Force Maintenance Accuracy Using a Tool: Effects of Magnitude and Feedback

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Abstract—The ability to precisely produce a force via a hand-held tool is crucial in fine manipulations. In this paper, we study the error in maintaining a target force ranging from 0.5 to 5 N under two concurrent feedback conditions: pure haptic feedback (H), and visual plus haptic feedback (V + H). The results show that absolute error (AE) increases along with the increasing force magnitudes under both feedback conditions. For target forces ranging from 1.5 to 5 N, the relative error (RE) is approximately constant under both feedback conditions, while the RE significantly increases for the small target forces of 0.5 and 1 N. The effect of force magnitude on the coefficient of variation (CoV) is not significant for target forces ranging from 1.5 to 5 N. For both the RE and the CoV, the values under the H condition are significantly larger than those under the V + H condition. The effect of manipulation mode (i.e., a hand-held tool or a fingertip) on force maintenance accuracy is complex, i.e., its effect on RE is not significant while its effect on CoV is significant. Only for the magnitude of 0.5 N, the RE of using the tool was significantly greater than that of using the fingertip under both feedback conditions. For both the RE and the CoV, no interaction effect exists between manipulation mode, force magnitude and feedback condition.

Index Terms—Force control, hand-held tool, force maintenance, relative error, coefficient of variation, feedback channel

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1 INTRODUCTION

THE ability to precisely produce a force via a hand-held tool is crucial in fine manipulations, such as probing the depth of a periodontal pocket [1], needle puncture [2], and surgical cutting of a capsule in a cataract surgery [3], etc. It is an important topic to understand human's performance on precise force control, and thus to develop effective methods to train force control skill. The capability to maintain a 1D constant force is a fundamental skill for more complex tasks such as following a temporal force profile, multi-dimensional force control, or even simultaneous control of force and motion [4], [5]. In this paper, we aim to measure the control accuracy of constant force maintenance using a hand-held tool, and to study how the accuracy is influenced by factors such as force magnitude and feedback condition.

Lots of work showed that accuracy of force control is not a constant fraction of a target force across varied force magnitudes [6], [7], [8], [9], [10]. For example, Slifkin and Newell found that force variability increased exponentially as a function of force level and the signal-to-noise ratio changed according to an inverted U-shaped function over the range of force levels [6]. Christou et al. illustrated that variability of force during continuous isometric contractions of the quadriceps femoris could be described by a sigmoidal logistic function with respect to the level of force [7]. While most work focuses on the force output accuracy of hand or leg muscles, the force maintenance accuracy in using a hand-held tool has seldom been studied.

The effects of visual feedback on force control have been widely studied. Athreya et al. investigated the relation between visual feedback and the degree of structure versus randomness in the variability of single-digit, isometric force output [11]. Their results revealed that force output is less structured when visual feedback is available than when it is not. Baweja et al. compared force accuracy, force variability, and muscle activity during constant isometric contractions at different force levels with and without visual feedback [12]. Their findings demonstrated that although removal of visual feedback amplifies force error, it can reduce force variability during constant isometric contractions. Hong et al. investigated the effects of spatial (gain) and temporal (frequency) properties of visual feedback on the control of isometric force output [13]. There was a significant effect of gain on the mean and standard deviation of the force output, whereas feedback frequency significantly affected the force standard deviation and root-mean square error. Mai et al. reported that subjects could maintain an isometric grasping force of 2.5 N to within 6 percent of its target level using only tactile and kinesthetic feedback over a time interval of 20 s, and the errors decreased to 1.5 percent with the addition of visual feedback [14]. Srinivasan and Chen found that the accuracy for force pressed by a fingertip was 0.039 ± 0.006 N with concurrent visual feedback, while the accuracy was 11 to 15 percent when the feedback was removed [15]. Voelcker et al. investigated the force-tracking performance of old and young adults using a precision grip [16]. The mean and standard deviations of young adults for force variability during the maintenance task were 0.14 and 0.08 N, respectively. Each of these results was based on force control using fingertips.

