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Chen, Y., van Zanten, J., Wiertlewski, M., & Stienen, A. (2025). Exploring Synergy Between Tactile Perception and Arm Usage. In *Proceedings of the International Conference On Rehabilitation Robotics (ICORR 2025)* (pp. 320-325). (IEEE International Conference on Rehabilitation Robotics). IEEE. https://doi.org/10.1109/icorr66766.2025.11062930

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2025 International Conference On Rehabilitation Robotics (ICORR)
May 12-16, 2025. Chicago, IL, USA

Exploring Synergy Between Tactile Perception and Arm Usage

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***Abstract*—Stroke causes severe tactile deficiencies which affects motor control when grasping and lifting objects. Understanding the fundamental neural disorders associated with tactile deficits is crucial to developing rehabilitation and treatment plans correspondingly. Earlier studies have studied the dynamics between finger grasping behavior and arm muscle activation in stroke patients. However, the exact neuromuscular synergy of tactile perception and arm usage is left unexplored. Here we designed a comprehensive experiment platform and tested the potential synergy on 12 healthy young adults, serving as a control group to establish a foundation for future studies on stroke patients. The experimental platform consists of a lever arm on which torques can be applied to the subject's arm. The end effector is equipped with a special ultrasonic friction modulation plate that can reduce the apparent friction of the object by up to 63%, simulating real-world grasping tasks in a controlled setting. The experiments were performed under varying conditions of friction and arm usage. Results indicate significant effects of tactile stimulation on grasping force adaptation ($p < 0.05$ in 8 of 12 experimental conditions). In the meantime, arm usage did not show a significant synergy with tactile perception ($p = 0.44$ in grasping force adaptation amplitude, and $p = 0.73$ in reflex delay). These findings demonstrate that the experimental platform can provide insights into human tactile behaviors, which is critical for studying tactile sensory and motor control synergy. The results will lay the groundwork for future research on underlying pathologies and rehabilitation strategies for stroke patients.**

***Index Terms*—tactile perception, ultrasonic friction modulation, stroke, synergy**

I. Introduction

STROKE is the second-leading cause of death and the third-leading cause of disability and death combined, as a study has revealed in 2021 [1]. More than 50% stroke patients reported perceptual disorders [2], including deficiencies in somatosensation [3] and proprioception [4]. These deficiencies cause stress, loss of daily task functions, and reduction of quality of life among stroke patients [5]. Especially, impairment of tactile perception has a detrimental impact since patients have reported difficulty in sensing touch, pressure, and temperature, discriminating textures, and recognizing objects through tactile senses [6], as well as reduced or altered pain sensations [7]. To develop targeted treatment and rehabilitation strategies, it is crucial to understand the fundamental neural discrepancies associated with tactile deficits.

Tactile perception plays a fundamental role in manipulation tasks. Tasks as mundane as holding a cup or writing with a pen become tedious in the absence of touch. This is especially true when estimating the grip force necessary to securely grasp an object [8]. Stroke patients may use abnormally high forces to ensure the security of grasping, and studies have suggested that during object-lifting tasks, their grasping force fluctuates with the acceleration and deceleration of the object [9]. Accelerations and decelerations involve extensive activation of arm muscles, and the fluctuations of grasping force that occur at these moments are likely to be caused by tactile sensibility deficits [9]. Their correlation implies a neuromuscular synergy between tactile perception and arm muscle activation.

Despite increasing knowledge of the effect of friction on grasping [10], the effect of stroke on tactile functions or its effect on grasping is understudied [11]. Specifically, few studies have explored the dynamics of stroke patients' tactile perception deficits, and how they correlate with other neurological effects in complex tasks that involve the coordination of multiple neural inputs and outputs.

The absence of detailed knowledge of the impact of impaired touch on grasp is partially due to the difficulty of controlling tactile stimulation. Traditionally, changing tactile interaction is done by changing surface materials or using different gratings [12]. This method is tedious and it is often difficult to establish a general standard. But more importantly, it is impossible to study real-time responses to tactile stimulations.

