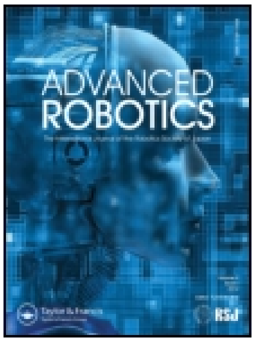

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FULL PAPER

Amplifying shear deformation of finger pad increases tracing distances

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Human sensory inputs and motor outputs mutually affect one another. We pursue the idea that a tactile interface can influence human motor outputs by intervening in sensory–motor relationships. This study focuses on the shear deformation of a finger pad while a person traces a line or circle. During these tracing movements, the finger pads were deformed using a tactile interface. The tracing distances increased when the finger pad deformations were amplified by the tactile interface, which indicates that the intervention in the haptic sensorimotor loop affected the tracing movements. Elucidation of such interaction between the tracing movements and the shear deformations of finger pads enhances the understanding of human-assistive haptic techniques.

Keywords: skin stretch; sensory–motor relationships; friction sensation

1. Introduction

Human sensory inputs and kinesthetic outputs mutually affect one another.[1] In this study, we pursue the idea that a tactile interface can influence human kinetic outputs by intervening in sensory–motor relationships. Attempts to demonstrate this phenomenon have been made in the field of haptics with regard to prehension adjustment,[2,3] the effects of sole sensation on body posture,[4–6] and the control of walking cycles.[7] These studies showed that effective stimulation of the human body through tactile interfaces almost unconsciously affects its motor outputs. Like these studies, we investigate how stimulation induces motor outputs rather than whether such inductions are unconscious or not.

We investigate the sensory–motor relationships between tracing tasks and finger pad deformations. A tracing movement is one in which a human traces characters or figures on a sheet of paper using a finger pad. The tracing movements are intimately related to the cutaneous sensation of the finger pad,[8] and the cutaneous deformations have been observed and mathematically modeled.[9–12] Although the effects of such deformations on perception have been studied,[13–15] their effects on hand motions have hardly been reported thus far. The objectives of this study are to intervene in the relationships between the shear deformation of the finger pad and the tracing movements by using a tactile interface and to examine how the deformation influences the movements. We use a tactile interface to apply a shear deformation to the finger pad when a human traces a line or circle on a sheet of paper.

We place emphasis on the sensory–motor relationships of tracing motions; however, tracing is intriguing from the perspective of interface design because it is linked with dragging with pointing devices. Tactile stimuli to the hand are known to influence hand motions and the performance of tasks that involve pointing interfaces. Campbell et al. studied how vibrotactile stimulation of the finger through a pointing stick improved performance on and reduced error ratios of a steering task.[16] Akamatsu et al. found that the use of a vibrotactile-feedback mouse improved performance on a target-selection task.[17] Vibrotactile stimulation of the finger pad has been shown to improve tapping performance on touch panels, which have recently become common as the input interfaces of information terminals.[18,19] However, there have been few attempts to identify factors influencing tracing or dragging movements, which are principal input motions for touch panels. To fill this gap, the present article reports a fundamental investigation of the possibility that the application of shear deformation to the finger pad influences tracing movements.

In the authors' earlier presentation, finger-tracing movements were influenced using a tactile interface that acted on skin stretch during tracing tasks.[20] Experiments 1 and 2 in the present article were grounded in the previous report but with the precisely controlled conditions of force and skin stretch measurements. This measurement allowed us to conduct an experiment in which the magnitude of shear deformations was controlled (Exp. 3). Such an experiment potentially supports the sensory-motor loop of tracing movements and finger pad stretches by showing the correlated

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relationships between the inputs and outputs of the sensory-motor loop. The experimental procedures described in the present article were approved by the ethical committee of the School of Engineering, Nagoya University.

2. Experimental system

Figures 1 and 2 show the tactile interface developed to apply the shear deformation to the finger pad. The interface used an acrylic plate placed beneath and affixed to the finger pad with double-sided sticky tape. The plate was activated by two independently controlled DC motors (RE-10, maxon motor, Switzerland, maximum torque 3.04 mN m) to which strings were fastened. The interface applied the shear deformations along the *X*-axis. An antiskid sheath restrained the fingertip in order to ensure that the acrylic plate effectively deformed the finger pad. The shear deformations applied to the finger pad were measured using two encoders (GP 10 K, maxon motor, Switzerland, 1024 ppr) with a resolution of 2.9×10^{-3} mm by way of the quadruple reduction gear and a pulley with a diameter of 3.8 mm. The interface hardly moved the finger, because the sum of the internal forces applied by the interface to the finger was zero. We verified that the drive of the interface shifted the finger by only 0.3 mm when the finger was still. This value was negligible compared to that of the spontaneous finger movement induced by the manipulation of the shear deformation, which was approximately 8 mm on average (see Section 3.2). The participants wore the interface and traced a line or circle on a flat panel. Furthermore, as shown in Figure 3, two load cells (Model 1004, Tedea Huntleigh, Canada) measured the finger pressing force along the *Z*-axis with a force measurement resolution of 1.0×10^{-4} N.

