ABSTRACT Motor control between the thumb and index finger is critical for holding and interacting precisely with an object. In case of an improper pinching force, especially when it stems from sensory problems, modulating the interaction gain by changing the contact surface properties is a promising solution because of its simplicity and minimal risk. In this pilot study, three healthy human subjects participated in the pinching experiment with two different surface areas to test the effect of interaction gain on motor control (88 mm² and 176 mm² as 1× and 2× surface areas). Subjects were asked to match their pinching force to the reference fingertip pressure applied to the other hand. The results demonstrated that subjects applied less force to the thumb when the contact surface area was smaller, perhaps to compensate for the increase in pressure, while the contact surface area did not change the force applied to the index finger. The ratio of the force applied to the 2× surface area to the force applied to the 1× surface area was 1.19±0.02 (Mean±STE) and 1.00±0.02 for the thumb and index finger, respectively. The pinching force was also affected by the tactile memory. When subjects pinched the 2× surface area after pinching the 1× surface area, the pinching force was higher than the one at pinching the 2× surface area from the beginning. These results suggest that environmental intervention is strong enough to bias the motor output of the sensorimotor system.

INDEX TERMS Fingertip, Pinch, Grip, Internal model, Interaction gain, Sensory feedback
Many prior works have reported successful modulation of pinching force by the sensory modulation, with numbing, vibrating, or stimulating the fingertip during a precision grip \cite{17,18,19}. The sensory modulation approaches also have a lot of potential in their long-term effect, mainly because the primary way in which human beings learn or improve motor performance is through sensory information via the well-distributed peripheral neural network \cite{20,21,22}. Furthermore, the sensory modulation approaches are linked with the body schema (or body ownership), which plays a vital role in intuitive motor control \cite{23}.

Environmental interaction is another promising approach to sensorimotor modulation due to its inherent simplicity and low entry barrier. It is also a crucial component bridging the motor output with the sensory feedback. As most finger motor tasks involve the physical interaction between the fingertip and objects under manipulation or the environment, the motor and sensory signals involved in finger operation are not independent of the interaction, and thus, a deep understanding of the interconnection among them is necessary. The interaction has been usually understood as a part of the sensory function, perhaps because the environmental interaction is perceived via sensory feedback. However, it is also an intermediate stage, which can be adjusted separately for sensorimotor modulation, between the motor output and sensory feedback. For example, the fingertip pressure sensory modalities \cite{15,16}. Many prior works have reported successful modulation of pinching force by the sensory modulation, with numbing, vibrating, or stimulating the fingertip during a precision grip \cite{17,18,19}. The sensory modulation approaches also have a lot of potential in their long-term effect, mainly because the primary way in which human beings learn or improve motor performance is through sensory information via the well-distributed peripheral neural network \cite{20,21,22}. Furthermore, the sensory modulation approaches are linked with the body schema (or body ownership), which plays a vital role in intuitive motor control \cite{23}.

Environmental interaction is another promising approach to sensorimotor modulation due to its inherent simplicity and low entry barrier. It is also a crucial component bridging the motor output with the sensory feedback. As most finger motor tasks involve the physical interaction between the fingertip and objects under manipulation or the environment, the motor and sensory signals involved in finger operation are not independent of the interaction, and thus, a deep understanding of the interconnection among them is necessary. The interaction has been usually understood as a part of the sensory function, perhaps because the environmental interaction is perceived via sensory feedback. However, it is also an intermediate stage, which can be adjusted separately for sensorimotor modulation, between the motor output and sensory feedback. For example, the fingertip pressure perceived while pinching an object can increase by having a pointer surface. Doing so does not modulate the motor and sensory functions, i.e., does not increase the sensitivity to the pressure (see Fig. 1b). Such environmental interaction can be modulated relatively easily compared to the motor or sensory gain modulation because no direct intervention in the human nervous system is required. Therefore, changing the parameters of environmental interaction, i.e., environmental intervention, has been frequently employed, especially for motor learning or rehabilitation. The use of vibration or textured insole has been employed to improve patients’ balance and has showed its efficacy \cite{24,25}. Finger pad friction is known to play an essential role in regulating the grip force \cite{26}, and textured surfaces on foot sole have changed subjects’ weight perception \cite{27}. Split-belt treadmills have been actively used in recovering the gait symmetry of people after stroke \cite{28}.