In recent years, however, a new class of haptic devices, called surface haptics have emerged. These devices can modulate friction with the bare finger directly either via electroadhesive effect or using ultrasonic vibration, see [13] for a comprehensive review. Contrary to electroadhesive devices, ultrasonic friction modulation can change the coefficient of friction on a wide dynamic range. It works by physically reducing the friction between the human finger and the surface [14] and the friction coefficient can be modulated from about 1 all the way to 0 [15]. The wide dynamics range makes it ideal for simulating real-world dynamics of grasping tasks.

The ultrasonic method was first introduced in 1995 [16]. Its functional mechanism to reduce friction involves the squeeze film effect in which ultrasonic waves create an overpressure between the finger and the vibrating plate. The air between the skin and the plate is squeezed into a thin film, which slightly levitates the skin and reduces the number of asperities in contact, thus lowering friction [14, 15, 17].

We leverage ultrasonic friction modulation to study how human participants grasp objects. This marks our first attempt to understand whether stroke patients, suffering from

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2025 International Conference On Rehabilitation Robotics (ICORR) | 979-8-3503-8068-2/25/$31.00 ©2025 IEEE | DOI: 10.1109/ICORR66766.2025.11062930

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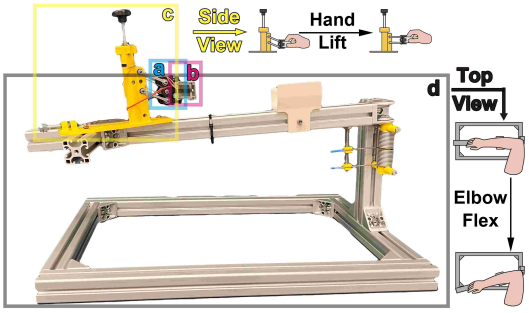


Fig. 1. The full assembly of the experimental setup. a) The grasping object. b) The friction-modulation plates. c) The constant force system. d) The elbow support.

neurological disorders, experience a synergy between arm usage and tactile perception. This pilot study, conducted on healthy subjects as a control group, serves as a preliminary step to develop an experimental platform that can be used for future studies involving stroke patients. The results of this study, while not directly conducted with stroke patients, will provide critical baseline data for understanding how tactile perception and arm usage may interact in individuals with stroke-related deficits.

II. Materials and Methods

A. Goal

The goal of this experiment is to mimic a casual lifting task: a person grabs an object with a certain weight, lifts it slightly with their hand and wrist, with or without activating arm muscles, and holds it for a short time. The person does these all without special focus on the task itself, to reflect real-life behaviors, where people also do not pay special attention when casually grasping objects. Specifically in this experiment, the friction level of the object is changed during a trial. The subject's grasping force and the object's angle are recorded and analyzed to evaluate the response to tactile stimulation.

B. Setup

The experiment setup (Fig. 1) consists of four distinct sections:

1) Grasping Object: The grasping object (Fig. 1a) mimics a general object to be gripped in everyday life. It is able to record the subject's grasping force with two load cells. The subjects' active grasping force represents how much force they think they need to secure the grasp, reflecting how slippery they perceive the object at hand to be. The width of the object is 50 mm, and the effective grasping area is 34 mm $\times$ 25.5 mm.

2) Friction Modulation Plates: Two glass-based friction modulation plates (Fig. 1b) provide tactile stimulation on both sides of the grasping object. When activated, the actuators vibrate the plates to an ultrasonic frequency (around 23 kHz), causing a 6.21 μm and a 5.72 μm displacement amplitude on the plates' centers respectively. This ultrasonic vibration provides the squeeze-film effect, greatly reducing the plates' surface friction.

3) Constant Force System: The constant force system (Fig. 1c) uses a pulley system and an extension spring to provide a constant vertical force on the grasping object. This system is designed to provide an adjustable vertical force from - 5 N to + 5 N, adjusted by turning the black knob on the lead screw.

4) Elbow Support: The elbow support (Fig. 1d) has a rotational stiffness. When the subject flexes their elbow to an angle, they have to use their arm muscles to counter this stiffness, thus this structure can mimic the use of the arm in the object-grasping task. When the subject is instructed to flex their elbow to a fixed angle (around 30 degrees), they will need to apply approximately 4.14 N·m of torque to counter this stiffness.

C. Controls and Data Acquisitions

Grasping force from the load cells and the object's angle from an angular sensor are gathered at 100 Hz. A Labview program visualizes the data in real time and automatically executes the progressions of each trial.