Previous work has shown that the force control accuracy may depend on the involved muscle groups. Tan et al. examined force control in a number of muscle groups [17]. They observed that the coefficient of variation (CoV) ranged from 0.88 to 1.98 percent for short periods of time (5 s). Jones reported that subjects were able to control the finger forces ranging from 2 to 6 N to within 1 N using only haptic feedback over a 120-s time period. Furthermore, subjects could control elbow flexion forces to within 4.5 N over a force range of 10-30 N [18], [19]. The results showed that there was no significant difference between the two muscle groups in the precision or accuracy with which the force could be controlled. In the study performed by Sosnoff et al., participants produced isometric force output of index-finger abduction at five levels with high and low visual feedback gain [20]. The findings showed that standard deviation increased non-linearly with force level and decreased with visual gain; and CoV decreased with force level as well as visual gain. Hamilton et al. demonstrated that proximal joints in the arm had lower levels of motor noise than weaker more distal joints [21].

Accurate force control using a tool is important for fine manipulations including surgical operations and mechanical assemblies. To the best of our knowledge, there is no previous work reporting the variance of force control accuracy via a hand-held tool at different force levels. It is unclear how much difference in the force control accuracy exists between using a hand-held tool and merely using a fingertip, and how this difference may interact with other factors including the magnitude of the reference force and the feedback condition. The answers to the above questions may provide clues to understand human's biological behavior of fine force control mediated through a tool. Furthermore, the observed variation of accuracy values under varied reference force magnitudes may provide guidelines to design human-computer interaction tasks that rely on precise force control [22], [23]. It is desirable that the allowable tolerance of the force control tasks match human force control accuracy in order to produce optimal attention workload to the users [24].

2 METHODS

2.1 Participants

Twelve right-handed participants (four female and eight male, aged 22 to 27, mean 25) with normal visual and tactile abilities participated in the experiments. None had previous experience with

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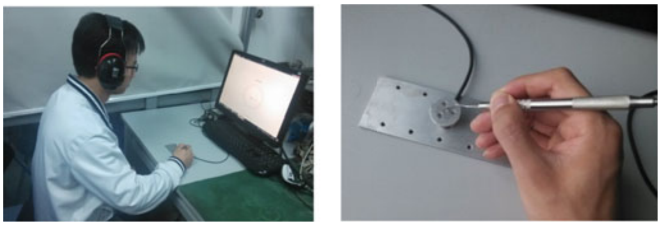

Fig. 1. Experiment system. a) A participant in test. b) Detailed view of pressing the probe on the force sensor.

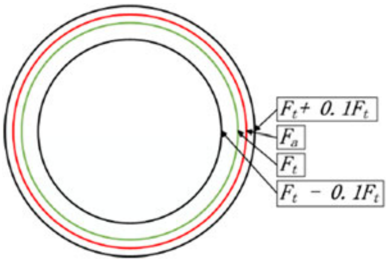

Fig. 2. Visual feedback.

the devices and they did not report any history of neurological illness or physical injury that might have affected their hand function. They were all graduate students at Beihang University. All participants gave written consent to participate in the study. Each participant received RMB60 Yuan (about $10) in compensation for their participation.

2.2 Apparatus

Fig. 1 shows the whole experiment system. The participant was seated so as to comfortably press a dental probe on the force sensor (ATI Nano-17 SI-12–0.12, ATI Industrial Automation Inc, USA) that was mounted on a large aluminum plate on a table. The handle of the dental probe was marked to help participants to hold it at the same position. The wrist and the forearm of the manipulating hand were resting on a table while the subject was performing the force control task.

Although the Nano-17 force sensor provided six-dimensional force and torque signal, we only used the z component of the sensor to measure the normal force. During the experiment, the participants were required to press on the top surface of the force sensor without producing lateral forces. The accuracy of the sensor is 0.003N, which is sufficient to detect subtle force fluctuations. The sampling rate of the sensor is 500 Hz and a low-pass filtering algorithm provided by the accompanied API from the vendor was used to filter noises.

