The effect of force sensation on the ability to control muscle force during fatigue condition

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Abstract.
BACKGROUND AND OBJECTIVE: Proprioceptive information from muscle receptors is important in force control and disturbed sensation due to fatigue may reduce the precision of force control. The aim of this study was to clarify the relationship between force sensation and force control ability in knee extensor muscles during fatigue.
METHODS: Eighteen healthy young volunteers participated in this study. Force matching tasks with and without feedback were performed immediately before and after the fatigue protocol consisting of 20 s isometric contractions. The target force was 10\% and 30\% of the maximal voluntary contraction force in the pre-fatigue protocol. The accuracy of force control ability was estimated by the root mean square error (RMS error) and average difference (average error) between the target and output force. Surface electromyograms were recorded simultaneously from the quadriceps.
RESULTS: In the 30\% task, there was a significant interaction effect of fatigue and feedback condition in RMS error and average error. RMS error and average error were degenerated significantly by fatigue in the feedback removal condition, but not in the feedback condition. Though the activation of quadriceps was increased by fatigue, increase of muscle activation was lower in the feedback removal condition than that in the feedback conditions.
CONCLUSION: Since participants controlled their force output depending on the force sensation in the feedback removal condition, these results indicate that the decline in force sensation may be a significant factor in the decreases of accuracy in force output during fatigue.

Keywords: Force control, force matching, muscle fatigue, knee, isometric contraction

1. Introduction

Repetitive or continuous muscle contraction induces muscle fatigue and decreases maximum voluntary contraction (MVC) force. Muscle fatigue results in a decline of performance and the occurrence of injury and falling. The incidence of sports injury is greater during fatigue conditions [1], and muscle endurance is decreased in older women with a history of falls than in older women without such history [2].

In addition to the reduction of muscle force output, joint position sensation may be disturbed by muscle fatigue in the upper and lower extremities [3]. A previous study reported that the knee extensors were perceived as longer than their actual length in the fatigue condition [4]. Antigravity movement requires the accurate perception of body alignment and the precise control of muscle output force, therefore muscle fatigue in the lower extremities results in an increase in postural sway [5–7]. Fatigue of the knee joint musculature dis-
turbed postural control in the frontal and sagittal plane during upright standing [8]. Previous study compared body disturbance in fatigue conditions with and without vibration stimulation to the gastrocnemius, soleus and tibialis anterior muscle. That study reported that the sensory disturbance evoked by vibration stimulation increased postural sway only in the no fatigue condition, but not in the fatigue condition, and concluded that central nervous system (CNS) relies less upon proprioceptive information from fatigued muscle for regulating postural sway because of reduced sensation of the fatigued muscle [9].

Moreover, force sensation may be altered by muscle fatigue [10,11]. Decline in the ability to control muscle force caused by muscle fatigue also may impair postural control and movement performance. The accuracy of force control was analyzed generally using a force tracking task with visual feedback. In force matching tasks during fatigue conditions, a greater steadiness and force control error were observed, mainly due to the increase in number and discharge rate of active motoneurons [12]. Proprioceptive information from muscle receptors, including the muscle spindles and tendon spindles, is important in force control [13,14]. Therefore, disturbed sensation due to fatigue may damage the accuracy of force control. However, to our knowledge, the effect of the decline in sensation on the force control during fatigue condition has not been clarified.

The purpose of this study was to clarify the relationship between sensation and force control in knee extensors during fatigue conditions. We compared the accuracy of force control ability using the task with visual feedback and feedback removal in the pre- and post-fatigue condition. We hypothesized that muscle fatigue would increase the force control error especially in the force matching task with feedback removal, which suggests that force control is reduced by disturbed force sensation due to fatigue.

2. Methods

2.1. Subjects

Eighteen healthy young volunteers (mean ± standard deviation; age, 24.8 ± 4.8 year; height, 1.70 ± 0.07 m; weight, 67.7 ± 1.8 kg) participated in this study. Subjects with lower limb injuries or a history of cardiovascular illness were excluded. Each participant read and signed an informed consent form approved by the Clinical Review Board of the Faculty of Medicine, Kagoshima University.

