

Anticipatory Vibrotactile Cueing Facilitates Grip Force Adjustment during Perturbative Loading

Shogo Okamoto, Michael Wiertelwski, and Vincent Hayward, *Fellow, IEEE*

Abstract—Grip force applied to an object held between the thumb and index finger is automatically and unconsciously adjusted upon perception of an external disturbance to the object. Typically, this adjustment occurs within approximately 100 ms. Here, we investigated the effect of anticipatory vibrotactile cues prior to a perturbative force, which the central nervous system may use for rapid grip re-stabilization. We asked participants to grip and hold an instrumented, actuated handle between the thumb and index finger. Under computer control, the handle could suddenly be pulled away from a static grip and could independently provide vibration to the gripping fingers. The mean latency of corrective motor action was 139 ms. When vibrotactile stimulation was applied 50 ms before application of tractive force, the latency was reduced to 117 ms, whereas the mean latency of the conscious response to vibrotactile stimuli alone was 229 ms. This suggests that vibrotactile stimulation can influence reflex-like actions. We also examined the effects of anticipatory cues using a set of perturbative loads with different rising rates. As expected, facilitation of grip force adjustment was observed for moderate loads. In contrast, anticipatory cues had an insignificant effect on rapid loads that evoked an adjustment within 60–80 ms, which approaches the minimum latency of human grip adjustment. Understanding the facilitative effects of anticipatory cues on human reactive grip can aid the development of human-machine interfaces to enhance human behavior.

Index Terms—Grip force adjustment, vibrotactile stimulus, asynchronous cues

1 INTRODUCTION

WHEN manipulating an object, humans adjust grip forces in a largely unconscious manner [1]. In the case of rapid, unexpected loading or unloading to the object, grip forces are automatically adjusted to stabilize the grip or to avoid overly large grip forces. Mechanoreceptors in the skin, tendons, and muscles contribute to an economical and secure grip via spinal and supraspinal sensorimotor circuits that operate at different levels of the nervous system [2]. Cutaneous mechanoreceptors play a particularly important role in this, as demonstrated by the observation that digital anesthesia significantly reduces corrective prehensile behavior [3], [4], [5]. During anesthesia, grip forces tend to exceed the minimum required force [2], [6], [7], [8], [9] as a consequence of a strategic change in motor control and compensatory behaviors. A loss of economic grip is also observed when tactile sensitivity is weakened as a result of wearing gloves [10] or during robotic telemanipulation [11]. Furthermore, vibrotactile stimulation of the finger pads, when synchronized with sudden loading, can promote grip force adjustment [12]. These findings indicate that cutaneous inputs provide early warning signals in advance of grip failure. In the field of robotics, grip force control that is based on early signaling

via artificial skin sensors is successful due to the sensitive response to variations in contact status that result from the low mechanical impedance of soft artificial skin [13], [14], [15], [16], [17], [18], [19].

In this study, we tested the potential for facilitation of grip force adjustment, taking advantage of cutaneous stimuli as early predictive signals, specifically, a vibratory cue that stimulated finger pads in advance of abrupt loading. In the first experiment, we demonstrated that vibrotactile cutaneous stimuli reduce the latency of adjustment. These results were based on previous work [20], where we also discussed the temporal relationship between the deformation of finger pads and grip force during loading. In the second experiment, we showed that the anticipatory effect of vibrotactile stimuli varied with the degree of external perturbation. Although previous studies have investigated the effects of a vibrotactile cue presented simultaneously with the load [12], [21], the present study focuses on the effects of vibrotactile cues that precede loading.

2 EXPERIMENTAL APPARATUS

The testing procedures and materials were approved by the “Comité de protection des personnes Ile-de-France II” permit 2011-06-16 (IRB registration 1,072). Fig. 1 shows the experimental apparatus. The main component was an instrumented grip handle, held by a thumb and index finger, and driven by two gear-less DC motors (2642W012CR, Faulhaber, Germany) through a differential capstan mechanism. The two motors were driven by a current driver (4-Q-DC Servo Amplifier, Maxon, Switzerland) and mechanically connected in parallel to provide additional torque. Use of a free idler as a tensioner enabled the application of a large torque with only a small loss to friction [22]. The system provided a stalling force of 20 N with a loss of less than

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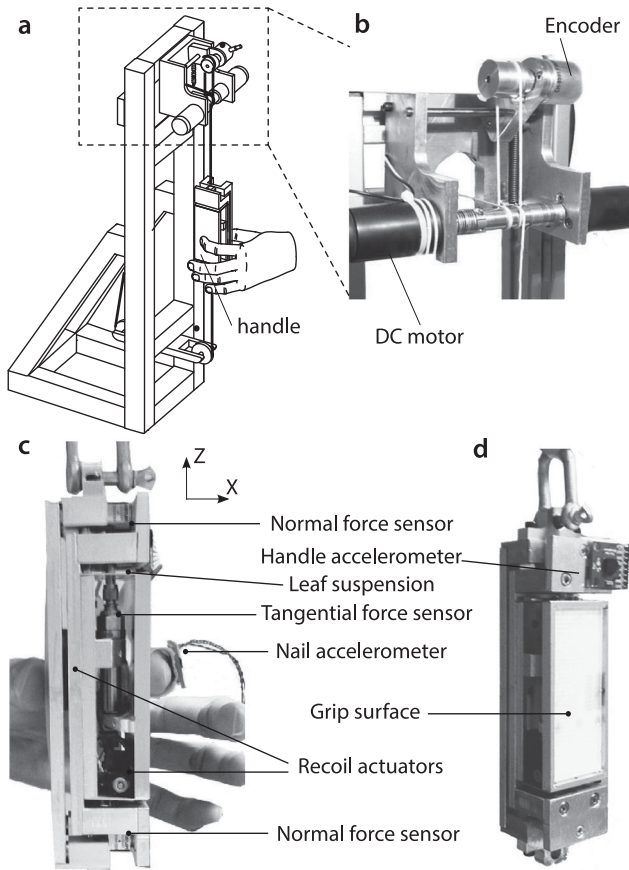


Fig. 1. Apparatus used, including the instrumented grip handle and a pulling mechanism. **a.** Overall view. **b.** Differential capstan drive with two DC motors. **c.** Side view of the grip handle. **d.** Perspective view of the grip handle.