D. Experimental Protocols

The main experiment studies three controlled variables: the net vertical force of the object (-0.5 N, 0 N, 0.5 N), flexion of the elbow (yes, no), and friction perturbation (high to low, low to high). Before a trial, the constant force system is adjusted to the destination force level, and the subject is asked to relax or flex their elbow to the fixed angle. Note that when the vertical force of the object is 0 N, there is no actual need to change the grasping force when there is a change in friction. This group acts as a "placebo" control to account for factors like vibration, heat, and habitual behavior, excluding the effects of friction change on the results.

The participant task includes three program-controlled phases (Fig. 2):

1) Lifting phase. This phase has no time limit. The initial friction state is applied before the start of this phase. During this phase, the subject is asked to use their hand and wrist to move the object from its beginning position to the middle (see Fig. 2), using an optimal grasp effort. The optimal effort means applying the minimal grasping force necessary while ensuring grasp stability.
2) Holding phase 1. This phase lasts for 2 seconds. It is used to establish a steady baseline of the initial grasping force. Data from the beginning of this phase are used for further analysis.
3) Holding phase 2. This phase lasts for 8 seconds. Immediately at the start of this phase, the friction state switches to the opposite as a perturbation. The subject's goal is to maintain the object's position.

Fig. 3 depicts a typical trial. During the experiment, the subject is asked to wear a pair of active noise-canceling headphones to avoid any audio cues. In the meantime, a nature documentary is played to them to divert their attention and mimic a casual grasping task.

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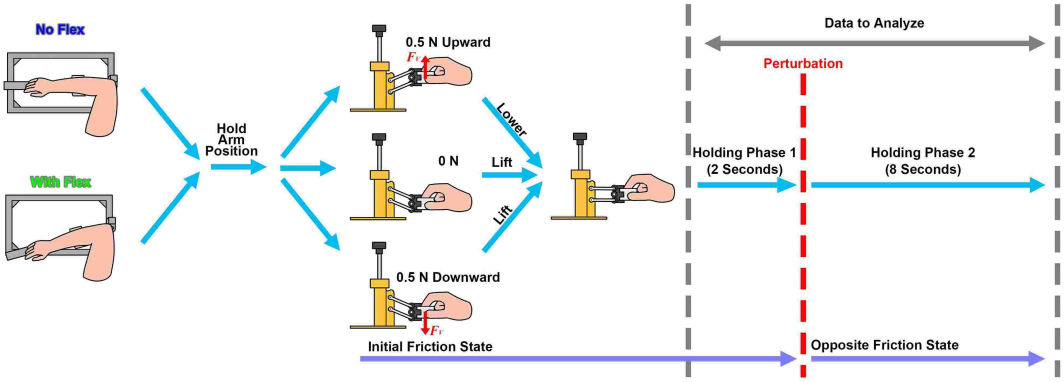


Fig. 2. Flowchart of the experimental protocol. Controlled variables are 1) Elbow position (no flex, with flex; illustrated by the elbow drawings on the left), the subject keeps their elbow position during the entirety of the trial; 2) Vertical force (0.5 N upward, 0 N, 0.5 N downward, illustrated by the hand drawings in the middle), the trial data used is the 10 seconds after they have lifted/lowered the object and stabilized; 3) Friction perturbation (high to low, low to high; shown by the purple arrows on the bottom), the initial friction state starts before the subject touches the object.

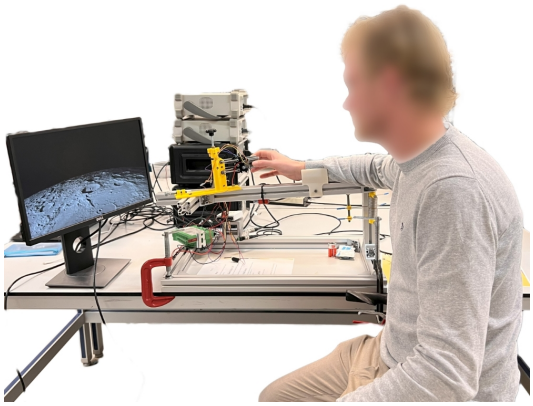


Fig. 3. A typical scene where a participant is performing the experiment. They are currently in the holding phase of a trial, not flexing their elbow, while watching the nature documentary.