2.2. Experimental protocol

Maximal isometric voluntary contraction and force control task were performed immediately before and after the fatigue protocol. The MVC force was examined before and after the force control task to decide the target force and to evaluate the fatigue status. We conducted a force matching task with visual feedback and feedback removal in the pre- and post-fatigue condition. In the feedback condition, participants can control their force output according to the visual information while in the feedback removal condition participants control their force output depending on the force sensation.

2.3. Force matching task and electromyography

A custom program in LabVIEW 8.6 (National Instruments, TX, USA) manipulated the targeted force level and visual feedback condition. The target force was provided as a yellow line and the force exerted by the subjects was provided as a white line progressing with time from left to right. At examination, subjects were seated on a chair consisting of a steel frame in the front of a computer screen (Fig. 1). A stabilization strap was placed over the pelvis and trunk and the subjects were instructed to grasp an arm rail to eliminate extraneous movement. Measurement of the MVC, force matching task and fatigue protocol were performed in the left knee extensors at 90° knee flexion. A strain gauge (9311B, Kistler, Winterthur, Switzerland) connecting wire was attached above the lateral malleolus, and was used to measure knee extensor force during all tasks.

Surface electromyographic (EMG) dual electrodes (#272, Noraxon, Arizona, USA) connected to an EMG system (KM-104, Mediarea support Business Co., Okayama, JPN) were placed over the rectus femoris (RF) and the vastus medialis (VM) according to SENIAM recommendations [15]. Skin preparation followed standard procedures and consisted of shaving and cleaning with alcohol. Force and EMG signals were sampled at 1000 Hz using a 16 bit A/D board (NI USB-6259, National Instruments, TX, USA) and stored on a computer for analysis.

To evaluate MVC, three 5 s maximal contractions were recorded with a 45 s rest between each contraction in the pre- and post-fatigue protocol. The subjects were asked to adjust their force output to match the target force indicated by a line on the visual display for 8 s. The target force was set to 10% and 30% of
the MVC force in the pre-fatigue protocol. The force matching tasks were conducted under two conditions: visual feedback presented throughout the trial (feedback condition) or visual feedback presented for the initial 5 s and then removed (feedback removal condition). After removal of visual feedback, participants were asked to maintain the force output. Participants practiced the task 5 times with feedback removal condition at each force level prior to the data collection trial. They performed a block of 3 trials in the visual feedback removal condition and one feedback condition in the pre- and post-fatigue protocol. Tasks with feedback were completed after tasks with feedback removal at each condition. The two force levels were completed in random order and there was 15 s of rest between each task.

2.4. Fatigue protocol

The fatigue protocol was designed in accordance with that of a previous study [12]. During the fatigue protocol, participants performed 20 s knee extensor contractions at 45% of the MVC. The force output and target force were displayed during fatigue protocol. Participants repeated the contraction until they were not able to maintain the contraction more than 5 s. The maximum number of repetitions was set to 15 times.

2.5. Data analysis

Signals from 6.0 s to 8.0 s in each contraction were analyzed to examine the effect of the force sensation on force control during fatiguing conditions (Fig. 2). The knee extensor force was filtered using a 2nd order Butterworth low pass filter with a 20 Hz cut-off frequency. We calculated the root mean square error (RMS error) and average error for the accuracy index of force control. The RMS error was the square root of the mean of the square of the difference between the target and output force. The average error was the average drift of output force from the target force (output force minus target force). The negative value of the average error indicates that the output force undershot the target force. These indicators were divided by the target force to allow comparison between the results obtained from different participants [16]. The raw EMG signals were filtered using a band pass filter (10–500 Hz), and were full wave rectified. The integrated EMG (IEMG) was calculated for each muscle to determine the total amount of muscle activity, and the IEMG was normalized to the MVC.

To evaluate the effect of muscle fatigue, paired t-test was used to compare the MVC and IEMG in the pre- and post-fatigue. The interaction of fatigue (pre versus post) and feedback condition (feedback condition versus feedback removal condition) on RMS error, average error and IEMG were examined for each force level using a repeated measures two way analysis of variance (ANOVA). If an interaction was observed, paired t-test was used to determine the effects of fatigue and feedback condition. All statistical tests were performed using the SPSS (SPSS Inc, Chicago, IL, USA). Statistical significance was set at 0.05.