0.1 N. The position of the handle was measured with a potentiometer (BTIV 24S 16.24 K, Baumer, Switzerland, resolution: 0.0146 mm). Data sampling and commands to the DC motor were attained using a data acquisition card (DAQ, PCI-6221, National Instruments, Austin, TX) at a rate of 10 kHz.

We installed three high-precision load cells on the handle as follows. Two force sensors (9313AA1, Kistler Instrumente AG, Winterthur, Switzerland) were located in load paths between the two main plates to measure the normal grip force component. Another load cell (9217A, Kistler Instrumente AG) measured the tangential component of the grip force. The normal force action on the lateral sensor was decoupled via a leaf-suspension mechanism. Each finger contacted a finely polished plastic surface embedded on each plate. The same instrument was also used previously to investigate the effect of slip-induced skin vibrations on grip adjustment [23].

Two recoil type actuators (Haptuator Mark 2, Tactile-Labs, Deux-Montagnes, Canada) were used to vibrate the handle. These were placed orthogonally to the load paths of the force sensors such that they would not interfere with the force measurement.

We also used two accelerometers to measure the net deformation of the fingerpad due to the tractive force, as previously described [20]. One accelerometer was mounted on the nail of an index finger and another on the grip handle. In the present study, these accelerometers were used

for detecting the slippage of grip, which constitutes a failure of adjustment.

3 EXPERIMENT 1: DO ANTICIPATORY VIBROTACTILE STIMULI FACILITATE GRIP ADJUSTMENT?

3.1 Tasks and Instructions

Five naive participants were included in the experiment. They were right-handed men (mean age, 31.2 years), and were free of self-reported neural and tactile disabilities. Each participant sat on a chair and held the grip handle with his index finger and thumb in a relaxed manner. The grip force used to hold the handle was not specifically controlled, and individual mean values were within 3.1-5.3 N, with standard deviations of 0.66-1.0 N. The participant was requested to maintain a natural grip under the force of gravity. In addition, participants were instructed “not to let go of the handle” and to “try to respond to the vibration as quickly as possible.” After each trial, participants released the handle and relaxed. During each trial, participants closed their eyes and wore headphones playing pink noise to conceal sounds emitted by the vibrotactile actuators. The noise level was adjusted for each participant, such that none of the sounds made by the equipment, including vibratory stimuli and loading stimulus, could be heard when the participants did not hold the grip handle.

3.2 Stimuli

3.2.1 Time Sequence and Magnitudes of Traction and Vibrotactile Stimuli

In each trial, after a random delay of 2-5 s, an impulsive force command was sent to the DC motor, and the grip handle was accelerated upward. As a result, the load experienced by the hand of the participant abruptly increased, as shown in Fig. 2A.

Although the time response of this interaction force depended on the dynamics of the human hand and capstan mechanism, the mean and standard deviation of the peak of the load increase for all trials were 2.9 ± 0.81 N, which was observed 195 ± 51 ms after the onset of the motor command. Hence, the mean increase in the rate of traction was 15.0 N/s. The time at which the load increase reached 10 percent of the peak value of traction was fairly stable (29 ± 4.8 ms). These conditions were selected through preliminary trials such that they would successfully induce grip adjustment for most people. Under certain test conditions, a vibratory stimulus was applied to the index finger and thumb of the participant. Its magnitude was set to ± 10 m/s², which corresponds to ± 4 and ± 25 μ m in displacement at 250 and 100 Hz, respectively.

3.2.2 Stimulus Conditions

We tested four types of conditions (with one control condition) that differed in traction and vibration. In a training session, each participant experienced these four conditions only once. In the main task, 40 trials, in which the following four conditions appeared in random order, were performed with each condition presented 10 times.

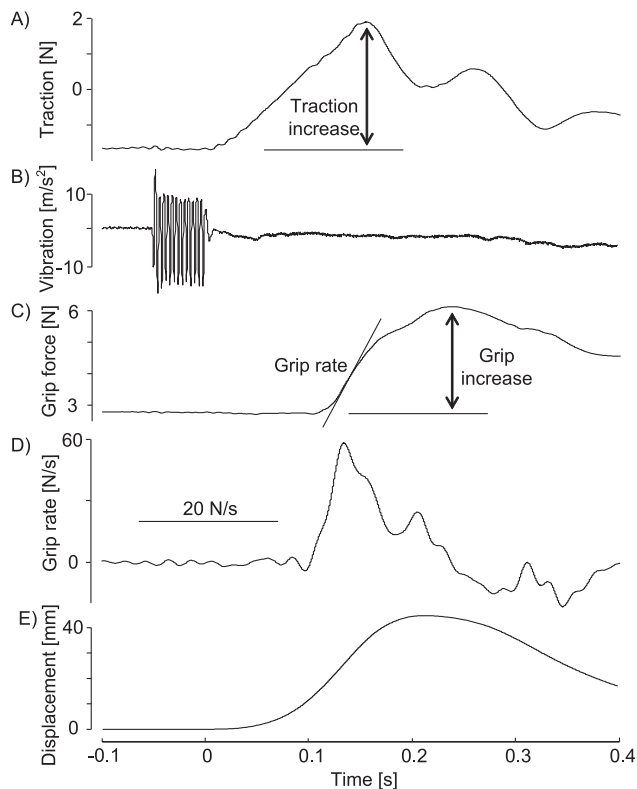


Fig. 2. Time course of the loading stimulus, vibrotactile stimulus, grip response, and net grip handle displacement. A: Tractive loading force typically reached a maximum at 130 ms after the torque command to the motors. B: Vibrotactile stimulus. C and D: Grip force response and grip rate. E: Net displacement of the grip handle, which reached a maximum at a different time from the load, due to the complex biomechanical dynamics coupled to the dynamics of the motor/handle subsystem.

Condition 1: Load only. Traction was abruptly produced without the preceding vibrotactile cue.