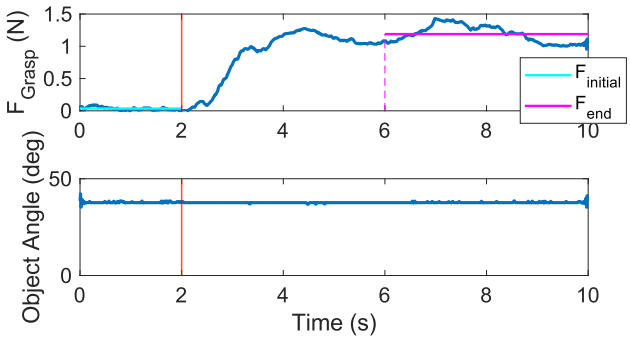


Fig. 4. A typical trial where the friction changes from high to low, and the object has a downward vertical force. The upper plot shows the grasping force over time, and the lower one shows the object's angle over time. The vertical red lines indicate the time of the friction change (2 s). The horizontal magenta lines show the initial force before the perturbation and the end force after the perturbation.

E. Friction Modulation Characterization

Before the main experiment, subjects were asked to perform a qualitative test to characterize the effectiveness of friction reduction. The object was adjusted to have a force of 0.5 N downwards. The subject would first squeeze the object with excessive force and lift it. Then, they would gradually reduce their grasping force, until the object starts to slip slowly. They were instructed to continue to release their grip until the object fully slipped from their fingers. They repeated this process with friction reduction either off (high friction) or on (low friction). Their grasping force and the object's position during the whole process were recorded and analyzed. Assuming a simple friction model, the minimum grasping force before the object slips provides a friction force equal to the object's vertical force.

F. Data Processing

1) Data Cleaning: Grasping force and object angle data were cleaned first before further analysis. First, their zero baselines were subtracted. Next, data were segmented into trials. The data acquisition rate was set to be 100 Hz; however, due to hardware limitations, the actual sampling was approximately 65 Hz, with a variable sampling rate. So, all segments were then resampled to 100 Hz by interpolation.

2) Data Exclusion: A threshold was used for detecting human errors in the trials. The value was determined by 10 times the minimum grasping force needed at the low friction condition (8.56 N in this case, as will be later shown in the results section). Further analysis excludes all trials with force exceeding this threshold. 12 trials were excluded in total among 432 trials.

3) Metric Extraction: Fig. 4 shows a typical trial where the friction changes from high to low on the two-second point (red lines), and the object has a downward vertical force. The object's position (angle) does not significantly change during a trial, and is not in the scope of this experiment, thus is not further studied.

3 metrics were extracted from each trial: the initial grasping force before the perturbation $F_{initial}$, the end force after full adaptation F_{end} (the cyan and magenta lines in Fig. 4), and the difference between them ΔF_{end}. They are calculated by:

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$$\begin{cases} F_{initial} = mean(F(t < 2)) \\ F_{end} = mean(F(t > 6)) \\ \Delta F_{end} = F_{end} - F_{initial} \end{cases} \quad (1)$$

The reason F_{end} is not calculated directly after the perturbation is because there is a delay in the adaptation for grasping forces, especially in friction-increasing conditions (which will be shown in the next section). So the calculation uses the second half of the data (from 6 s to 10 s) after the perturbation.

G. Participants

This experiment recruited 12 participants, 7 males and 5 females. They are all healthy adults with no diagnosed tactile or arm usage deficiencies. Their age ranges from 24 to 30 (mean 26.4). Since the experiment setup is specifically designed for right-hand use, only right-handed individuals were recruited.

III. Results

A. Friction Modulation Effect

A paired t-test was performed for the mean values of each subject's minimum grasping force before slippage in the characterization test. It confirmed that friction modulation has a significant effect on the grasping force ($t_{12} = -3.3, p = 0.0069$). The average minimum force for the high friction condition is 0.32 N, while that of the low friction condition is 0.86 N. Assuming a simple friction model without viscosity, the ultrasonic friction effectively reduced the surface friction coefficient by 63%. Note that the actual friction model is more complex and depends on the subject [18], so this value is just for qualitative reference.