Under natural tracing motions, the finger pad experiences full slippage across the floor. The above tactile interface did not provoke such slippage. One option to achieve full slippage is to activate the floor itself, as was done in the study of Terada et al. [8]. However, such a mechanism is not appropriate for our purposes because it exerts forces to the hands and directly influences their tracing motions.

A camera (320×240 pixels, 30 fps, PlayStation Eye, Sony Computer Entertainment Inc., Japan) measured the position of a marker attached to the interface. The resolution of measurement was 1.00 mm. We calculated the velocities of the fingers using a Savitzky–Golay filter of length five.[21] The computer controlled the motor torques of the interface with a control cycle of 0.3 ms on the basis of the equations presented in Section 3.1.3.

3. Experiment 1: linear trace

We show the effects of shear deformation applied to the finger pad on the displacement and speed of the tracing movements while the finger traces a 150 mm line drawn on a sheet of paper.

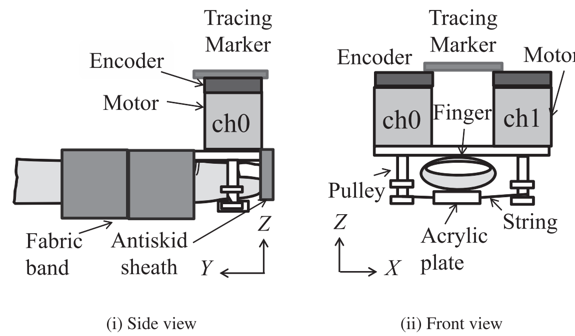

Figure 1. Interface to apply shear deformation to the finger pad.

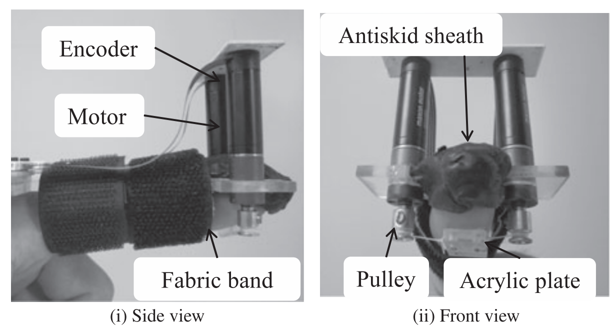

Figure 2. Photograph of the interface to apply shear deformation to the finger pad.

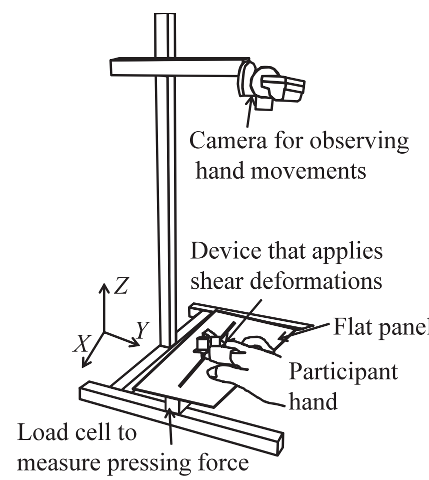

Figure 3. Experimental setup.

3.1. Method

3.1.1. Participants

The participants (P1–P10) were 10 right-handed students aged 20–24 from Nagoya University. All of them were ignorant of the objective of the experiment and none were researchers specializing in human interfaces. Because we were interested in the haptic sensory–motor relationships, we instructed participants to close their eyes during each trial so that they would not see their fingers, to reduce the effects of visual feedback. Additionally, they were required to listen to pink noise through headphones, intended to aurally block the sound of the finger sliding on the paper.

3.1.2. *Task*

The participants wore the tactile interface on the right index finger. They traced the line with the index finger without visual cues while following a metronome played through the headphones with the pink noise, as accurately as possible. It should be noted that our interests are in the comparison between control and test stimuli rather than in the accuracy of tracing tasks. In fact, most participants could not correctly follow the line length (see the Results section). The metronome was introduced to approximately control the tracing speeds of participants. This was because in pilot tests, we found that some participants traced a line at irregularly slow speed without any rhythmic cues. A single line trace was performed with the beat of a metronome set at 0.75 Hz, and then a reciprocating motion was performed with the second beat. This reciprocation was repeated three times in each trial. Before the experiment, participants practiced following the metronome for a few minutes until they felt familiar with the task. At the beginning of each trial, they visually confirmed the position and length of the line and then placed the finger on the far right of the line, which had been designated as the starting position. During the trial, they maintained the finger's posture so that it would follow the *Y*-axis.

3.1.3. *Stimuli*

We randomly subjected the finger pads of the participants to three shear deformation conditions. We did not give the participants any information about these stimuli. Ten trials were performed for each stimulus. The conditions were as follows:

- amplify condition – the finger pad shear deformations were amplified along the *X*-axis (Figure 4(i));
- reverse condition – the shear deformations were reversed along the *X*-axis (Figure 4(ii)); and
- control condition – the shear deformations were not altered.

We were essentially interested in the comparison between the amplify and control conditions. However, we prepared a reverse condition, which is implausible under natural tracing movements, to investigate the effects of the direction of the applied shear deformation on tracing movements.