Condition 2: Vibration (250 Hz) only. A vibration of 250 Hz was presented without subsequent traction. This condition was aimed to measure voluntary reactions to the vibration.

Condition 3: Vibration plus load (250 Hz). The anticipatory vibration of 250 Hz lasted 50 ms and then the tractive force was initiated. This condition aimed to determine the influence of the preceding vibration on grip force adjustment.

Condition 4: Vibration plus load (100 Hz). This condition was the same as condition 3, except for the frequency of vibration (100 Hz). The aim was to determine if vibration frequency influenced grip force adjustment, given the likely contribution of fast adaptive mechanoreceptors.

Condition 5: Vibration (250 Hz) only. After all the trials of conditions 1-4, we repeatedly tested condition 2 10 times to measure the delay in voluntary reaction toward the vibration in a more controlled manner. During this follow-up test, the participant was informed that only the vibration would be presented, and was instructed to respond to it as quickly as possible.

As described above, we tested two types of vibration frequencies: 100 and 250 Hz. It has been shown that neurophysiologically that the two types of fast adaptive units, FA I and FA II, respond to incipient slippage in the finger-object contact area [24]. However, FA II units do not localize partial slippage because of their large receptive fields, although they exhibit high dynamic sensitivity [24]. Some studies suggest that it is

predominantly FA I units that detect local slippage and are responsible for grip adjustment [25]. We attempted to gain greater insight into this matter; the use of 250 Hz was intended to activate FA II units preferentially, whereas the lower frequency, 100 Hz, was intended to activate both FA I and FA II units. The magnitude of our vibratory stimuli was sufficiently large to activate these receptors in terms of their detection thresholds, which are below $1 \mu\text{m}$ for FA II at 100-250 Hz, and below $10 \mu\text{m}$ for FA I at 100 Hz [26].

3.3 Data Analysis

Fig. 2 shows representative time courses for the data acquired from a single trial. They include (A) traction applied to the handle, (B) the vibrotactile cue, (C) grip force response, (D) grip force rate, and (E) displacement of the handle. The onset of grip force adjustment was observed approximately 100 ms after the onset of the traction instruction, which is noted as $t = 0$. Based on these data, we defined the four parameters that are described in Sections 3.3.1-3.3.4 for each trial.

Some trials were excluded from the analysis. First, the trials for which the increase in grip force was not clearly observed with a 20 N/s threshold were not included in the analysis. For most of these trials, the effect of perturbative load was mitigated by the reflective motions of the hand and arm, rather than by the increase in grip force. Second, we excluded trials that involved full slippage of the fingerpad. Grip slippage rarely happened; at most, in two trials per participant. The occurrence of slippage was judged based on the outputs from the two accelerometers. If the short-period (200 ms) integral of the difference between the two accelerometers exceeded 10 mm, which far exceeds the deformation of the fingerpad, we judged that slippage had occurred. Nonetheless, in most cases, the occurrence of slippage was noticeable for both the participant and the experimenter. These erroneous or irregular trials were observed for all stimulus conditions and constituted only 7 percent of all trials. Since no control condition was used, it is not known whether the vibrotactile cueing induced or prevented these erroneous trials.

The data from the four parameters were then separately pooled, and for each parameter, the largest and smallest values were automatically excluded within a single participant, and the remaining values were used for statistical analysis. After removal of these outlier samples, 30, 29, 30, 31, and 29 trials were considered for P1-P5, respectively, in the statistical analysis. Note that this process implied that the analyses of each of the different parameters were based on data from slightly different sets of trials. We therefore repeated the analysis on a trial-by-trial basis, and eliminated the trials with the longest and shortest delay in the grip force adjustment. Using this coupled approach to outlier rejection, we nevertheless arrived at the same statistical conclusions for analysis of each of the four parameters.

We performed two-way ANOVA for each type of parameter, using the 4-level experimental conditions and participants as factors. Because we were mainly interested in differences between condition 1 and conditions 3 and 4, we also tested these two pairs, with Bonferroni correction, via two-way ANOVA. Furthermore, in order to investigate the effect of voluntary reaction to the vibratory stimuli,

condition 2 was compared with conditions 3 and 4. For this analysis, we used six samples that were randomly selected in terms of the combination of participant and experimental condition, because the number of valid samples differed among the combinations. Hence, 120 samples (six samples \times five participants \times four conditions) were used for the analysis of each parameter.

3.3.1 Latency of Grip Force Adjustment

For conditions 1, 3, and 4, the delay in grip force adjustment was defined as the time period between the onset of the load instruction to the DC motor and the start of the change in grip forces. For conditions 3 and 4, the instruction to the motor began at the end of the period of the vibratory stimulus, as described above. For conditions 2 and 5, the delay was defined as the period from the end of the vibratory stimulus. These definitions enabled us to compare delays under different stimulus conditions on the same temporal baseline. To determine the onset of grip adjustment, we computed first-order derivatives of the grip force after applying a FFT filter with a cut-off frequency of 100 Hz. An example of the computed grip force rate is shown in Fig. 2 D. The increase in grip force was judged with a threshold of 20 N/s, which was two to three times the level of background noise.

3.3.2 Change in Grip Force

The increase in grip force was calculated as the difference between the maximum force after onset of the tractive force and the average of a 100-ms period before traction started or vibration ended. Although the vibration caused a brief noise upon the output from the force sensor, this did not produce any systematic bias. For this calculation, the low-pass filter above described was used. The magnitude of the grip force is directly associated with grip stability and has been used as a parameter to characterize grip adjustment in earlier related studies [27], [28].

3.3.3 Rate of Increase in Grip Force

After the start of grip adjustment, the grip force reached its maximum value within approximately 200 ms, which was 300 ms after the onset of the tractive load. The rate of increase in the grip force was defined by the maximum grip force increase from commencement of the adjustment to the point of maximal grip force. This parameter also characterizes human adjustive behaviors.

3.3.4 Handle Displacement

Handle displacement was defined as the difference between the highest position of the handle after traction and the average position recorded over the last 100 ms prior to the start of traction. The position of the handle was calculated directly from the output of the encoder, without the use of filters. A small handle displacement was considered as indicating a successful response to the perturbation. As discussed below, handle displacement corresponded to the change in posture of the hand and arm, as we excluded trials with apparent slippage.