In the experiments, the force applied by participants was displayed on a 21 inch computer monitor to serve as visual feedback. The distance between the eyes of participants and the monitor was about 50 cm. To decrease the interference of noise to participants, a head-mounted earmuffs (PELTOR H10A, 3M Inc, USA) was used in the whole procedure. The software used in the experiment was developed in C++ with Visual Studio 2008.

To compare the differences of force control between the finger and the tool, a second experiment was performed. Each participant used his/her right index fingertip to press the force sensor directly, while all the other conditions were same as the first experiment.

The same group of participants was used to compare the differences between using a hand-held tool and using the fingertip. The same posture was maintained for the force control tasks for both the fingertip and the tool. In both manipulation modes, the wrist and forearm were resting on the table. In order to avoid a possible practicing effect, the time interval between the two experiments was three days. Furthermore, the twelve participants were randomly divided into two groups with equal number, the first group performing the tool test before the fingertip test, and the second group in the reverse order.

2.3 Experimental Procedure

Before the formal test, each participant was given three minutes to familiarize themselves with the target force, which was set as 1, 2, and 3 N. Each force magnitude was practiced for about 30 seconds. First, a picture as shown in Fig. 1(b) was displayed for the participant to learn the correct grasping location and posture of the dental probe. The participants were given instructions to adjust their force magnitude based on the concurrent visual feedback shown in Fig. 2. The participants were required to press the force sensor to produce an actual force F_a (displayed as the red circle) to approach a target force F_t (displayed as the green circle). The two black circles illustrated a ± 10 percent force tolerance with respect to the target force, which helped participants to determine the current differences between the actual force and the target force. The radius of the red circle changed proportionately to the amount of actual force applied by the participant.

In the formal test, 10 levels of target forces were measured, while the magnitude varied from 0.5 to 5.0 N in 0.5 N step. Each participant needed to perform 10 sets of 10 trials. In each trial, a force magnitude from the 10 levels was used as the target force. The sequence of the 10 different target forces was randomly arranged in each set.

In our study, we measured the force control accuracy under different target force levels, which was different from the purpose of previous study to determine if humans can learn to more accurately recreate forces [25], [26]. In the beginning of each trial of our experiment, visual feedback was used for participants to adjust their output force to match the target force instead of intensively training them to reproduce the force.

In each trial, a participant used the probe or the fingertip to press the force sensor. When the actual force was larger than 0.1N, the current trial started. Fig. 3 showed a sample force curve during a trial, in the first 4 seconds, participants were required to adjust the actual force (displayed as the red circle) to approach the target force (displayed as the green circle) as quickly as possible. In the following 4 seconds, participants were required to constantly maintain the magnitude of the actual force as much closer to the target force as possible. At the 8th second, the visual feedback disappeared and participants were required to maintain the magnitude of the actual force in the next 4 seconds. At the 12th second, there was a visual cue flashing on the screen, which alerted participants to release the pressure on the sensor, and the current trial finished.

When the participant pressed the probe again on the sensor, the next trial started. After finishing 10 trials of different constant target forces, the current set ends. The approximate time cost for a set is about 150 seconds. A one-minute time break was given between each two adjacent sets to avoid muscle fatigue.

The force signal in the second phase (4th-8th seconds) before the disappearance of the visual feedback signal was used to compute

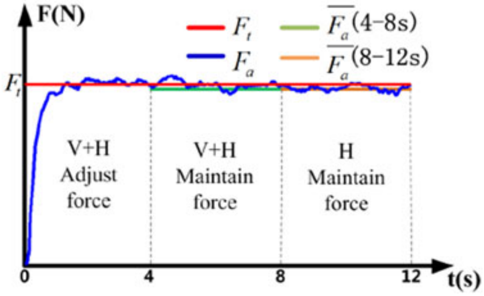

Fig. 3. A sample force curve during a trial.