3.1.3.1. *Amplify condition.*

When humans trace a line on a paper, the finger pad commonly undergoes shear deformations in the direction opposite to the velocity of finger.

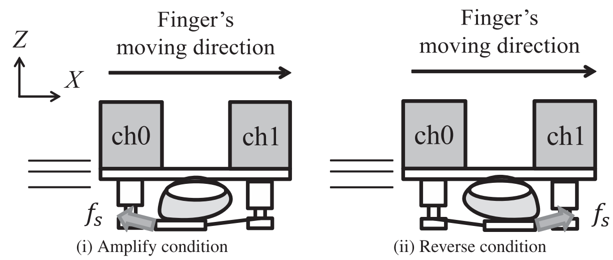

Figure 4. Shear deformation of finger pad during linear tracing-task.

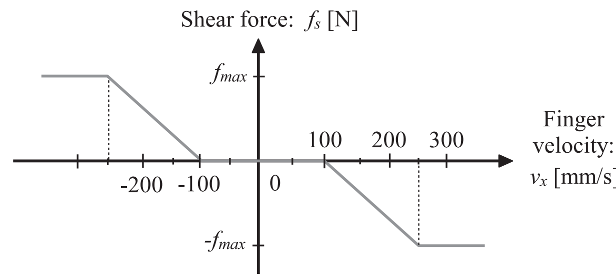

Figure 5. Shear force applied to the finger pad under amplify condition.

Under amplify condition, the motor torque increased to amplify the shear deformation of the finger pad. Because we approximated that the kinetic friction was constant in the relative motion, the force exerted to the plate by the motors was either the maximum or zero. Only when the speed was relatively small, the motor torques changed linearly in order to ensure the smoothness of the changes in shear force. When a finger was moved along the *X*-axis, as shown in Figure 4, the tensions on the strings exerted by the two motors were controlled in a feedforward manner such that the net shear force $f_s(v_x)$ applied to the finger pad became

$$f_s(v_x) = \begin{cases} 0 \quad \text{if} \quad |v_x| < 100\,\text{mm/s} \\ \alpha(|v_x| - 100) \cdot \text{sign}(-v_x) \quad \text{if } 100\,\text{mm/s} \le |v_x| < 250\,\text{mm/s} \\ f_{\max} \cdot \text{sign}(-v_x) \quad \text{if} \quad 250\,\text{mm/s} \le |v_x| \end{cases} \tag{1}$$

where α and $f_{\max}$ were 1.33×10^{-2} N s/mm and 2.0 N, respectively. sign(v_x) returns the sign of v_x. We chose α and $f_{\max}$ so that the deformation of the finger pad would feel natural. Note that f_s reached $-f_{\max}$ at $v_x = 250$ mm/s. In order to prevent frequent switch of the force directions applied to the plate, we set an insensitive zone of ±100 mm/s. Figure 5 shows the profile of the applied shear force depending on the finger velocity. The friction of the gear of each motor was specified as 2.0 N and compensated for.

3.1.3.2. *Reverse condition.*

This condition transposes sign($-v_x$) of (1) to sign(v_x). Under this condition, the finger

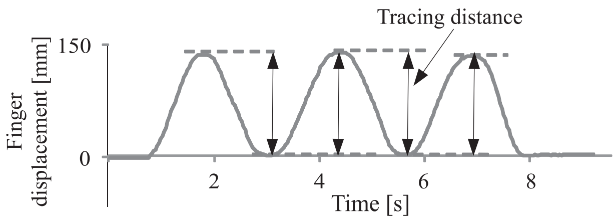

Figure 6. Example of tracing movements of the finger.

pad is deformed in the direction of finger movement, which is inconsistent with our daily experiences.

3.1.3.3. Control condition. Under this condition, the tactile interface did not apply any shear deformation to the finger pad. The motor outputs were controlled so that the normal force exerted on the finger pad along the *Z*-axis became equal to that under both the amplify and reverse conditions. The outputs from motors 0 and 1 were given by

$$f_{0,1}(v_x) = \begin{cases} 0 \quad \text{if } \ |v_x| < 100\,\text{mm/s} \\ \mp\frac{1}{2}\alpha(|v_x| - 100) \ \text{ if } 100\,\text{mm/s} \leq |v_x| \leq 250\,\text{mm/s} \\ \mp\frac{1}{2} f_{\max} \quad \text{if } \ 250\,\text{mm/s} \leq |v_x|. \end{cases} \tag{2}$$

3.2. Results

3.2.1. Tracing distances

We compared the three conditions in terms of the tracing distances along the *X*-axis (Figure 6). Six strokes were observed in each trial. We used four strokes, excluding the first and last, to statistically analyze tracing distances. Figure 7 shows the averages and standard deviations of the individual tracing distances. P3 was removed from any statistics due to his extraordinarily strong finger forces along the *Z*-axis (see also the paragraph on fingers' pressing force). For a few trials, the interface did not function correctly due to the friction of strings on pulleys. We excluded these trials from the statistics. We applied a Steel–Dwass test on all participants' data to compare three conditions. The numbers of samples used for calculation were 360 (9 participants × 10 trials × 4 strokes/trial) for the control condition, and 336 and 352 for the amplify and reverse conditions, respectively. The comparison revealed that the amplify condition produced larger tracing distances than did the control condition ($q(3, \infty) = 4.96$, $p = 2.1 \times 10^{-6}$), with an average difference of 8.5 mm. The reverse condition also produced larger tracing distances than did the control condition ($q(3, \infty) = 3.51$, $p = 1.3 \times 10^{-3}$), with an average difference of 5.6 mm. These trends were observed for the eight of nine participants, the exception being P6. In the preliminary experiment with different α and f_{max} values being 5.75×10^{-3} N s/mm and 1.07 N, we observed the same trends as in this study.[20]

Table 1. Averages of shear deformations of finger pad for each condition in Exp. 1.