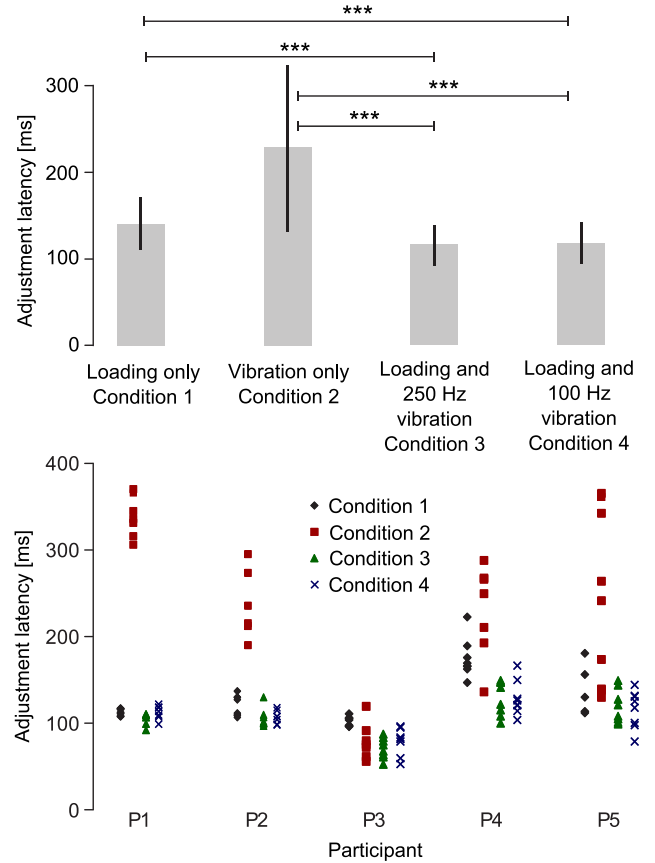


Fig. 3. Latency between pulling force and grip force adjustment. Means and standard deviations among trials. For condition 2, latency was measured from the end of the vibratory stimulus. For conditions 1, 3, and 4, latencies were measured from load onset. Top panel: All trials. Bottom panel: Trials for participants P1-P5. Markers corresponding to conditions 1-4 are indicated from left to right for participants. ***: $p < 0.001$ by ANOVA between two conditions.

3.4 Results

3.4.1 Latency of Grip Force Adjustment

Fig. 3 (top) and Table 1 show the means and standard deviations for the latency in grip force adjustment in each stimulus condition. Fig. 3 (bottom) shows the distribution of individual latencies. The latencies of adjustment were significantly longer for the vibration-only condition (condition 2). The mean latency for this condition was 229 ms from the end of the vibration, which corresponds to 279 ms from the onset of the vibratory cue. Lower latencies than in condition 2 were observed in the load-only condition (condition 1: 139 ms) and vibration plus load conditions (conditions 3 and 4: 116 and 117 ms from load onset, respectively). As seen in Table 1, the grip force changes did not differ significantly among the conditions.

The effects of both the experimental condition ($F(3, 100) = 143.9$, $p < 0.001$) and participant ($F(4, 100) = 51.2$, $p < 0.001$) were indicated as significant factors in two-way ANOVA of data of all conditions and participants. The comparison between condition 1 and conditions 3 and 4 indicated that the latencies of condition 1 were significantly larger than those of conditions 3 ($F(1, 50) = 61.4$, $p < 0.001$) and 4 ($F(1, 50) = 48.4$, $p < 0.001$). Furthermore, the comparison between condition 2 and conditions 3 and 4 indicated that the latencies of condition 2 were larger than those of

TABLE 1
Means and Standard Deviations of the Grip Adjustment Parameters among All Trials in All Participants

		Latency [ms]	Grip increase [N]	Grip increase rate [N/s]	Handle disp. [mm]	Time for max. grip [ms]
Condition	1 (load only)	139 ± 30	8.76 ± 4.21	47.6 ± 25.4	32.4 ± 17.0	352 ± 82
	2 (vibration only)	229 ± 97	9.11 ± 4.52	51.8 ± 17.7	–	419 ± 124
	3 (load + vibration)	116 ± 23	9.91 ± 4.55	49.8 ± 19.3	32.0 ± 15.0	319 ± 64
	4 (load + vibration)	117 ± 24	10.5 ± 4.88	54.9 ± 22.5	30.5 ± 13.8	315 ± 59

conditions 3 ($F(1, 50) = 195.8, p < 0.001$) and 4 ($F(1, 50) = 186.4, p < 0.001$). As shown in Fig. 3 (bottom), these trends were observed in most of the participants.

To summarize these results, latencies under vibration plus load conditions (conditions 3 and 4) were lower than those under the load-only (condition 1) and vibration-only (condition 2) conditions. From the onset of the vibratory stimuli, the average response to the vibration was 279 ms (condition 2) or 222 ms (condition 5), whereas the responses to the vibration plus load were 166 ms (condition 3) and 167 ms (condition 4). Hence, latencies were significantly reduced in the vibration plus load conditions. These values indicate that the reduced latencies in the vibration plus load conditions were not due to voluntary responses to the vibration, but that the preceding stimuli themselves influenced grip force adjustment.

To check for learning effects during the trial, we also compared the latencies for the first and second halves of the trials for each participant, but found no significant learning effects.

Table 1 also lists the mean time at which maximum grip forces were observed. These values show trends similar to those of the latencies. Maximum grip forces were observed latest for condition 2 with a mean value of 419 ms. The values for conditions 3 and 4 tended to be smaller than that for condition 1 which indicates that the latency of adjustment influences the subsequent dynamics of the adjustment.