In this study, we extend the environmental interaction approach to deliberate finger control and particularly study the effect of environmental intervention on the pinching force during a precision grip. As described in the internal model (Fig. 2) presented in our prior work \cite{29}, which was developed based on previous internal models \cite{30,31}, both interaction gain (k) and sensory gain (β) can increase sensory feedback on the fingertip corresponding to the pinch. Therefore, the interaction gain (k) is likely to affect the closed-loop motor control performance as well as sensory feedback. Note that the gain (k) can be adjusted simply by modulating the surface profile or parameters below the fingertips during a pinch, whose effect on the finger control is investigated and compared with the model-based understanding.

II. SYSTEM IMPLEMENTATION

A. Overall system for measuring the pinching force

As shown in Fig. 3a, subjects were requested to pinch a cylinder on each side with an embedded force sensor. The surface area of the cylinder in contact, because it determines the pressure, was chosen as the parameter varying the interaction gain (k) during the environmental interaction on subjects’ fingertips during a pinch. The cylinder was interchangeable between two pairs of cylinders with different contact surface areas, 2× and 1× area cylinders. The 2× area cylinder had 176 mm² contact surface area, whose diameter corresponds to about 15 mm, while the 1× area cylinders with 176 mm² contact surface area, whose diameter corresponds to about 15 mm, while the 1× area cylinders
area cylinder had 88 mm² contact surface area, whose diameter corresponds to about 6 mm. Note that the cylinder sizes were determined to make both contact surface areas sufficiently smaller than the average area of the fingertip so that the cylinder surface press the middle of the fingertip [32]. The S15-45N (SingleTact, UK) capacitive force sensor was selected to measure the pinching force, as it provides high precision of <0.09 N force resolution. Two of them were firmly attached below the cylinders to measure the pinching force on each fingertip (the thumb and index finger).

B. Spring to provide the reference pinching force

A 50-mm spring was selected to consistently provide the reference fingertip pressure to the non-dominant hand during the experiment. The spring constant is 4.12 N/cm (Fig. 3a). The reference spring handle has a 324 mm² surface area, comparable to the fingertip area, to cover the entire fingertip surface [15]. In the middle of the spring, a foam stopper was installed for subjects to stop the pinch and then apply a consistent force when requested. The stopper was designed to have a hollow structure to avoid contact with the outer border of the spring and not to affect the overall spring constant.

III. EXPERIMENTAL DESIGN

A. Subject Recruitment

Three naive right-handed human subjects (two male and one female) participated in this study following the procedure described in the protocol approved by the Texas A&M University Institutional Review Board (IRB2019-1434D) on June 3rd, 2020. The age of all three subjects ranged from 23 to 52 years, with an average age of 31 years. All of them used their right hand as a dominant hand.

B. Experimental procedure

Each subject went through a total of 20 trials, as described in Fig. 3b. During the first 3 minutes, subjects were asked to sit on a chair and position their thumb and index fingers of their dominant hands at the cylinder surface. Subjects were also asked to place their thumb and index fingers of their non-dominant hands at the surface of the spring handles. Subjects were then asked to pinch the spring until they felt the foam stopper. Note that subjects were blindfolded from the end of the first 3 minutes until the end of the experiment to prevent them from recognizing the change of the cylinder surface area.

At the beginning of the experiment, subjects were asked to pinch the spring surface with their thumb and index fingers of the non-dominant hands. Subjects were then asked to squeeze the cylinder surface with their thumb and index fingers of the dominant hands, with the same level of force as the one perceived from their non-dominant hands (i.e., reference force). Before the end of each trial, the operator changed the surface area of the cylinder (the operator...
concurrently replaced cylinders for both fingers) at random timing between the 2nd and 5th pinches, as shown in Fig 3b. The trial ended when subjects pinched over the cylinder with the new surface area. Each pinch duration was 5 seconds, and the operator asked subjects to stop pinching after 5 seconds. After the 5-seconds of pinching, subjects were asked to stop pinching and rest both of their hands. There were also 5-second rests between pinches. Total 20 trials were conducted for each subject, with a 1-min resting time in the middle.