Participants	Amplify (mm)	Reverse (mm)	Control (mm)
P1	1.7	1.2	0.2
P2	2.7	2.5	0.2
P4	4.3	4.4	0.3
P5	4.3	4.9	0.2
P6	2.7	2.9	0.3
P7	3.1	3.4	0.2
P8	3.8	3.5	0.2
P9	3.1	3.0	0.3
P10	4.1	4.0	0.2
Mean ± S.D.	3.3 ± 0.9	3.3 ± 1.1	0.2 ± 0.1

3.2.2. Peak tracing speeds

We also compared the three conditions in terms of the peak tracing speeds along the *X*-axis. We used the six peaks observed in each trial in the statistical analysis. Figure 8 shows the averages and standard deviations of the peak tracing speeds for each participant. For the control condition, 540 samples were analyzed (9 participants × 10 trials × 6 peaks/trial). We used 498 and 512 samples for the amplify and reverse conditions, respectively. The peak tracing speeds under the amplify condition did not significantly differ from those under the control condition ($q(3, \infty) = 1.61$, $p = 0.24$). In contrast, the reverse condition produced larger peak speeds than did the control condition ($q(3, \infty) = 3.72$, $p = 0.58 \times 10^{-4}$). The difference in average speeds between these two conditions was 9.5 mm/s.

3.2.3. Finger pressing force

Figure 9 shows the individual comparisons of the finger pressing forces (f_z) under each conditions. We calculated the average of f_z while the finger slid on the paper. Standard deviations were among trials. As described already, one participant, P3, showed irregularly large f_z values and was excluded from the analysis. Apparently, there were no common trends among the participants. The f_z values of both the amplify and reverse conditions did not significantly differ from those under the control condition. Stimuli conditions exerted a nonsignificant influence on pressing force.

3.2.4. Finger pad deformation

We averaged the maximum deformations of finger pads during a single trace. These values are the displacements of the plate from the natural position. Table 1 shows that the average finger pad shear deformations along the *X*-axis

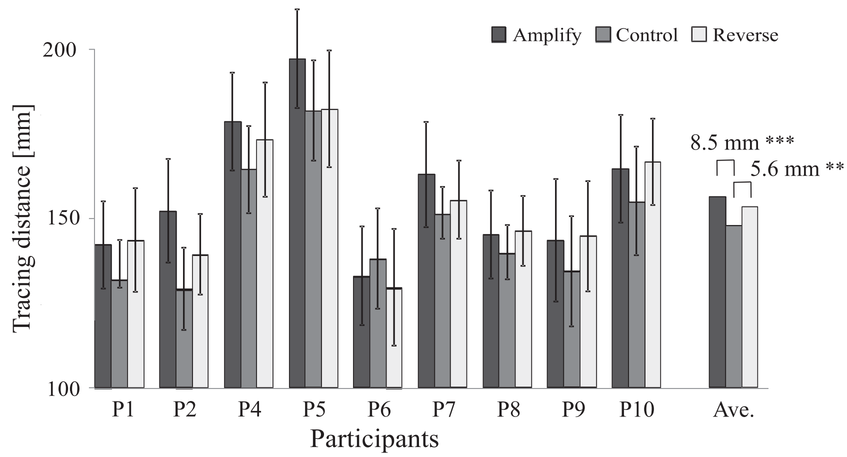

Figure 7. Tracing distances in Exp. 1 (linear trace). ** and *** indicate significance level of 0.01 and 0.001, respectively.

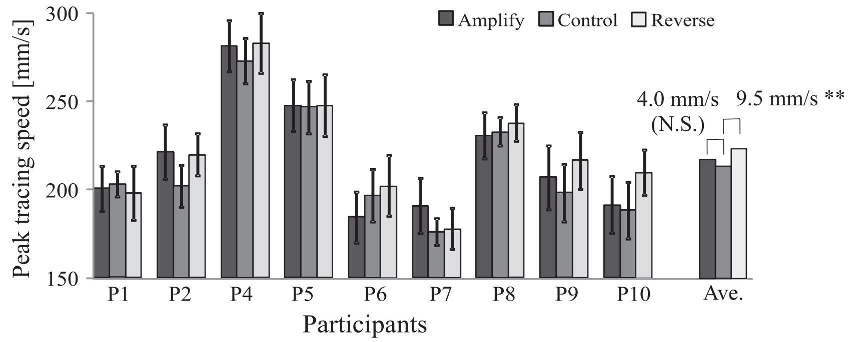

Figure 8. Tracing speeds in Exp. 1 (linear trace). ** indicates significance level of 0.01. N.S. means *not significant*.