Participant 3 responded to the tractions under all stimulus conditions more quickly than the other participants. This may be partly because this individual's force increase was 16.6 N on average, which was greater than those of the other participants: 10.2 (P1), 4.4 (P2), 7.7 (P4), and 9.5 N (P1). Accordingly, the average force increase rate of P3, which was 68.6 N/s, was greater than those of the others: 52.7 (P1), 34.4 (P2), 45.0 (P4), and 55.2 N/s (P5). Since latency was defined based on the onset of the force increase, such a large grip force increase may have led to the relatively smaller latencies seen for P3.

3.4.2 Change in Grip Force and Handle Displacement

Table 1 shows the means and standard deviations for the increase in grip force for each stimulus condition. In terms of changes in grip force, there was no statistical difference between the conditions; although there was a weak trend for the preceding vibration to lead to a larger increase in grip force, this was observed in only three of the five participants (P1-P3). Moreover, in the second experiment, described below, vibration had no effect on grip force. Therefore, no conclusions could be reached regarding the effect of preceding vibration on any potential changes in grip force. Although the increase in grip force and speed of grip force adjustment were correlated in earlier studies [27], [29], our results suggest they are not necessarily associated. Such a difference between our results and those of earlier

studies may be due to the different profiles of tractive loads used, as earlier studies used stepping or trapezoidal loads, whereas we employed impulsive loads in this study.

Table 1 also shows the means and standard deviations for handle displacement and the rate of increase in grip force for each condition. There were no clear differences among the conditions.

Although the latency of grip adjustment, handle displacement, and grip force are dynamically linked, no correlations were observed. This may be because the variations in handle displacement are also influenced by elbow and shoulder joints, and are not merely determined by correction of prehension.

3.4.3 Representative Time Course

Fig. 4 shows the mean time course of grip adjustment for one participant (P5). All data were averaged while referring to each trial's temporal origin. As described above, grip forces most rapidly responded under the vibration plus load conditions (conditions 3 and 4), followed by the load condition (condition 1) and the vibration condition (condition 2). In terms of the increase in grip force and handle displacement, although there were no statistical differences among all the participants, for participant 5 the vibration plus load conditions (conditions 3 and 4)

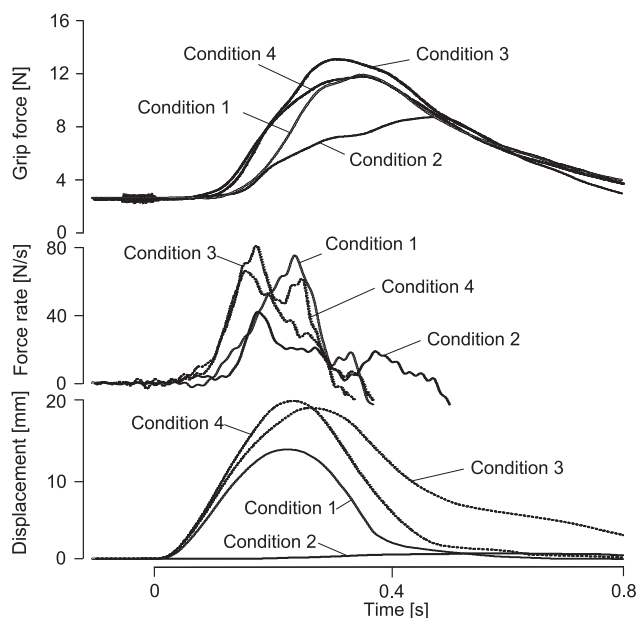


Fig. 4. Average results of one participant. Top panel: Grip force. Middle panel: Derivative of grip force. Bottom panel: Position of the grip handle. Condition 1: Load stimulus only. Condition 2: Vibrotactile stimulus only. Condition 3: Load + vibrotactile stimuli (250 Hz). Condition 4: Load + vibrotactile stimuli (100 Hz).

appeared greater than or at least equal to the load condition (condition 1).

3.5 Summary and Discussion of Experiment 1

In the above experiment, the average latency in grip force adjustment toward the perturbative load was 139 ± 30 ms (condition 1). This value was consistent with those of earlier studies [1], [4], [4], [27], which suggested that the delay may vary over a wide range (60 to 170 ms), depending on the characteristics of the loads and experimental conditions. When the average latency toward the load was 139 ms, the use of the anticipatory vibrotactile stimulus reduced adjustment response times by 22-23 ms to 116 or 117 ms.

Mrotek et al. [28] suggested that preparatory activities of muscles and cutaneous mechanical receptors may facilitate grip force adjustment. They compared grip force adjustments during static holding as well as active lifting of an object, and found lower latencies in the active lifting condition. Notably, pre-activated muscles potentially increase motor responses [30], [31]. Mrotek et al. also noted that pre-activated cutaneous receptors may reduce adjustment latencies. Because of inertia, fingers receive larger loads and cutaneous receptors are more highly stimulated while lifting an object than in the static holding condition. Our results are consistent with those of Mrotek et al., with the exception that we stimulated cutaneous receptors using vibratory stimuli rather than inertia forces, which also led to faster response times.

No significant differences in adjustment parameters, including response latency and changes in grip force, were observed between conditions 3 and 4, in which different vibratory frequencies were presented, although we had expected some effects of frequency based on differing frequency characteristics between different classes of mechanoreceptors. Despite the absence of vibration frequency effects, it is not possible to draw any conclusions regarding relationships between receptor classes and grip force adjustment, given the strong vibratory stimuli used in our experiments.

4 EXPERIMENT 2: IS THE ADJUSTMENT IN GRIP FORCE DURING RAPID LOADING ENHANCED BY ANTICIPATORY VIBROTACTILE CUES?

In Experiment 1, anticipatory tactile cues reduced response latencies by 20 ms, from 139 to 119 ms. This finding prompted us to ask whether a delay of approximately 60 ms shortest value reported in the literature [4], [27], can be reduced by an anticipatory cue? In Experiment 2, we investigated the effects of anticipatory cues when a faster tractive force was applied to the handle.