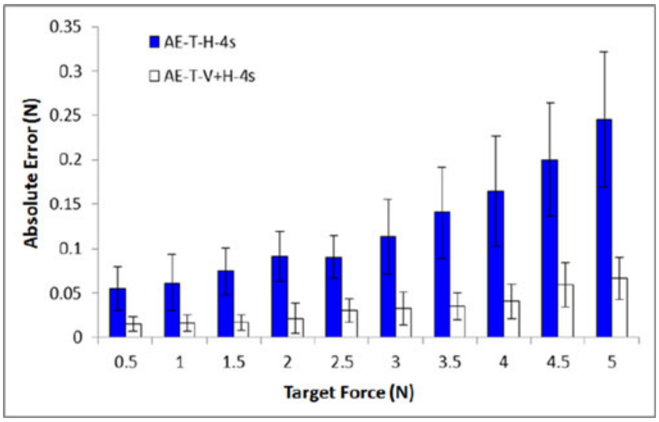

Fig. 4. The mean and std. of the absolute error for each target force. The meaning of the symbols: T—tool, V + H—visual plus haptic feedback, H—haptic feedback, and 4s—four seconds.

the force maintenance error for visual plus hapticfeedback (V + H) condition, and signal in the third phase (8th-12th seconds) immediately after the disappearance of the visual feedback signal was used to compute the force maintenance error for pure haptic feedback (H) condition.

3 EXPERIMENTAL RESULTS

3.1 Effects of Magnitude and Feedback on the AE

Fig. 4 shows the mean and standard deviation of the absolute error (AE) using the probe. The results show that AE increased along with the increase of the target force under either H or V + H feedback condition.

Based on the data in Fig. 4, two-way RM-ANOVA analyses were performed between two factors (Factor A: force magnitude, Factor B: feedback condition). The results show that the effect of force magnitude on AE was significant with F_A (1.8, 19.9) = 37.9, $p < 0.001$. Fractional degrees of freedom was due to the Greenhouse-Geisser correction when Mauchly's Test of Sphericity shows that the assumption of sphericity has been violated. The effect of feedback condition on AE was also significant with F_B (1,11) = 281, $p < 0.001$. The AE under H condition was significantly larger than that under V + H condition. Interaction effect existed between feedback condition and force magnitude with F_{AXB} (2.1, 23.2) = 18.4, $p < 0.001$.

3.2 Effects of Magnitude and Feedback on the RE

Fig. 5 shows the mean and standard deviation of the relative error (RE) for each target force under H and V + H feedback conditions.

Two-way RM-ANOVA analyses show that the effect of force magnitude on RE was significant with F_A (1.4, 15.6) = 23.6, $p < 0.001$. The effect of feedback condition on RE was also significant with F_B (1,11) = 356, $p < 0.001$. For all target force magnitudes, the RE with V + H condition was significantly smaller than that of H condition. Interaction effect existed between feedback condition and force magnitude with F_{AXB} (1.5, 16.9) = 9.56, $p < 0.01$.

As illustrated from the Fig. 5, under the H condition, the mean value of RE was approximately constant (4~5 percent) while the target force ranged from 1.5 N to 5N, and the mean of the RE became higher for 0.5N and 1N. Under the V + H condition, the mean of RE was approximately constant (1 percent) for all target forces except for the target forces of 0.5 N (3 percent) and 1N (1.6 percent). Post hoc multiple-comparison tests using Bonferroni method show that, there were significant differences in RE between the smallest magnitude (0.5N) and the other nine magnitudes with $p<0.05$. Also there were significant differences in RE between the 1N magnitude and the other two magnitudes (3.5N, 5N) with $p < 0.05$. For the other pairs of force magnitudes, there were no significant differences ($p > 0.05$) in RE between each pair.

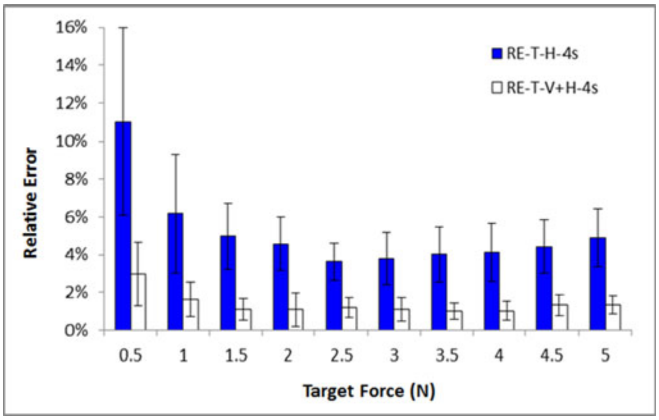

Fig. 5. The mean and std. of the RE for each target force.

