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The Effect of Manipulator Gripper Stiffness On Teleoperated Task Performance

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***Abstract*—During robot-assisted minimally invasive surgery, surgeons perform challenging dexterous tasks, including the manipulation of soft tissue and suture tying. In the absence of environment force sensing of tool-tissue interaction forces to provide force feedback, surgeons must rely on visual feedback to modulate the grip force they apply on the environment. Clinical systems, like the da Vinci Surgical System (Intuitive Surgical, Inc.), use physical springs to provide closing resistance on the gripper degree-of-freedom (DOF) of the master manipulator. This feedback provides increasing force resistance as the gripper is closed. To determine the effect of master manipulator gripper stiffness on performance in a teleoperated manipulation task, we designed a new and open source gripper, the OmniGrip. The OmniGrip attaches to a SensAble Phantom Omni (now available as Geomagic Touch), replacing the stylus end effector, and providing the ability for user programmable force characteristics. We conducted a study in which participants used an OmniGrip to teleoperate a Raven II surgical robotic system in a pick-and-place task. Increasing the stiffness of the OmniGrip resulted in reduced interaction forces at the slave-side environment. Additionally, these interaction forces were significantly lower when the OmniGrip as compared to when using the Phantom Omni stylus.**

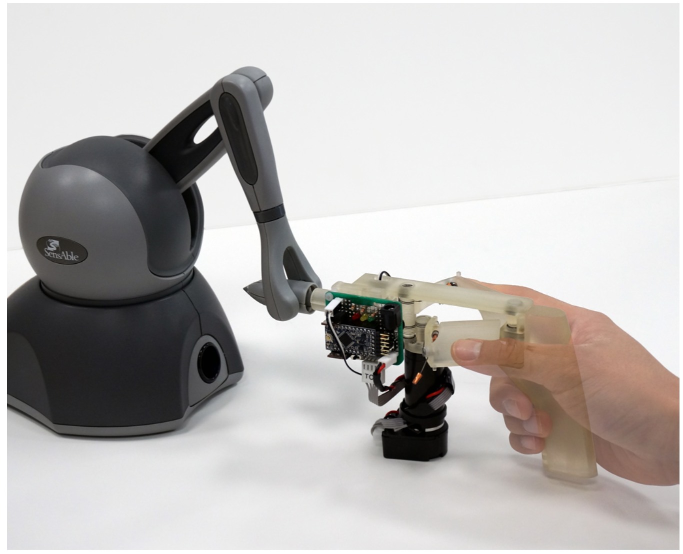

Fig. 1. SensAble Phantom Omni with OmniGrip attached. The OmniGrip turns the Phantom Omni into a 7-DOF device with a gripper interface.

I. Introduction

Robot-assisted minimally invasive surgery (RMIS) has many advantages over both open surgery and laparoscopic minimally invasive surgery, including smaller incisions, reduced pain, and shorter recovery time for the patient [1]. When using commercially available telesurgery systems like the da Vinci Surgical System (Intuitive Surgical, Inc.), surgeons interface with a master console that relays their commands to a patient-side (slave) robot. However, unlike open surgery, the surgeon cannot directly feel tool-tissue interaction forces, which could lead to excess in grip force and higher rates of tissue damage for the patient [2] and hand fatigue for the surgeon [3]. One option to partially recover the sense of touch for the surgeon is through force feedback, where patient-side forces are sensed by the robot and reflected back to the surgeon through the master manipulator. However, cost, size, biocompatibility, and sterilization issues make it difficult to incorporate force sensors on the patient-side robot. For these reasons, currently available teleoperated surgical robots have highly attenuated or no force feedback.