4.1 Stimuli and Tasks

The presence of an anticipatory vibrotactile cue and the rate of increase in traction were the two stimulus parameters examined in Experiment 2. Fig. 5 shows the five load forces. The rates of these loads were greater than those used in Experiment 1, and their peak forces were approximately 3 N. Peak loads were separated by approximately 30 ms. The frequency, amplitude, and duration of the

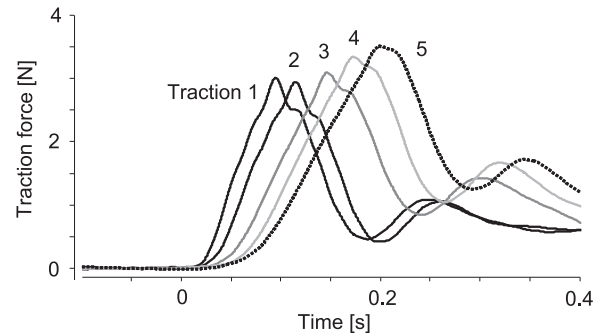


Fig. 5. Averages of the five types of traction increases seen in one participant. Each condition reaches a peak load at a different loading rate. The average and standard deviation of the peak load, time at which the peak was observed, the time to reach 10 percent of the peak, and the rising rate for each type of traction among all the participants were as follows. Traction 1: 3.1 ± 0.35 N, 95 ± 0.7 ms, 28 ± 1.7 ms, and 32.4 N/s; Traction 2: 2.9 ± 0.39 N, 115 ± 0.6 ms, 37 ± 3.5 ms, and 25.7 N/s; Traction 3: 3.2 ± 0.39 N, 146 ± 1.8 ms, 52 ± 4.0 ms, and 22.0 N/s; Traction 4: 3.3 ± 0.59 N, 172 ± 0.8 ms, 65 ± 6.2 ms, and 19.4 N/s; and Traction 5: 3.5 ± 0.44 N, 200 ± 11.3 ms, 75 ± 6.0 ms, and 17.4 N/s, respectively. Traction 1 was the most rapid, and Traction 5 was the slowest.

vibrotactile stimuli were the same as those in the previous experiment (250 Hz, 50 ms before traction onset). Ten conditions (with/without vibrotactile stimuli \times five types of load) were tested in a random order in each set, and 10 sets were performed by each participant.

The five participants from the previous experiment were included in the second experiment, which was performed on a different day, together with one additional right-handed female participant in her 20 s. The procedures and experimental apparatus were the same as those used in Experiment 1.

4.2 Data Analysis

We analyzed the data in a similar manner as for Experiment 1. In order to test the general effects of the traction level and vibration on grip adjustment, we conducted a three-way ANOVA on each type of parameter, with the level of traction, the presence of vibration, and participants as the three factors included. For each combination, eight valid samples were used, hence in total 480 samples (five traction levels \times two vibration mode \times six participants \times eight samples) were analyzed. In order to investigate the potential dependence of the effect of vibration on the traction level, we also tested the effect of vibration for each traction level by a two-way ANOVA, with the presence of vibration and participants included as the two factors.

Finally, to compare the effects of vibration among the traction levels directly, we calculated the differences of latencies between the conditions with and those without vibration, for each traction level. Each difference was calculated using the two samples in the same set of experimental tasks. Hence, all the samples from the 10 sets were used for this purpose. The number of data points was 300 (five traction levels \times six participants \times 10 differences). We then compared the differences in latencies among the traction levels using two-way ANOVA, with the traction levels and participants as factors. Two among the five traction levels were repeatedly tested (10 comparisons), with adjustment of the significance levels by Bonferroni correction.

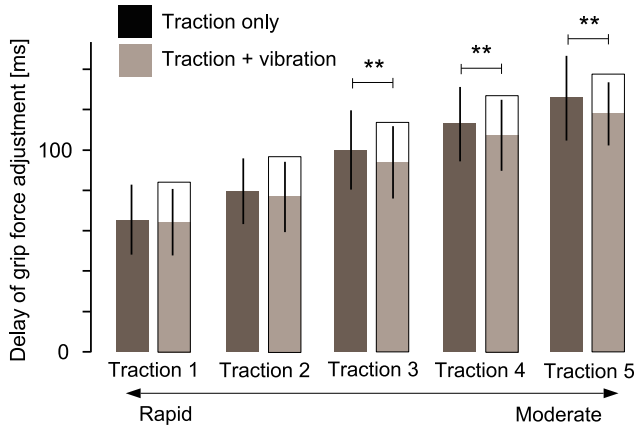


Fig. 6. Latency in grip force adjustment. Means and standard deviations of each condition are shown. Filled bars are from load onset. Open bars are from the onset of vibratory stimuli. **: $p < 0.01$ by two-way ANOVA that tests the effect of vibration for each traction level.

4.3 Results: Latency to Different Degrees of Tractive Force

Fig. 6 and Table 2 show the mean and standard deviation of the adjustment latency for each condition. Latencies reduced as the tractive load rates increased, and this trend was consistent with a previous report [27], where the latencies varied with the magnitude and rate of traction. The three-way ANOVA indicated that the level of traction ($F(4, 420) = 599.6, p < 0.001$), the presence of vibration ($F(1, 420) = 25.2, p < 0.001$), and the participant ($F(5, 420) = 237.7, p < 0.001$) were significant factors. Two-way ANOVAs for each traction level suggested significant effects of vibration for traction 5 ($F(1, 84) = 10.9, p < 0.01$), traction 4 ($F(1, 84) = 7.2, p < 0.01$), and traction 3 ($F(1, 84) = 8.3, p < 0.01$). For the two most rapid levels of traction, no significant effect of vibration was observed. The reduction in latencies due to vibration was significantly larger for traction levels 5, 4, and 3, than for traction levels 2 and 1. The effects of vibrations for level 5 were larger than those for levels 2 ($F(1, 108) = 53.1, p < 0.001$) and 1 ($F(1, 108) = 20.6, p < 0.001$). Similarly, those for levels 4 ($F(1, 108) = 21.6, p < 0.001$) and 3 ($F(1, 108) = 30.9, p < 0.001$) were larger than those for level 1.

We also tested the effects of vibration on other parameters; however, vibration had no significant effect on grip force or handle displacement, similar to the findings of Experiment 1.