3. Results

3.1. MVC

The muscle contraction was repeated $6.9 \pm 3.0$ times for each participant in fatigue protocol. One par-
Participant repeated muscle contraction 15 times. The pre- and post-fatigue MVC were 636.8 ± 153.9 N and 450 ± 108.1 N, respectively (t = 8.40, P < 0.001). The MVC in knee extension of the post-fatigue protocol was 28.5 ± 9.6% less than that of the pre-fatigue protocol.

3.2. RMS error

All participants showed an immediate decline in force output when visual feedback was removed during the force matching task in the pre- and post-fatigue conditions (Fig. 2).

In the 10% task, RMS error was increased slightly in the post-fatigue condition, but there was no significant effect by fatigue (Fig. 3A, \(F_{(1,17)} = 0.69, P = 0.418\)) and interaction (\(F_{(1,17)} = 0.000, P = 1.000\)). The RMS error in the feedback removal condition was significantly greater than that in the feedback condition (\(F_{(1,17)} = 38.98, P < 0.001\)). In the 30% task, ANOVA showed a significant interaction effect (Fig. 3A, \(F_{(1,17)} = 8.37, P = 0.010\)). In the pre- and post-fatigue condition, the RMS error was greater in the feedback removal condition (pre-fatigue, t = 7.16, \(P < 0.001\); post-fatigue, t = 5.61, \(P < 0.001\)). RMS error was increased significantly by fatigue in the feedback removal condition (t = 2.49, \(P = 0.023\)), but not in the feedback condition (t = 0.38, \(P = 0.710\)).

3.3. Average error

In the 10% task, the average error was increased significantly due to fatigue in both feedback conditions (Fig. 3B, \(F_{(1,17)} = 5.43, P = 0.032\)). ANOVA showed a significant effect of feedback condition (\(F_{(1,17)} = 9.32, P = 0.007\)), but no interaction effect (\(F_{(1,17)} = 2.24, P = 0.153\)). In the 30% task, there was a significant interaction effect (Fig. 3B, \(F_{(1,17)} = 7.03, P = 0.017\)), and the average error decreased by fatigue in the feedback removal condition (t = 2.28, \(P = 0.036\)), but not in the feedback condition (t = 0.29, \(P = 0.772\)). The average error in the 30% task was lower in the feedback removal condition especially in the post-fatigue condition (pre, \(t = 7.66, P < 0.001\); post, \(t = \ldots\))
5.76, \( P < 0.001 \)), which indicated that the output force undershot the target force.

### 3.4. EMG

In the 10% task, the IEMG of RF increased significantly by fatigue in the feedback and feedback removal conditions (Fig. 4A, \( F_{(1,17)} = 28.76, P < 0.001 \)). ANOVA showed significant effect of feedback (\( F_{(1,17)} = 7.64, P = 0.013 \)) and no interaction effect (\( F_{(1,17)} = 1.58, P = 0.226 \)). In the 30% task, a significant interaction effect was observed in the IEMG of RF (\( F_{(1,17)} = 14.61, P = 0.001 \)), which was significantly increased in both feedback conditions by fatigue (feedback condition, \( t = 4.82, P < 0.001 \); feedback removal condition, \( t = 3.95, P = 0.001 \)). The IEMG of RF was significantly smaller in the feedback removal condition (pre-fatigue, \( t = 3.38, P = 0.004 \); post-fatigue, \( t = 5.54, P < 0.001 \)), and the difference between these two feedback conditions was especially larger in the post-fatigue condition. The IEMG of VM was very similar to that of RF (Fig. 4).

### 4. Discussion

The purpose of this study was to clarify the effect of altered force sensation due to muscle fatigue on the control of force. Our results show that despite no change in RMS error and average error by fatigue in the feedback condition, RMS error and average error degraded significantly in the feedback removal condition in the 30% task. These results suggest that the decline of force sensation induced by muscle fatigue interferes with precise force control.

In this study, we quantified the accuracy of force control using the RMS error and the average error. Similar to previous findings [17], the removal of feedback decreased the force output and increased the RMS error and average error at moderate force levels. In the 30% task, fatigue did not affect the average error in the feedback condition, but the average error was decreased significantly by fatigue in the feedback removal condition. The decreased average error indicates that the force output by fatigued muscle undershot the target force, and resulted in an increase of RMS error.