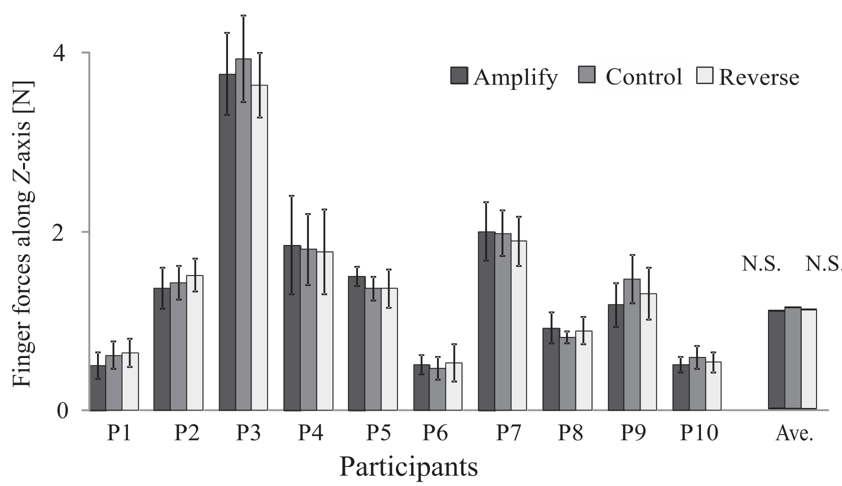

Figure 9. Individual finger pressure forces (f_z) by type of stimulus in Exp. 1.

under the amplify, reverse, and control conditions were 3.3 ± 0.9 mm, 3.3 ± 1.1 mm, and 0.2 ± 0.1 mm, respectively. The variations in shear deformation were attributed to the differences in skin stiffness and size among the individual fingers.

4. Experiment 2: circular trace

In Experiment 1, both amplifying and reversing shear deformations of the finger pad increased the tracing distances. Nevertheless, the applied shear deformation and the finger motion were along the same *X*-axis. Our question now is

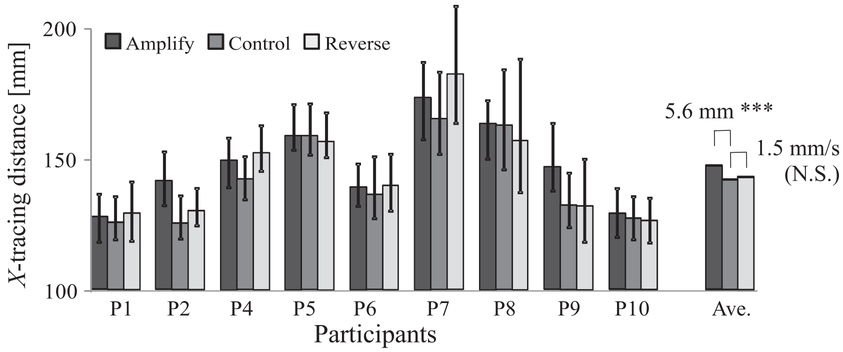

Figure 10. X-axis tracing distances in Exp. 2 (circular trace).

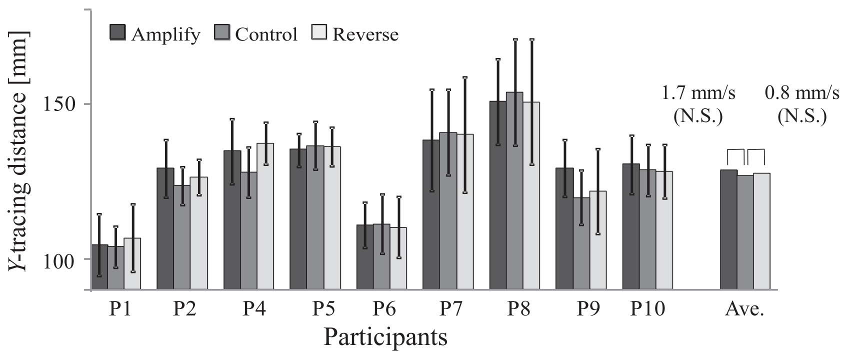

Figure 11. Y-axis tracing distances in Exp. 2 (circular trace).

whether the applied shear deformation influences finger motion in a perpendicular direction or whether the X-axial deformation selectively affects the X-axial components of finger motions. In order to investigate this question, we asked the participants in Experiment 2 to trace a circle that involved both X and Y-axis motions, while the finger pad deformations were altered only along the X-axis. We show that the applied shear deformation does not affect the perpendicular finger motion when tracing a circle in Experiment 2.

4.1. Method

4.1.1. Task

Participants who were aurally blocked and blindfolded traced a circle of 150 mm in diameter in accordance with the beat of a metronome set at 0.5 Hz so as to trace the circle once every 2 s. They traced the circle three times in each trial. At the beginning of each trial, they visually confirmed the circle and then placed a finger at the bottom of the circle, which had been designated as the starting position.

4.1.2. Participants and stimuli

The participants (P1–P10) were the same 10 students as in Experiment 1. The tactile interface subjected their finger pads to the same three shear deformation conditions described in Section 3.1.3. Ten trials were performed for each stimulus.