4.4 Summary and Discussion of Experiment 2

The minimum delay observed in the experiment was 65.3 ± 17 ms for traction 1 (32.4 N/s, the maximum rate) in the absence of vibration, which is comparable to the minimum values obtained in earlier studies in humans (ca. 60 ms) [1], [4], [24], [27]. This minimum delay may be associated with the shortest neural path, which begins at sensory inputs evoked by cutaneous deformation and changes in the length of muscles and tendons of the hand and ends at the musculoskeletal response to motor instructions transmitted through spinal or supraspinal circuits. The anticipatory vibrotactile cue was effective for moderate perturbative loads, while no significant effect was observed for rapid loads, for which the average response was shorter than that of the moderate perturbation. Thus, anticipatory vibrotactile

TABLE 2
Means and Standard Deviations of Latencies from the Onset of the Tractive Force

Traction level	Without vib. [ms]	With vib. [ms]
1	65 ± 17	65 ± 16
2	79 ± 16	77 ± 17
3	99 ± 20	94 ± 18
4	113 ± 19	108 ± 17
5	125 ± 21	118 ± 15

Abbreviation: vib., vibration.

cues appear to induce the best possible human response performance, rather than exceed it.

5 GENERAL DISCUSSION

The tactile afferents at the fingertip are responsible for the partial slippage associated with an increase in the load to the gripped object, and allow us to adjust grip forces largely unconsciously before the object slips out of the hand [1], [24]. Partial slippage within the finger-object contact area predicts subsequent full slippage. Our experiments indicate that further anticipatory vibrotactile cueing, which starts before loading, facilitates a correction in grip force. Here, we discuss the possible effects of anticipatory vibrotactile cues from two angles: facilitation of perception and muscle activity, which are not necessarily mutually exclusive.

5.1 Facilitation of Perception via Vibrotactile Cueing

A number of studies have investigated the possibility of facilitating human motor responses by using multiple synchronous or asynchronous sensory cues [32], [33], [34], [35], [36]. Most previous studies used visual or auditory cues; however, in studies of tactile cues, an electric stimulus that preceded the subsequent cue by 20-80 ms was found to decrease human response times to the second stimulus in both a simple reaction task [37] and in an identification task [38]. One classical explanation of such phenomenon is the independent race model [36]. In this model, multiple signals from different channels are processed separately, and the human response depends on which of these are detected first. This hypothesis can be discussed by examining joint probabilistic variables.

Let latencies to vibrotactile and loading stimuli be probabilistic variables following a Gaussian distribution, respectively, $X_v \sim N(\mu_v, \sigma_v^2)$ and $X_l \sim N(\mu_l, \sigma_l^2)$, of which population parameters follow the results of Experiment 1. The response to the vibrotactile cue plus load would follow $X_{v+l} \sim N(\mu_{v+l}, \sigma_{v+l}^2)$. The temporal baseline of these variables is shown in Fig. 7. The lower of the two latencies is expressed by $Y = \min(X_v, X_l)$. By definition, the center of the distribution of Y is smaller than those of X_v and X_l . The probability density function of Y is determined by the following equation:

$$\begin{aligned}
 p(y) &= p(x_v, x_v < x_l) + p(x_l, x_l < x_v) \\
 &= p(x_v)p(x_v < x_l|x_v) + p(x_l)p(x_l < x_v|x_l) \quad (1) \\
 &= p(x_v)(1 - P_l(x_v)) + p(x_l)(1 - P_v(x_l)).
 \end{aligned}$$

Where $P_v(\cdot)$ and $P_l(\cdot)$ are the distribution functions of X_v and X_l , respectively. Since Y no longer follows a Gaussian

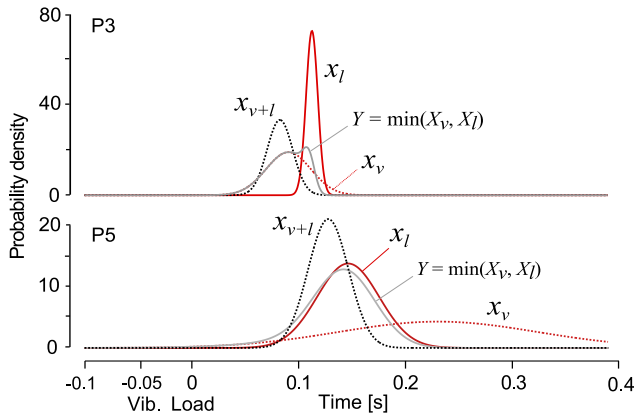


Fig. 7. Probability densities of response latencies in two participants: P3 and P5. X_v , X_l , and X_{v+l} are the responses to the vibrotactile stimulus, load, and load with vibrotactile stimuli, respectively. Y is the density function estimated by the independent race model. For both the participants, X_{v+l} (observed) does not match Y (race model).

distribution, it is not expressed parametrically. Fig. 7 shows examples of density functions of Y for P3 and P5, of whom the population parameters were, respectively, $(\mu_{v_r}, \sigma_{v_r}, \mu_{l_r}, \sigma_{l_r}, \mu_{v+l_r}, \sigma_{v+l_r}) = (91, 21, 113, 5.5, 83, 12)$ and $(231, 93, 147, 29, 128, 19)$, in ms. The peak density of Y shifted slightly to the left of that of X_l ; however, the joint effect of X_v on X_l did not allow Y to approximate the distribution of X_{v+l} . Clearly, Y and X_{v+l} do not match for both the participants, and the observed facilitation in the experiment is not consistent with the independent race model. For the other participants, the distributions of Y and X_{v+l} were less similar than those of P3 and P5.

Other representative models include the co-activation model or the energy summation model, in which sensory activations are summed across multiple sensory channels [34], [35], [36]. The independent race model and these models are not mutually exclusive [33]; however, since the race model does not fit our data, the energy summation model may be useful for interpreting our results. Unfortunately, our experiments did not provide data for exact validation of this model. Furthermore, the two-channel theory of perceptual masking [39] may also be relevant to our observations. According to this theory, human responses to stimuli are collectively mediated by transient (fast adaptive) and sustained (slow adaptive) information processes. A weak anticipatory stimulus activates the slow adaptive process and biases the detection of the following rapid stimulus, which decreases reaction times to the latter stimulus.