B. Data Overview

Fig. 5 plots the force data of all 12 conditions separately. The blue lines indicate when the subject does not flex their elbow, while the green lines indicate the opposite. Shaded areas are their standard deviations. The left column indicates when the friction changes from low to high, while the right one indicates otherwise. The rows from top to bottom indicate 0.5 N upward, 0 N, and 0.5 N downward force on the object respectively. Fig. 6 further illustrates the mean and standard deviations of the difference in force $\Delta\overline{F}$ over time. ΔF has a similar definition as ΔF_{end}:

$$\Delta F(t) = F(t) - F_{initial} \quad (2)$$

IV. Discussions

A. Experiment Validation

Before addressing the primary research question, it is essential to establish the validity of the experiment. This entails demonstrating that the results accurately reflect the participants' tactile perception and align with established findings in the field. Fig. 7 shows the confidence levels $(1-p)$ of paired t-tests ($N = 12$) between $\overline{F}_{initial}$ and $\overline{F}_{end}$ of each subject under different conditions. Since the confidence levels

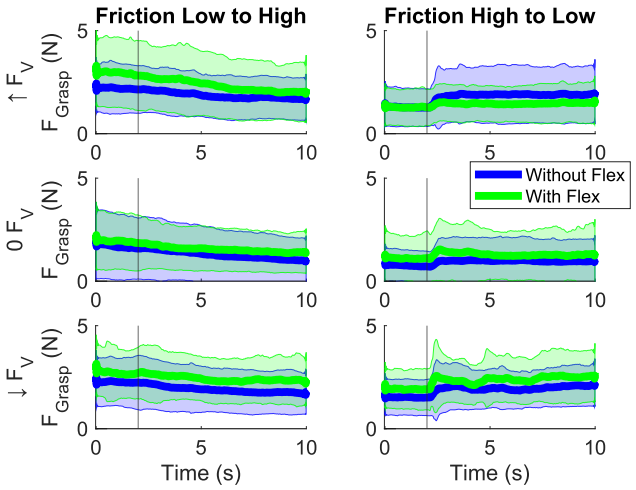


Fig. 5. Overview of the means of grasping force over time under 12 different conditions. The blue lines indicate when the subject does not flex their elbow, while the green lines indicate otherwise. Shaded areas are their standard deviations. The left column indicates when the friction changes from low to high, while the right one indicates otherwise. The rows from top to bottom indicate 0.5 N upward, 0 N, and 0.5 N downward force on the object respectively.

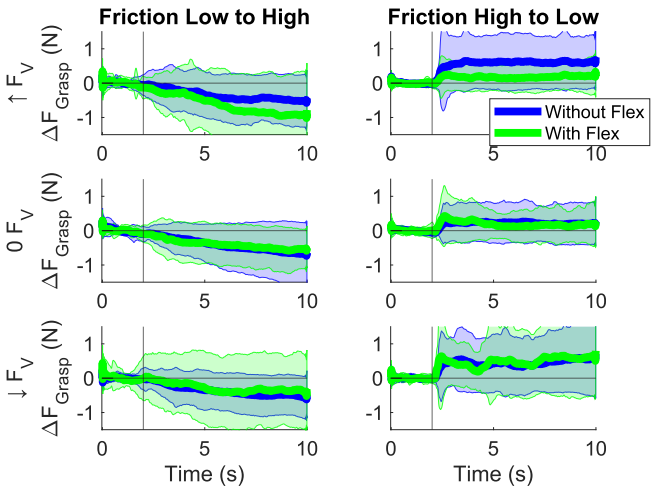


Fig. 6. Overview of the means of $\Delta\overline{F}$ over time under 12 different conditions. ΔF is the force data subtracted by $F_{initial}$. The blue lines indicate when the subject does not flex their elbow, while the green lines indicate otherwise. Shaded areas are their standard deviations. The left column indicates when the friction changes from low to high, while the right one indicates otherwise. The rows from top to bottom indicate 0.5 N upward, 0 N, and 0.5 N downward force on the object respectively.

are all above 85% and 8 out of 12 are above 95%, it is a clear indication that the friction perturbation has a significant impact on the participants' ability to regulate their grasping force.