During the first 10 trials, the 2x cylinder was used as a default cylinder, and the 1x cylinder was introduced at a random timing between 2nd and 5th pinches, and vice versa concurrently replaced cylinders for both fingers) at random timing between the 2nd and 5th pinches, as shown in Fig 3b. The trial ended when subjects pinched over the cylinder with the new surface area. Each pinch duration was 5 seconds, and the operator asked subjects to stop pinching after 5 seconds. After the 5-seconds of pinching, subjects were asked to stop pinching and rest both of their hands. There were also 5-second rests between pinches. Total 20 trials were conducted for each subject, with a 1-min resting time in the middle.

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Fig. 4. Transient change of the force output for each finger at pinching (a) 2x surface area and (b) 1x surface area, sampled from one of the three subjects.

Fig. 5. (a) Pinching force output for each finger at different surface area and (b) force ratio between 1x and 2x surface areas for each finger.

for the second 10 trials where the 1x surface area was introduced as a default.

IV. EXPERIMENTAL RESULTS

A. Statistical analysis

We performed a linear mixed model analysis (SPSS, IBM, Chicago, IL, USA) per each experimental result to determine the efficacy of the independent factors (surface area of the cylinder) on dependent variables (force output and force ratio) and to account for both within-subject and across-subject variability. Both subjects and trials were set as random factors. The significance level was set at 0.05 (95% confidence interval). All statistical data are reported as Mean±STE (standard error) in the experimental result section, and all statistical comparison results are shown with the corresponding p values.

B. Transient change of the force output on the contact surface of each fingertip

Fig. 4 shows the transient change of the pinching force applied onto the different cylinder surfaces, as the average data of one of the three subjects. The plot shows that the pinching force increased and settled to a specific value, as expected, after 1-2 s at each pinching trial. Therefore, we set the plateau range as the 2nd half of the force output, sufficiently excluding the transient response.

C. Effect of the surface area on the pinching force

Fig. 5a shows the pinching force applied for two different cylinder surface areas, one with 176 mm$^2$ (2x area) and another with 88 mm$^2$ (1x area). The thumb applied 7.48±0.13 (N) and 6.32±0.14 (N) for the 2x and 1x areas, respectively, while the index finger applied 6.11±0.20 (N) and 6.08±0.14 (N) for the 2x and 1x areas, respectively. The force applied by the thumb is statistically different between the 2x and 1x areas (p<0.001), and the force applied by the index finger is not statistically different between the 2x and 1x areas (p=0.898).

Fig. 6. Pinching force output for each finger at different surface area with different previous pinch history.
D. Ratio of pinching force applied onto the 2x and 1x surface areas

Fig. 5b shows the ratio of the pinching force applied onto the different cylinder surfaces. The ratio of the pinching force over 2x surface area to the pinching force over 1x surface area was 1.19±0.02 and 1.00±0.02 for the thumb and index finger, respectively. The ratio of the pinching force between 2x and 1x areas was statistically larger in the thumb than the index finger (p<0.001).

E. Effect of the previous pinch history on the current pinching force

Fig. 6 shows the pinching force applied with previous pinch history for the 2x and 1x surface areas. When subjects pinched the 2x surface area after pinching the 1x surface area, the pinching force was higher than the case of subjects pinching the 2x surface area from the beginning (as a default) for both the thumb (p=0.002) and the index finger (p=0.044). Conversely, when subjects pinched the 1x surface area after pinching the 2x surface area, the pinching force was lower than the case of subjects pinching the 1x surface area from the beginning (as a default), but only for the thumb (p=0.009). The pinching force of index fingers onto the 1x surface area was not changed by the previous pinch history (p=0.085).

V. DISCUSSION

The results present that the pinching force at the dominant hand is successfully modulated by changing the contact surface area when the consistent reference fingertip pressure is provided to the thumb and index finger of the non-dominant hand. The results also present the asymmetric control between the thumb and index finger and the role of tactile memory in regulating the pinching force. Detailed interpretations and limitations are discussed in the following sections.