4.2. Results

The means and standard deviations of the finger pad shear deformations along the X-axis under the amplify, reverse, and control conditions were 3.2 ± 0.9 mm, 3.0 ± 0.9 mm, and 0.3 ± 0.2 mm, respectively.

4.2.1. X-axial tracing distance

We compared the three conditions in terms of the tracing distances along the X-axis. Figure 10 shows the means and standard deviations. We applied a Steel–Dwass test on these values. We used 344, 360, and 332 samples in the calculations for the amplify, control, and reverse conditions, respectively. The amplify condition significantly differed from the control condition ($q(3, \infty) = 3.99$, $p = 1.9 \times 10^{-4}$). On average, the distances along the X-axis under the amplify condition were larger than those under the control condition by 5.6 mm. As in the linear trace in Experiment 1, for most participants, the values under the amplify condition were larger than those in the other conditions. No difference was seen between control and reverse conditions ($q(3, \infty) = 0.63$, $p = 0.80$).

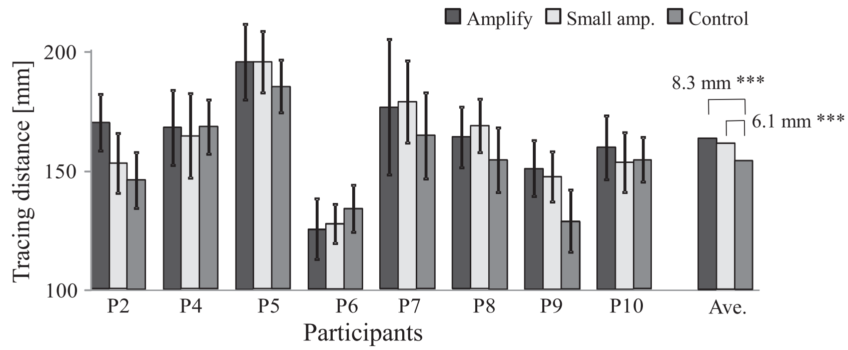

Figure 12. Tracing distances under the amplify, small-amplify, and control conditions in Exp. 3.

4.2.2. *Y-axial tracing distance*

Figure 11 shows the means and standard deviations of tracing distances along the *Y*-axis. Trancing distances did not significantly differ across the three stimuli conditions (amplify-control: $q(3, \infty) = 1.78$, $p = 0.18$, reverse-control: $q(3, \infty) = 1.22$, $p = 0.44$).

4.2.3. *X and Y-axial peak tracing speed*

The *X* and *Y*-axial peak tracing speeds did not significantly differ across the three conditions. The means and standard deviations of *X*-axial peak speeds were 262.0 ± 48.3, 256.4 ± 50.6, and 265.5 ± 54.6 mm/s for the amplify, control and reverse conditions, respectively. Values tended to be higher for the amplify and reverse conditions than the control condition. However, no significant differences were observed between any conditions (amplify-control: $q(3, \infty) = 1.65$, $p = 0.22$, reverse-control: $q(3, \infty) = 1.91$, $p = 0.14$). The *Y*-axial speed values were even closer across the three conditions: 212.6 ± 48.3, 209.7 ± 46.0, and 213.4 ± 46.7 mm/s for the amplify, control, and reverse conditions, respectively.

To summarize the results, the amplify condition influenced only *X*-axial displacements and did not affect *Y*-axial movements. This condition also affected *X*-axial displacements in Experiment 1. These results suggest that *X*-axial shear deformations are linked with only *X*-axial components of movements. The impact of the reverse condition was mitigated in Experiment 2. Because the participants underwent irregular finger deformations in the reverse condition that they never experience in daily lives, the impact of such deformations might be unstable.

5. Experiment 3: the effect of degree of shear deformation

In Experiments 1 and 2, we confirmed that amplifying the shear deformation of the finger pad significantly increased the tracing distances along the direction of applied deformation. In Experiment 3, in order to seek the relationship between the sensory and kinetic information of the feedback loop, we investigated how the degree of deformation influences the degree of increase in the tracing movement. In this experiment, we applied large or small deformations to the finger pad during linear tracing tasks.

5.1. *Method*

5.1.1. *Stimuli*

We randomly subjected the finger pads of the participants to three shear deformation conditions. Ten trials were performed for each stimulus. The conditions were as follows:

- amplify condition – the finger pad shear deformations were amplified along the *X*-axis with an $f_{\max}$ of 2.0 N;
- small amplify condition – the shear deformations were slightly amplified along the *X*-axis with an $f_{\max}$ of 1.12 N; this value would result in roughly half the skin stretch as under the amplify condition; and
- control condition – the shear deformations were not altered.

The amplify and control conditions were the same as those in Experiments 1 and 2.

5.1.2. *Participants and task*

The participants (P2–P10) were the same nine students from Nagoya University. They performed the same task as was given in Experiment 1.