Furthermore, there is no statistical difference when it comes to the direction of the vertical force ($t_{24} = -1.1, p = 0.3$, and $t_{24} = -0.96, p = 0.34$ for friction increasing and decreasing respectively). Thus, the upward force and downward force conditions can be combined as "with vertical force" experimental groups, with respect to "no vertical force" control groups.

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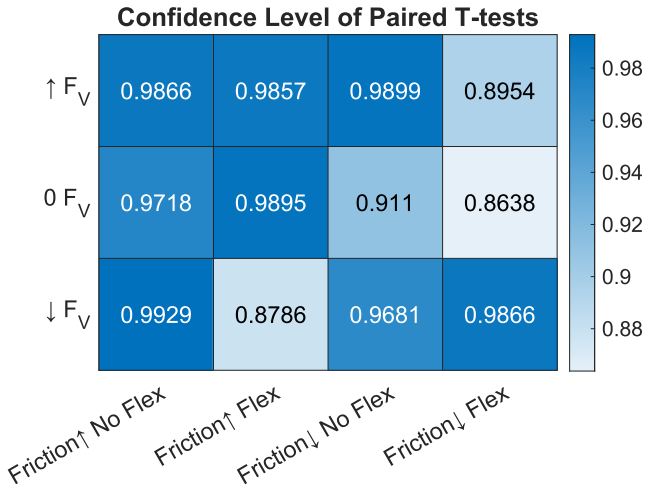


Fig. 7. Heatmap of confidence levels of paired t-tests between $\overline{F}_{initial}$ and $\overline{F}_{end}$ (as in Fig. 4) of each subject under different variable combinations. The higher the value, the deeper the color, and the more significant that the perturbation had an effect.

However, it seems that the control groups (no vertical force but with friction perturbation) also demonstrated a significant effect of tactile stimulation on the grasping behaviors. So, paired t-tests of $\Delta\overline{F}_{end}$ comparing trials with and without a vertical force are performed. In these tests, all other conditions are combined except for the friction perturbation, because the difference in it affects the direction of ΔF_{end}. Results showed that there is no significant difference between the control groups and the group where friction increases ($t_{24} = 1.1, p = 0.3$). In contrast, when the friction decreases, the groups exhibit significantly larger effects ($t_{24} = -2.9, p = 0.0088$).

Taking all factors into account, it is clear that the subjects can perceive the change in friction and adapt accordingly, thus this experiment is able to reflect their tactile perceptions.

B. General Grasping Behavior

1) Decreasing Friction: Subjects increase their grasping force when the friction decreases and they sense an actual need to grip tighter. Their reactions can resemble a first-order system, where there is a small delay after the impulse (perturbation), and then the system output (grasping force) increases negative exponentially to a new steady state, as the lines on the right side of Fig. 6 suggest. In fact, the delay t_{delay} can be calculated if fitting the force curve with a piecewise function after the perturbation:

$$\begin{cases} \Delta\hat{F}(t < t_{delay}) = 0 \\ \Delta\hat{F}(t \geq t_{delay}) = A \times (1 - e^{\frac{-(t-t_{delay})}{\tau}}) \end{cases} \quad (3)$$

where A is the gain and τ is the time constant. Because individual trials often have very large deviations, the goodness of fit is not always satisfactory. As a consequence, only the average of every trial with decreasing friction and non-zero vertical force was fitted with the non-linear least squares method, as shown in Fig. 8. The resulting time delay is 184 ms. The delay is slightly larger than previous findings on friction-induced reflex response time [19], but still in the same magnitude. It is also consistent with the previous study [20]. This short delay implies that there is an intrinsic reflex pathway in humans to react to sudden grasp instability.

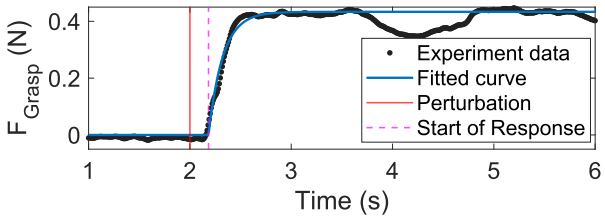


Fig. 8. Fitted curve of the mean of all trials with decreasing friction and non-zero vertical force. The black dots represent the experiment data points, while the blue line is the fitted curve. The red vertical line marks the start of the perturbation. The fitted time delay of the system is 184 ms, which is marked by the dashed magenta line.