A. Pinching force decreased as surface area increased, but in a different ratio

In the condition of pinching with precision, the pinching force applied to the cylinder surface area was increased when the surface area was increased. As the pinching force is dispersed over the surface, we interpret this relationship as a mechanism to compensate for the force dispersion and maintain the fingertip pressure at a similar level. The tactile sensory receptors of the fingertip respond to not the force but the pressure. This result demonstrates the promise of environmental intervention in modulating the finger motor output by adjusting the contact area and resultant pressure.

However, the pinching force does not change as much as the contact area. The ratio of change in pinching force was smaller than the ratio of change in the surface area, i.e., the contact area. When the pinching surface area decreased by 50% (from 2x area to 1x area), the average pinching force of the thumb decreased by only 9% (from 6.80 N to 6.20 N). It is perhaps because the pinching force was determined by both the feedforward and feedback neural pathways. The internal model established based on previous studies (Fig. 2) also suggests that those two neural pathways determine the motor output together, with partial influence from each neural pathway [30], [31]. The observed contribution of feedforward and feedback neural pathways to the motor output agrees with the prior studies on the predictive grip force with visual recognition [33]. However, the presented result was not obtained with visual recognition but with tactile recognition, as subjects were blindfolded, suggesting that the grip force (or pinching force) prediction and feedforward solution is determined by the tactile feedback as well as the visual feedback.

B. The thumb mainly responded to the environmental change while the index finger did not

As shown in Fig. 5a, the change of the pinching force was observed only on the thumb but not on the index finger. The force ratio depicted in Fig. 5b also indicates that the pinching force did not change in the index finger, although the contact surface area was significantly changed. This result indicates that the thumb mainly responds to the change in contact surface area while the index finger maintains its motor response despite the difference in the contact surface area.

As the thumb and index finger usually pinch the object in the middle, the increase in the pinching force at the thumb will naturally increase the pinching force at the index finger, based on Newton's law of action and reaction. However, in our experiment, the thumb and index finger independently pinched the cylinder with the object fixed in the middle. Therefore, we were able to observe the pinching force from each finger separately. Interestingly, our result suggests that the thumb plays an important role in regulating the pressure at a pinch, while the index finger maintains its pressure applied to the contact surface at a pinch. We speculate that the index finger may help stabilize or hold the object in place, while the thumb varies the pinching force.

C. Pinching force in each finger depends on the tactile memory as well as the current surface area

Pinching force depends on the previous environmental interaction, as well as the contact surface area. When subjects pinched onto the 2x surface area, the pinching force was higher with the history of pinch onto the 1x surface area before (see the left side of Fig. 6). This result suggests that tactile memory as well as the contact surface area plays an essential role in regulating the pinching force. As the fingertip pressure decreases by increasing the contact area under the same level of force, the human tactile system will respond to the change and increase the pinching force to compensate for the decrease of pressure. Although the system consistently provides a reference fingertip pressure at the non-dominant hand, the tactile memory was strong enough to bias the motor output of the sensorimotor system.

Also, when subjects pinched the 1x surface area, the history of pinching the 2x surface area lowered the pinching force than the case without prior pinch (see the right side of Fig. 6). As the area decreased by 50% and fingertip pressure increased accordingly with the same force applied, the tactile
system responded to the change and further decreased the pinching force to compensate for the pressure increase. This result also supports the notion of tactile memory playing an important role in regulating the pinching force. Such a change was observed for both the thumb and index finger, but the difference in the index finger was not statistically meaningful, suggesting that the thumb is more sensitive to the environmental change than the index finger (i.e., stronger tactile memory on the thumb than the index finger).

D. Limitation and future direction

This study is a pilot study with a limited number of subjects (N=3), even though each subject went through 20 trials of area change and the experimental data provided statistical significance to interpret the effect by setting both subject and trial as random factors. Thus, a larger-scale study with a larger number of subjects would be needed to confirm the result over the biological variation. Also, the kinetic coordination between the thumb and index finger needs to be thoroughly investigated in multiple scenarios. Although experimental data showed that the thumb mainly adjusts the environmental change during a pinch with precision, we did not investigate the underlying mechanism in this study. Lastly, the experiment can be extended by employing grasping instead of pinching to involve the interaction among all five fingers. The kinetic coordination among the fingers for grasping at multiple conditions of interaction gains by changing the contact surface would provide more valuable knowledge to understand the human grasping mechanism.

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