3.3 Effects of Magnitude and Feedback on the CoV

Fig. 6 shows the mean and standard deviation of the CoV for each target force, while both conditions are illustrated.

Two-way RM-ANOVA analyses show that the effect of force magnitude on CoV was significant with F_A (2.5, 27.5) = 69.4, $p < 0.001$. The effect of feedback condition on CoV was also significant with F_B(1,11) = 129, $p < 0.001$. The CoV under V + H condition was significantly smaller than that under H condition. There was no interaction effect between force magnitude and feedback condition with F_{AXB}(2.7,29.8) = 2.02, $p > 0.05$.

Under H condition, a large mean value of CoV existed for the smallest target force (0.5N), and the mean value fluctuated between 2.5 and 4 percent for other target forces. Under the V + H condition, for force magnitudes smaller than 4N, the mean value of CoV decreased monotonically along with the increase of the target force. Post hoc multiple-comparison tests using Bonferroni method show that there were significant differences in CoV between the smallest magnitude (0.5N) and the other nine magnitudes with $p < 0.05$. Also there were significant differences in CoV between the 1N magnitude and the other eight magnitudes with $p < 0.05$.

3.4 Effects of Manipulation Mode on RE and CoV

Fig. 7 shows the comparison of the RE between the index finger and the hand-held tool under H and V + H feedback, while the data under the tool condition is the same as the data in Fig. 5.

3-way RM-ANOVA analyses were performed between three factors (Factor A: force magnitude, Factor B: feedback condition, Factor C: manipulation mode). Results show the effect of

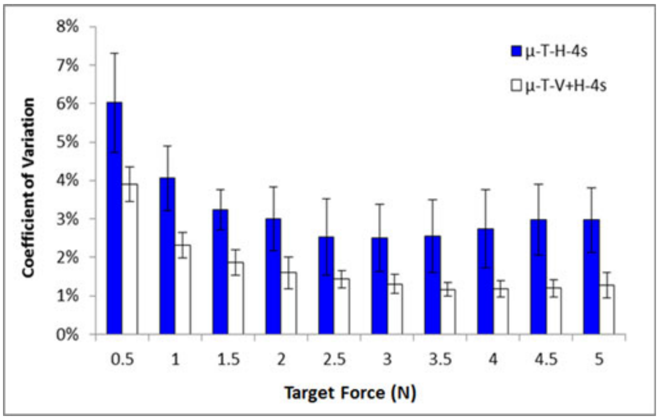

Fig. 6. The mean and std. of the CoV for each target force.

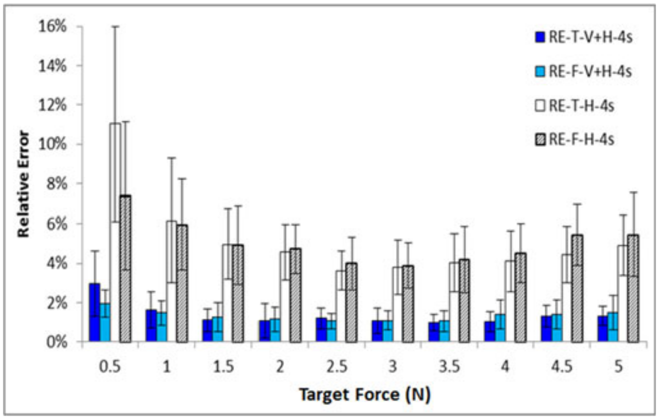

Fig. 7. Relative error using tool or fingertip under the different feedback conditions.