5.2 Anticipatory Cues May Enhance Motor Preparation or the Cutaneous-Motor Reflex

Although we discussed the possibility that anticipatory cues may enhance the perception of traction-associated stimuli, vibrotactile stimuli may also facilitate motor preparation.

First, it remains possible that the facilitation of grip adjustment observed in this study was due to a reflexive flexion of fingers toward vibratory stimuli to the skin. Eklund et al. [40] reported an involuntary increase in finger flexion force caused by vibrotactile stimuli to the palmar side of the proximal interphalangeal joints. Their stimuli were 0.5-1.0 mm in amplitude at 100 Hz, which were potentially stronger than those used in our experiments.

They considered that these reflexive phenomena were mediated by mechanoreceptors in the skin, unlike a tonic vibration reflex in which muscle spindles activated by vibrations evoke a reflexive motion, because full or partial anesthesia of the finger led to a similar attenuation of reflexive responses to the vibrations [40], which is consistent with the effects of digital anesthesia on grip force adjustment [3], [4], [5]. Such an unconscious increase in finger flexion forces have also been reported in other studies [41]. Similar reflexive responses hold for finger extension by electric or mechanical tapping stimuli to the dorsal skin [42], where excitatory and inhibitory reflexes were alternately evoked approximately 40 ms after the stimuli. Furthermore, the magnitudes of the vibrotactile stimuli we used were comparable to those needed to activate sensitive muscle spindles by imposing a vibration on the skin above the muscles [43]. Under the vibrotactile stimulus conditions 2 and 5 in Experiment 1, we did not observe such reflexive increases in grip forces. Nonetheless, in our experiment, the anticipatory vibrotactile stimuli may have improved grip-associated muscle activity within a subthreshold level, which may have facilitated subsequent adjustive behaviors, whereas they did not induce apparent reflexive increases in grip forces per se.

Another explanation for the facilitation of grip adjustment could be a preparatory modulation toward a subsequent stimulus by the supraspinal system. Rossetti et al. [44], [45] and Imanaka et al. [37] argued that conscious detection of and motor preparation by cutaneous stimuli are processed in a neurally parallel or dissociated manner to some degree, based on studies of motor responses to perceptually masked tactile inputs and studies involving tactile and somatosensory tasks in patients with brain disorders. For example, Imanaka et al. noted the following features [37]. A weak first stimulus approximating threshold level is perceptually masked by a subsequent relatively strong stimulus; however, such an unconscious first stimulus reduces response latencies in cognitive and non-cognitive tasks [37], [38]. Cutaneous inputs usually reach the somatosensory cortex in a few tens of milliseconds [46], whereas the experience of perception arises 23-550 ms after stimulation [47], [48]. In a study of grip adjustment in monkeys, reflex-like changes in cerebellar cortical neurons appeared with an average latency of 36 ms after the onset of a perturbative load to the gripped object [49]. These reports suggest that motor preparation does not necessarily start after the cognition of sensory stimuli, and that the stimulus may affect motor responses before it is even consciously recognized [48]. Moreover, cutaneous reflexes are facilitated or inhibited by supraspinal systems [50], [51], although grip force adjustment is not considered a definite cutaneous reflex. For example, magnetic stimulation of the motor cortex promotes grip force adjustment [52] as well as the flexion reflex of the lower leg during walking [51]. Furthermore, ablation of the cerebellum influences the withdrawal reflex in response to cutaneous pain stimuli [50]. Collectively, these reports suggest that the supraspinal system receives early warning stimuli (including vibrotactile stimuli) to modulate reflexive behaviors to the subsequent stimulus (tractive load).

5.3 Possible Application of the Anticipatory Vibrotactile Cueing

It is somewhat premature to apply the findings of this study to practical problems; however, one possible application is suggested below. As previously described, a grip adjustment strategy using a sensor to detect incipient slippage of a robotic finger [19], [53] has been implemented on several robotic hands [13], [14], [15], [16], [17], [18]. In contrast, anticipatory tactile cueing for facilitating grip adjustment functions more effectively in humans. For example, a situation can be imagined where an object is held by an individual wearing a device that can present vibrotactile stimuli to the hand. Upon detecting a risk that a perturbative load is likely to be applied to the held object, the vibrotactile device can deliver anticipatory signals to the wearer to facilitate grip adjustment in case the actual perturbation occurs. The results of this study are expected to contribute to the design of such a warning system that can facilitate an action to avoid risks as well as warn of upcoming risks.

6 CONCLUSIONS

Grip force adjustment is an intelligent human function that does not require significant cognitive engagement. The objective of this study was to demonstrate and determine how this reflex-like movement may be facilitated. In particular, we focused on the effects of an anticipatory cue that preceded a perturbative tractive force, which triggered an adjustment for stabilizing the grip on a handle. Participants were presented with a vibrotactile stimulus, via stimulators mounted on the grip handle, 50 ms before the onset of the tractive force. In other conditions, either tractive force or vibrations were presented alone. The participants attempted to maintain their grip on the handle and respond to the vibration quickly. With the anticipatory vibrotactile cue, the adaptive behavior started on average 116 ms after the onset of the tractive force. This latency was less than that in the absence of the anticipatory cue (139 ms) and that of the voluntary response to vibratory signals alone (229 ms). This indicated that the anticipatory cue itself likely facilitated grip adjustment, rather than a conscious perception of the vibration. Furthermore, such facilitation was not effective under rapid perturbations that involved latencies of approximately 60–80 ms, which were comparable to those of the shortest latencies described in previous studies. Anticipatory signals reduced the latencies of adjustment when moderate perturbations were applied, and these moderate perturbations evoked adjustments more slowly than did rapid perturbations. Although MacIntyre and McComas [38] and Imanaka et al. [37] showed that anticipatory tactile cues could facilitate motor responses in choice tasks or simple reaction tasks, this study demonstrated that anticipatory tactile cues also affect grip force adjustment. These adjustments were non-cognitive, automatic corrective actions. Our findings will aid the development of robotic and rehabilitative applications for promoting and potentially improving human reactive behaviors.

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