5.2. *Results*

Table 2 shows the means and standard deviations of the finger pad shear deformations along the *X*-axis under the amplify and small amplify conditions: 3.3 ± 0.4 mm and 2.0 ± 0.5 mm, respectively. We compared tracing distances along the *X*-axis among the three conditions. Figure 12 shows the mean and standard deviation of the tracing distances for each participant. We used 320 samples (8 participants ×

Table 2. Shear deformation of finger pad in Exp. 3.

Participants	Amplify (mm)	Small amplify (mm)	Control (mm)
P2	3.1	2.5	0.3
P4	3.6	2.5	0.2
P5	3.9	1.0	0.2
P6	2.8	2.3	0.3
P7	3.0	2.5	0.3
P8	3.1	2.0	0.2
P9	3.9	1.7	0.2
P10	3.1	1.6	0.3
Mean ± S.D.	3.3 ± 0.4	2.0 ± 0.5	0.3 ± 0.1

10 trials × 4 strokes/trial) from the control condition and 304 each for the amplify and small-amplify conditions. The Steel–Dwass test showed that tracing distances under the amplify condition were significantly larger than those under the control condition ($q(3, \infty) = 5.08$, $p = 1.2 \times 10^{-6}$), with the average difference being 8.3 mm. The small-amplify condition produced larger tracing distances than control condition ($q(3, \inf) = 3.95$, $p = 2.3 \times 10^{-4}$) with the average difference being 6.1 mm. Tracing distances did not significantly differ between the amplify and small-amplify conditions. The tracing distances were largest under the amplify condition, followed by the small-amplify condition, and smallest under the control condition. However, owing to the lack of statistical evidence, no clear relationships such as proportional one were found between the degree of amplified shear deformations and the increases in tracing distances.

6. Discussion: sensory–motor relationships underlying experiment

6.1. Prospective feedback model of sensory–motor relationships in tracing movements

Figure 13 shows the conjectured sensory–motor relationship between the tracing movements and the shear deformation of the finger pad. A human inputs a target planar trajectory $\boldsymbol{x}_d(t)$ into an internal model to output the tracing movement through his/her musculoskeletal system. We describe this operation as $\ddot{\boldsymbol{x}}(t) = I[\boldsymbol{x}_d(t), \mu_k(t)]$. As shown in Figure 14(i), by the Amontons–Coulomb law, the shear force on the finger pad, $\boldsymbol{f}_s(t)$ is given by

$$\boldsymbol{f}_s(t) = -\mathrm{sign}[\dot{\boldsymbol{x}}(t)]\mu_k f_n \tag{3}$$

where μ_k is the coefficient of kinetic friction between the finger and the floor, while f_n is the finger pressing force on the plane. A human does not change f_n depending on the applied deformation of the finger pad as shown in Experiment 1. The shear deformation, $\boldsymbol{d}_s(t)$, is described by

$$\boldsymbol{d}_s(t) = S[\dot{\boldsymbol{x}}(t)] = \frac{\boldsymbol{f}_s(t)}{k_f} = -\frac{\mathrm{sign}[\dot{\boldsymbol{x}}(t)]\mu_k f_n}{k_f} \tag{4}$$

where k_f is the stiffness of a human finger pad and approximated to be isotropic, although it is known as an increasing function of applied pressure.[22,23] Using $\boldsymbol{d}_s(t)$, the human estimates the friction coefficient of the surface [14,24] and the force applied to the finger pads.[25–27] For tracing movements intimately related to kinetic friction, an increase in shear deformation affects the kinetic friction perceived by humans.[14] We express this estimation process as

$$\hat{\boldsymbol{\mu}}_k(t) = E[\boldsymbol{d}_s(t)] \tag{5}$$

where $\hat{\boldsymbol{\mu}}_k(t)$ is the estimated coefficient of kinetic friction between the finger and the floor. We speculate that humans feed this perceived friction back to their internal models, and that $\ddot{\boldsymbol{x}}(t)$ is then determined to realize the desired trajectory of the tracing.

6.2. Effect of additional shear deformation of finger pad on tracing movements

As shown in Figure 13, we applied the shear deformation $\Delta\boldsymbol{d}_s(t)$ to the finger pad of the participant using the tactile interface. Then, the deformation increased to $\boldsymbol{d}_s(t) + \Delta\boldsymbol{d}_s(t)$, as shown in Figure 14(ii). In this case, the perceived coefficient of friction increases to

$$\hat{\boldsymbol{\mu}}_k(t) + \Delta\hat{\boldsymbol{\mu}}_k(t) = E[\boldsymbol{d}_s(t) + \Delta\boldsymbol{d}_s(t)]. \tag{6}$$

As described above, the participants feed $\hat{\boldsymbol{\mu}}_k(t) + \Delta\hat{\boldsymbol{\mu}}_k(t)$ back to their internal models that determine their generative forces. Due to this underlying mechanism, the tracing movements are influenced by the tactile interface. Experiments 1, 2, and 3 showed that $\Delta\boldsymbol{d}_s(t)$ influenced $\Delta\boldsymbol{x}(t)$ in the linear and circular tracing tasks, respectively. However, Experiment 3 did not fully support such feedback system because the incremental changes in $\Delta d_s(t)$ and $\Delta x(t)$ were not statistically accompanied with each other.

The above explanation is still just one possibility with which the experimental results are not inconsistent. This article does not completely vindicate the underlying mechanism and does not rule out other possibilities. The explanation does not cover some issues.