The repetition of knee extensor isometric contraction decreased the MVC force to 71.5%, which was greater than twice the target force. Additionally, the decline in force was not observed in the feedback condition performed after completing the task in the feedback removal condition. The main factor of the decline of force was not fatigue, but force sensation, which plays an important role in force control in the feedback removal condition.

Neural information related to force control includes signals from proprioceptive receptors in muscles or tendons, and the sense of effort generated by the CNS or the efference copy of motor command [5,6,18]. It has been noted that Golgi tendon organs appear well suited to provide reliable information concerning muscle force. It has also been reported that la muscle spindle afferents are capable of signaling intramuscular tension [19], and that the signal muscle spindle afferents decreased following muscle fatigue [20]. Studies have reported that these mechanoreceptor deficits induced by fatigue are related to perception of the joint position [3]. Similarly, this alteration of signals from proprioceptive receptors may interfere with accurate perception of muscle force [21].

On other hand, the CNS increases the number of recruited motor units to compensate for the decline of force output by fatigue [22]. This increased drive...
to motor units by CNS can be observed in the increased EMG activity, but the excessive muscle activation makes it difficult to estimate the force output. Previous studies using the contralateral limb force matching task, in which participants are required to match the level of the force output in the fatigued limb with that in the contralateral limb, indicated that the force output in the fatigued muscle overestimated the level due to an increase in the excitatory input to the fatigued muscle [23,24]. The overestimation of force output due to excessive drive from the CNS to fatigued muscle is related to the lack of force output for the target force during feedback removal conditions at moderate force levels in this study. In the 30% task, RF and VM activation were increased in post-fatigue, but those activities in the feedback removal condition were reduced compared to that in the feedback condition. The shortage of compensative muscle activation caused by incorrect force sensation was related to the decreased average error.

Another factor associated with the incorrect force output during sustained submaximal contraction in muscle fatigue is an increased force variability, which is caused by the activation of larger motor neurons, an increased firing rate, or inhibitory influence to the α motoneurons from Type III and IV afferents [12,25]. The RMS error included force variability and the drift of output force from the target force. Since the RMS error in the feedback condition did not show a significant difference between pre- and post-fatigue in the 30% task, the increase of the force variability should not affected the results in this study.

In the 10% task, significant interaction between fatigue and the feedback condition was not observed in RMS error and average error. Muscle activation in the 10% task increased post-fatigue, but the differences in the IEMG between the two feedback conditions was imperceptible compared with that of the 30% task. Therefore, we assume that the effect of decreased force sensation depends on the volume of compensatory muscle activation.

In our study, the disturbed force sensation due to fatigue interfered with accurate control of the force output at 30% MVC, which is used in daily activity [26]. Most activities of daily living require monitoring internal feedback regarding submaximal force, so the force control estimated in the feedback removal condition reflects the actual daily performance. In addition to the declined MVC force and the delay in the activation, decreased force sensation makes it difficult to generate the proper muscle force to meet environmental demands. It would be more difficult to control muscle force output accurately when the activations require increased muscle activation, such as when running or participating in recreational sports. Furthermore, larger relative force to the MVC and less endurance has been demonstrated in the elderly [27]. Therefore, the effect of decreased force sensation by fatigue would be greater in the elderly. Enhancing the maximal force and endurance are required to prevent fall and injury during physical training.

There are limitations to our study. Although isometric muscle force in an open kinetic chain was used to analyze the accuracy of force control in this study, concentric and eccentric contraction in a closed kinetic chain are used in daily activity. Force control in those conditions is more difficult than that in the condition used in this study [28]. Also, the current study sampled only young subjects, and an analysis of elderly subjects is required. Further studies are needed to clarify the effects of force sensation impairment by fatigue on force control during daily activity.

5. Conclusion

Muscle fatigue increased force control error during isometric contraction in the force matching task with feedback removal at moderate force level, but not in the feedback condition. This result suggests that precise force control was impaired by deficits of force sensation caused by muscle fatigue. We assume that the effect of decreased force sensation depends on the volume of compensatory muscle activation by fatigue. The degraded performance in the fatigue condition was induced by not only the decline in maximal force output, but also the deficits of accurate force control due to decreased force sensation.

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References