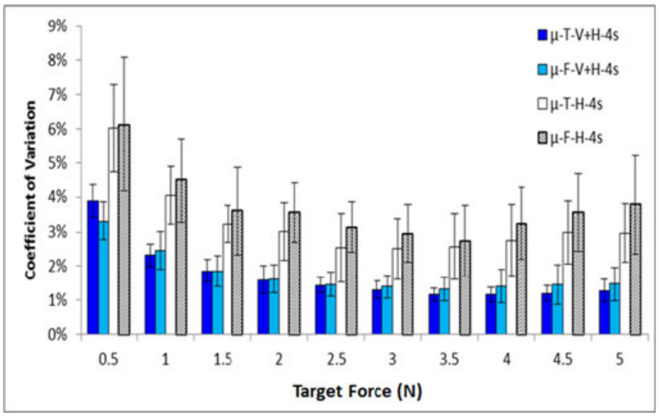

Fig. 8. Comparison of the CoV between the finger and the hand-held tool under different feedbacks.

manipulation mode on RE was not significant with F_C (1,11) = 0.006, $p > 0.05$. Interaction effect existed between manipulation mode and force magnitude with F_{AXC} (1.56, 17.2) = 5.153, $p < 0.05$. No interaction effect existed between manipulation mode, force magnitude and feedback condition with F_{AXBXC} (1.49, 16.43) = 2.19, $p > 0.05$.

Under the H condition, for each force magnitude level, a single-factor ANOVA (Factor C: manipulation mode) was performed to identify at which force level/s the manipulation mode may produce possible statistically significant differences in RE. The results show that, for the magnitude of 0.5N under the H condition, the RE of using the tool was significantly greater than that of using the fingertip with F_C (1,11) = 6.324, $p < 0.05$. For the other force magnitudes, no significant difference in the RE could be observed between using the tool and using the fingertip.

Under the V + H condition, for each force magnitude level, a single-factor ANOVA was performed to identify at which level/s the manipulation mode may produce possible statistically significant differences in the RE. For the magnitude of 0.5N under the V + H condition, the RE of using the tool was significantly greater than that of using the fingertip with F_C (1,11) = 4.874, $p < 0.05$. For the other force magnitudes, no significant difference could be observed between the tool and the fingertip.

Fig. 8 shows the comparison of the CoV between the finger and the hand-held tool under different feedback conditions, while the data under the tool condition is the same as the data in Fig. 6.

3-way RM-ANOVA results show the effect of manipulation mode on CoV was significant with F_C (1,11) = 5.72, $p < 0.05$. No interaction effect existed between manipulation mode and force magnitude with F_{AXC} (2.02,22.3) = 0.876, $p > 0.05$. No interaction effect existed between manipulation mode, force magnitude and feedback condition with F_{AXBXC} (2.31, 22.4) = 0.239, $p > 0.05$.

Under the H condition, the mean value of CoV using the hand-held tool was smaller than that using the fingertip for all target force magnitudes. The statistical results using ANOVA analyses show significant difference between using the tool and the fingertip with F_C (1,11) = 5.652, $p < 0.05$. This result revealed better stability (or repeatability) of force controlling using the tool than using the fingertip under the H condition. Under the V + H condition, the mean value of CoV using the tool was smaller than that using the fingertip for most target forces except for 0.5N, while no significant difference between using the tool and the fingertip with F_C(1,11) = 0.049, $p > 0.05$ for the V + H condition.

4 DISCUSSIONS AND CONCLUSIONS

Effect of magnitude and feedback condition on force maintenance accuracy using the hand-held tool was observed based on the interaction effect analysis results. The interaction effect implied that the increasing gradient of AE along with the increase of the target force magnitude is modulated by the feedback condition. The RE was not a constant value with respect to various target forces. For the H condition, the relative error using the hand-held tool fluctuated in a small range (from 4 to 5 percent) within a specified range of 1.5N to 5N, and became larger for 0.5N and 1.0N. A possible reason leading to the variation of the RE might be that force with suitable magnitudes (1.5N to 5N) match the range of daily dexterous manipulation task, and human's hand muscle could be tuned in a fine resolution within this range, while a force smaller than this range might require more accurate muscle control. Physical evidences for the variance could be studied in future by introducing electromyography (EMG) measurement to monitor muscle activity during the force control task under varied target forces. For the V + H condition, the mean of RE fluctuated in a small range (from 0.9 to 1.2 percent) for all target forces except for the target force of 0.5 N (the mean of the relative error is 3 percent) and 1N (the mean of the RE is 1.6 percent). This implies the benefit of concurrent visual feedback to calibrate the force controlling error and the relative error was smaller than in the H condition. These results are consistent with the findings in [27], in which Henningsen et al. found that isometric force resolution under visual feedback was higher than the resolution under cutaneous or muscle spindle feedback.

