxi}$ and $M_0 (i = f_1, f_2, f_3, e_1, e_2, e_3)$ has been derived in a previous study (Liu et al., 2002). Therefore, $M_0$ can be determined from the measured MVC $M_{Amaxi}$, which are determined as described in section 4.1, as

$$M_{Amaxi} = M_0 i \times 97\% \quad (i = f_1, f_2, f_3, e_1, e_2, e_3) \quad (8)$$

The parameters $%ST_i$ and $%FT_i (i = f_1, f_2, f_3, e_1, e_2, e_3)$, which are the proportions of ST and FT fibers in each muscle, were set in reference to the values given by Johnson et al. (1973). The parameter $B$ was set as 5 following a previous study (Liu et al., 2002). The parameters $Fs$, $Ff$, $Rs$, $Rf$, which determine the muscle fatigue and recovery characteristics, were obtained by iterative calculation so that the difference between the measurement and prediction results of the output force in the four directions as described in section 3.2 was minimized. The results of the parameters for the participant determined in this way are given in Table 3 and the measured and predicted variation of the output force shown in Fig. 13.

For the experiment with a force applied under MVC at an offset of 30° from the front–rear direction, the measurement results were compared with the results predicted by the proposed model, as shown in Fig. 14. As demonstrated by Fig. 14, the variation of the output force predicted by the proposed model agrees well with the measured force in both the
positive and negative directions along the considered 30° orientation. Thus, the results indicate that the variation of the output force in various directions could be predicted using the parameters determined from a few preliminary experiments without requiring the determination of the parameters for each output force direction.

| Participant | $M_{\theta_1}$ | $M_{\theta_2}$ | $M_{\theta_3}$ | $M_{\theta_4}$ | $M_{\theta_5}$ |
|-------------|----------------|----------------|----------------|----------------|----------------|
| $\%ST_{f_1}$ | 254.1          | 269.0          | 69.2           | 192.0          | 106.3          |
| $\%ST_{f_2}$ | 57             | 43             | 60             | 43             | 57             |
| $\%ST_{f_3}$ | 60             | 43             | 57             | 43             | 57             |
| $\%ST_{f_4}$ | 40             | 43             | 57             | 67             | 43             |

Table 3 Parameters for the proposed model determined from the experimental results

![Fig. 13 Measured and predicted output force under MVC](image-url)
4.3 Measured output force under maximum voluntary contraction alternating with periods of rest

The output force measured in the experiment described in section 3.3 was compared with the output force predicted using the proposed model. Furthermore, the output force was predicted with the previous muscle fatigue model without considering antagonistic muscles (Miura et al., 2019). The measured output force was compared with the output forces predicted by the proposed and previous models, as shown in Fig. 15.
Fig. 15 Measured output force and the output forces predicted with the proposed model and the previous model neglecting the roles of antagonistic muscles.

As demonstrated by the results shown in Fig. 15, the variation of the output force predicted by the proposed model agrees better with the measurement results than that predicted by the previous model. The reason for this is as follows. When the output force is directed to the rear, muscles f2 and f3 are under MVC, and muscles f1 and e1 are in the antagonistic state. When the output force directed to the left, muscles f1 and f3 are under MVC, and muscles f2 and e2 are in the antagonistic state. Thus, muscles f1, f2, and f3 are always activated. However, because the previous muscle fatigue model does not consider the roles of antagonistic muscles, when the direction of the output force changes, the recovery of the muscle was overestimated, and the difference between the predicted and measured forces was larger than that when the proposed model was used for the prediction.

4.4 Measured output force under a constant applied force

The output force measured in the experiment described in section 3.4 was compared with the output force predicted with the proposed model. The measured and predicted output forces are shown in Fig. 16.

As demonstrated by the results shown in Fig. 16, the variation of the output force predicted by the proposed model agrees well with the measurement results. In the case of pattern 1 (front and rear directions), the activated muscles are opposite in the two parts of the pattern, with muscles f2, f3, and e1 activated in the rear direction and muscles f1, e2, and e3 activated in the front direction. Therefore, when the direction of the output force changes, all activated motor units are allowed to recover. Thus, even if the target output force cannot be maintained over the entire 30 s duration in which the force is applied in one direction, the muscle recovers from its fatigued state before the next iteration of the output force in the same direction, and the target output force can be achieved again. As demonstrated by the prediction...
results, this behavior can be captured by the proposed model. In the case of pattern 2 (rear and left directions), muscles f1, f2, and f3 are always activated. Therefore, when the direction of the output force changes, these muscles do not recover from the fatigued state. Thus, once the target output force can no longer be maintained, it cannot be achieved again. As demonstrated by the prediction results, this behavior can also be captured by the model. The results here demonstrate that the proposed model can realistically predict different muscle fatigue and recovery behaviors for different combinations of muscle activated patterns because it considers the activated pattern of each muscle.

5. Conclusion

The present study proposed a model of muscle fatigue and recovery considering both the behavior of ST and FT fibers and the role of antagonist muscles. The achievements of the present study can be summarized as follows.

• A method of predicting the variation of the output force of each muscle was developed by applying a dynamical model of muscle fatigue and recovery considering the behaviors of ST and FT muscle fibers to a musculoskeletal model considering the role of antagonistic muscle pairs.
• The parameters necessary to predict the degree of muscle fatigue of each muscle can be determined from a few preliminary experiments in which a participant applies a force in only four directions.
• The degree of muscle fatigue can be predicted during a motion in which the muscle activation pattern dynamically changes.

In future work, we aim to predict and validate the degree of muscle fatigue during motions in which the posture of the upper arm dynamically changes.

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