First, the participants could have known the increases in their hand motions through the proprioception. Such perceived increases potentially functioned to curtail the hand movements because participants were instructed to sustain the tracing distances. Nonetheless, the distances were eventually facilitated by the dominant effects of the increased skin stretches under the present series of experiments. Such conflicts or integration of the effects of cutaneous and proprioceptive sensations have attracted the interest of some researchers.[8,28–30]

Second, Figure 13 suggests that human tracing velocity and acceleration are also potentially influenced by $\Delta\boldsymbol{d}_s(t)$. If the effects on the hand velocities had been observed, our hypothetical model would have been further consolidated. However, these effects were not statistically

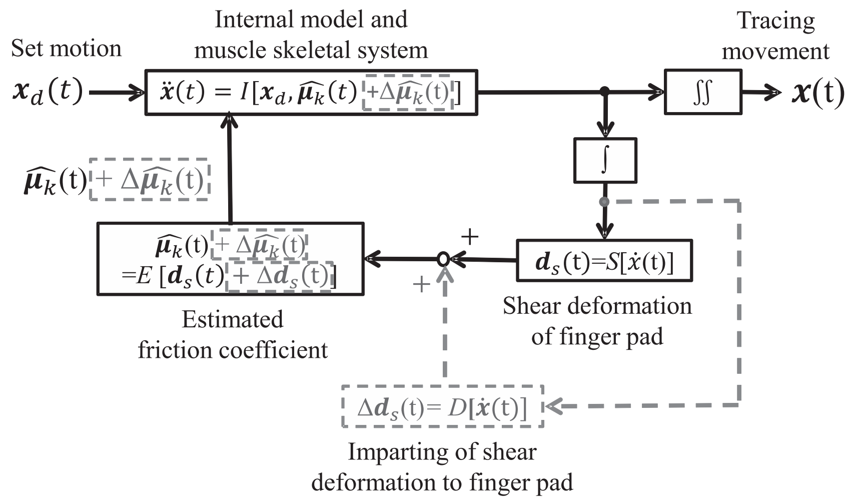

Figure 13. Prospective relationships between shear deformation of the finger pad and tracing movements. Solid lines represent a closed loop with no presentation of shear deformation applied. Dashed lines represent a closed loop with additional shear deformation $\Delta\boldsymbol{d}_s(t)$ applied using the tactile interface.

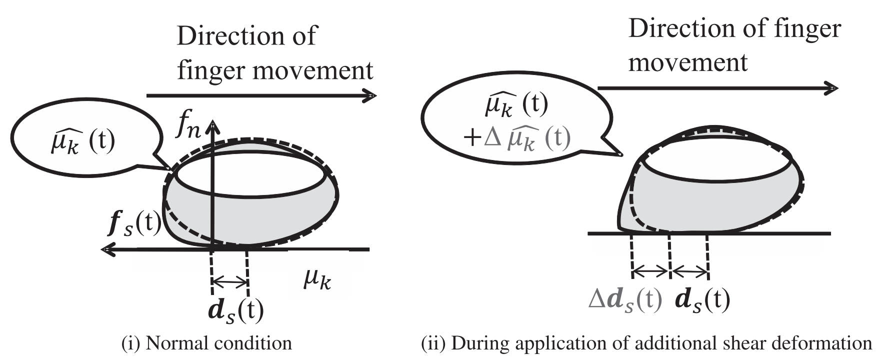

Figure 14. Shear deformation of finger pad by using tactile interface and perceived friction coefficient.

validated, mainly because of the fluctuations in hand speeds; in contrast, differences in less-fluctuated hand displacements could be validated statistically.

Furthermore, the mechanism mentioned above involves a hypothesis that humans feed the perceptually increased friction coefficient back to their internal models. In order to validate this hypothesis, we need to observe status variables in the internal model of generative force, which is generally very difficult to achieve.

Finally, the effects of the reverse condition are not explained by this mechanism. Provided that reverse stimuli should be perceptually different from control stimuli,[13,31,32] we feel inclined to consider a model that explicitly involves the direction of shear deformations. However, the effects of the reverse condition on tracing movements are not conclusive. In Experiment 1, the reverse condition increased tracing distances and speeds, whereas its impact was reduced in Experiment 2. Hence, it is somewhat risky to make conclusions about the influences of reverse conditions.

7. Conclusion

In the present study, we investigated the effects of finger pad deformations on tracing movements. These finger pad deformations and tracing movements form a sensory–motor relationship in which sensory information and kinetic outputs are intimately connected to one another. We intervened in this relationship using a tactile interface that produced shear deformations of the finger pad. When the shear deformations were amplified, the tracing distances increased by approximately 8 mm on average for a traced line of 150 mm length. Moreover, such effect is sensitive to their directional information. The amplification of shear deformation effectively influenced the tracing motions when their directions were the same. These experimental results suggest that the information on finger pad deformations is fed back to the generator of kinetic outputs and composes the sensory–motor relationship. Well-designed skin stimuli possibly result in stronger effects on tracing movements. Finding such conditions and understanding the underlying mechanism will lead to the development of human-assistive haptic technology.

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