The results of the CoV using fingertip control were consistent with the data in [17]. For the CoV under H condition, the results of the proposed work was about 2.5-4 percent (as shown in Fig. 6), which was much smaller than the value of 12-15 percent in [17]. One possible reason is that the required time duration is different. In [17], 120 seconds were required while only 4 seconds were measured in our experiments.

As illustrated by the work of Sosnoff et al. [20], standard deviation of force error increased non-linearly with force level. Our results show that forces lower than 1 N were generally hard to control regardless of the feedback condition and manipulation type. As shown in Figs. 5 and 6, for both the RE and for the CoV, the value under the smallest force (i.e. 0.5N) was significantly larger than the corresponding value under other target forces. The possible reasons of lower accuracy at low forces might be a smaller number of motor units (degree of freedom) are recruited to perform a low force than a large force. Based on findings from Dideriksen et al. [28], motor unit recruitment and muscle properties are tuned to limit the influence of synaptic noise on force steadiness to low forces. These results imply that fine control of a small target force was more challenging for the participants. This inspires us to develop haptic-enabled training systems that focus on practicing force control skill on small force magnitude. It is thus possible that trainees reap greater benefits from the training. This hypothesis will be validated in the future work.

The effect of manipulation mode on force maintenance accuracy can be observed based on the comparison between using the fingertip and the hand-held tool. The force control using the fingertip involves activation of three joints and related muscles on the right-index finger, while the palm and the other fingers are not actively involved in the force adjustment process. In comparison, the force control using the tool involves the activation of the wrist joint and synergetic muscle control of three fingers (thumb, index, and middle fingers). Thus, during the force maintenance process, wrist needs to produce fine displacement to adjust the force magnitude. It seems that force control using the tool recruited more degree-of-freedom in terms of muscle. Previous work on the effect of degrees of freedom on force control accuracy may provide a possible reason to explain the lower coefficient of variation of the hand-held tool than the fingertip [29]. In the future, it is needed to verify this point by measuring EMG activity and compare the involved muscle groups during the force maintenance and adjustment process.

Besides the feedback condition and the recruited muscle groups, differences in the maximal force could possibly account for some of the differences in force control accuracy between using a hand-held tool and using a fingertip. In the future, it is necessary to design new experiments to measure maximal force using a hand-held tool and analyze its influence on the force control accuracy of different target force magnitudes.

One limitation of the experiment is that the lack of fully counterbalancing, i.e., the H condition always being after the V + H condition in all the trials. One may wonder whether the force maintenance under V + H condition could lead to fatigue and thus to degrade the accuracy of the following force maintenance tasks under the H condition. In order to validate whether this same order may bias the responses, a complementary small-scale experiment was performed to verify this effect. Three participants were recruited to perform the task with the order of the H condition being before the V + H condition using a hand-held tool. The results show that there was no difference between two sequences of the feedback condition arrangement, i.e., the relative error under H condition was still much larger than that under V + H condition. Furthermore, 120s was used for force maintenance in previous study [17], and no fatigue effect was observed. This may explain the 4-second force maintenance under V + H condition could not lead to fatigue and could not degrade the accuracy of force maintenance under H condition.

The identified accuracy of force maintenance may provide guidelines to design systems for motor skill training. In the next step, we plan to develop force-based games to translate user's pressure force into motion or behavior of the virtual objects in a virtual environment. This type of game could be used for motor rehabilitation to improve the user's fine motor skill, and can even be used in the cognitive training to promote user's attention through precise muscle control.

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