2) Increasing Friction: A decrease in grasping force is observed when the friction increases during a trial, but at a significantly slower rate than when friction decreases (Fig. 6). In both increasing and decreasing friction conditions, the amplitude of grasping force change is similar (comparing the left and right sides of Fig. 6). This means they adapt to the same level of friction change, no matter the direction, with the same level of grasping force change. Also, the F_{end} in increasing friction conditions is close to $F_{initial}$ in decreasing friction conditions (comparing the left and right sides of Fig. 5). This implies subjects adapted their grasping effort to their perceived optimal level. These similarities suggest that grasping forces are actively adapting to the level of friction to expend as little energy as possible while maintaining the stability of the grasp. The control groups, however, showed the same pattern of grasping force decrease as the experimental groups, despite that there is no actual need for the grasping force to change. This might be explained by: 1) Since the actual grasping forces are a lot higher than the minimum required grasping force, even in low friction conditions, the decrease in the grasping force is merely an attempt to optimize the grasping effort. 2) Since there is no actual grasping force needed in the control group, the subjects also felt the need to reduce their grasping force, as in situations where friction increases. However, the amplitude of this reduction happens to coincide with that in non-zero vertical force conditions, thus the results yield no statistical difference.

C. Effects of Arm Usage

1) Effects on Grasping Force: Fig. 5 suggests that there is a difference between the grasping force with and without arm usage, regardless of the perturbation. The control groups were not taken into account. A paired t-test between each subject's $\overline{F}_{initial}$ without and with arm usage under all other conditions confirmed there is a significant effect of arm usage on the level of force generated ($t_{48} = -3.8, p = 4.2 \times 10^{-4}$). The same test on their $\overline{F}_{end}$ yields similar results ($t_{48} = -3, p = 0.0039$), suggesting that when participants are using

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their arms, they use a significantly higher grasping force both at the beginning of the grasping task and at the steady state where they have adapted to the new friction level.

2) Effects on Force Change: Since it is not confirmed that the friction-increase conditions reflect tactile perception, only friction-decrease conditions are used in this evaluation. A paired t-test between each subject's $\Delta\overline{F}_{end}$ without and with arm usage proved no significant difference ($t_{24} = 0.79, p = 0.44$). The subjects adapt to the same level of friction change with the same amplitude of force change, regardless of the usage of their arm.

3) Effects on Time Delay: Using the same function 3, response delay t_{delay} can be calculated for every subject under decreasing friction. However, due to the high deviations of each trial, this function was only successfully fitted to 8 subjects with meaningful results. A paired t-test between these subjects' t_{delay} without and with arm usage proved no significant difference ($t_{24} = -0.35, p = 0.73$). This possibly means that arm usage does not affect the time delay of response to tactile perception.

4) Is There a Synergy?: In conclusion, subjects tend to use a higher grasping force with arm usage whatever the condition; however, they respond to the same level of tactile perturbations with the same amplitude of force adaptation and likely the same level of time delay. Since several subjects reported that they involuntarily use their hand to assist in bending the elbow support (see the mechanism in Fig. 1), it is highly likely that the higher grasping force is just the additional hand pressure on the plates. With this factor accounted for, we can conclude that with healthy young adults, there is no significant neuromuscular synergy between arm usage and tactile perception.

V. Conclusions

We presented a pilot study that explores whether there is a neuromuscular synergy between humans' arm usage and their tactile perception of the object in hand. This study serves as a preliminary step, using healthy subjects as a control group, to develop an experimental platform that can be used for future research involving stroke patients. The results revealed a general grasping behavior that is consistent with earlier findings, confirming that this experiment is valid to reveal possible tactile perception discrepancies. In the end, we found no significant evidence that arm usage has a synergy with healthy subjects' tactile perception. This conclusion suggests that for healthy humans, the regulation of grasping force may function independently of general motor control. However, the findings from this study will lay the groundwork for future research on stroke patients, providing critical baseline data to explore how these dynamics interact in individuals with stroke-related deficits.

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