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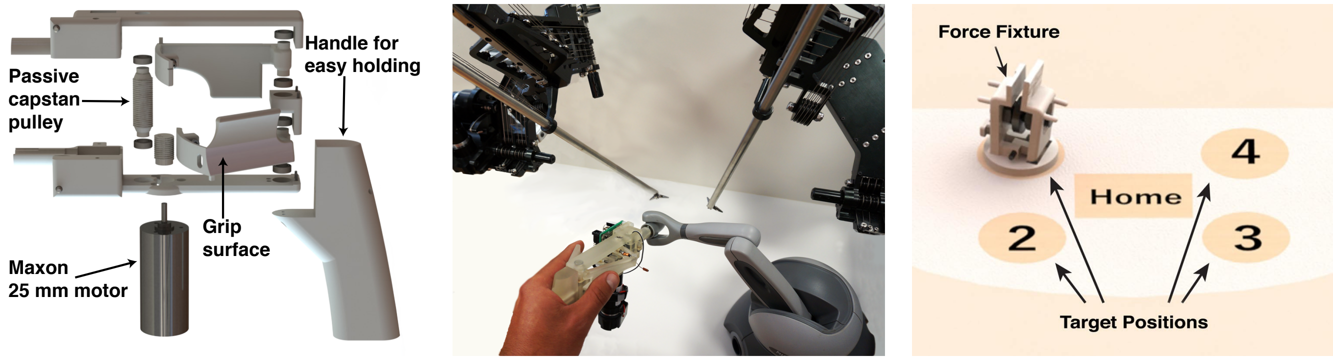
Because the master manipulator cannot reflect forces directly from the slave environment, surgical master manipulators frequently implement simple spring force feedback on the gripper DOF. In this implementation, springs are used to increase the grip force resistance as the master side gripper is closed. It has been shown in the past that gripper stiffness is related to user performance in teleoperated tasks that require grasping. Lambercy et al. used a 1-DOF gripper and showed that higher stiffness allowed participants to perform faster grasp movements but with less stability [4]. Christiansson et al. [5] used a 1-DOF gripper in a teleoperation setting and showed that higher grip stiffness increased the ability of participants to discriminate the shape of objects. However, not much attention has been paid to the effect of gripper stiffness on grip force modulation. We hypothesize that increasing gripper stiffness could decrease grip force in teleoperated tasks. This is particularly interesting in RMIS because finding an optimal gripper stiffness may allow surgeons to maneuver more dexterously and with higher grip force precision.

II. Background

Previous work has shown that humans have an internal model that defines the way they interact with an object during grasping [7] [8] [9]. This internal model is affected by the dynamic properties of the object being grasped. Upon grasping an object and understanding its dynamic properties, the user's internal model is updated to account for the object's behavior during manipulation [10] [11]. In the context of robot teleoperation, we expect the master manipulator's gripper stiffness



(a) (b) (c)

Fig. 2. (a) Exploded view of the OmniGrip showing key components. The passive capstan pulley reverses the direction of the motor torque allowing both gripping surfaces to be actuated in opposite directions. (b) The OmniGrip was attached to the distal link of a Phantom Omni and used to teleoperate the Raven II system [6]. (c) A render of the workspace for the teleoperated pick-and-place task. The fixture was moved between the numerical positions in the workspace and the participants returned to the home position between each motion.

to also influence grip force applied when grasping objects on the slave robot side.

We developed the OmniGrip, a hand-held 1-DOF gripper with variable gripper stiffness that attaches to a SensAble Phantom Omni (now available as Geomagic Touch). A few features of the device were drawn from the master manipulator of the most common commercial surgical robot, the da Vinci Surgical System [12]. But instead of using a fixed spring stiffness in the gripper, the OmniGrip is actuated with a DC motor to provide user programmable stiffness.

Various gripper devices have been designed to incorporate haptic feedback. Lambercy et al. [4] developed 1-DOF gripper device that enables the variation of grip forces displayed to the user. Rosen et al. [13] developed a similar device but for use in teleoperation. However, this device is not designed to augment higher-DOF haptic feedback, is restricted to grasping movements only and does not allow manipulation of objects on the slave-side workspace. Similarly, Verner and Okamura [14] developed a 1-DOF teleoperation gripper. While this device was designed to augment a Phantom Premium to create a 4-DOF system, it does not provide movement in orientation. Bleuler et al. [15] developed a similar device to the OmniGrip which interfaces with the Omega 3 by Force Dimension rather than the Phantom Omni.

In this study, we use the OmniGrip to investigate the effect of gripper stiffness on participants' ability to minimize grasping forces exerted by the slave robot gripper.

III. OmniGrip Design and Control

A. OmniGrip Design

The OmniGrip is an open source gripper designed to integrate with the distal link of a Geomagic Touch (hereafter referred to as the Phantom Omni). The OmniGrip provides precise operation of a 7^{th} DOF, extending the range of slave robots that the Phantom Omni can be used to control. The main OmniGrip components were 3D printed using the ProJet HD 3500 making it lightweight and easy to manufacture. The weight of the device, including the motor and encoder, is about 250 grams. The entire design of the device, including CAD files, materials list, and instructions for assembly can be found at http://charm.stanford.edu/Main/Resources.

The OmniGrip is designed to emulate the pinch grasp traditionally used in surgical robot manipulators. Important features of the OmniGrip are shown in Fig. 2(a). A handle was included on the OmniGrip in order to enable the user to easily counteract the torques generated by the weight of the device. Two lever arms form the grip surfaces and are constrained by pin joints on the same rotational axis. The lever arms are actuated by a Maxon RE-25 DC motor with an Avago 1024 counts-per-revolution encoder. The motor torque is transmitted through a double capstan mechanism that allows actuation of the lever arms in opposing directions while rotating the motor in a single direction. The motor is fixed to the OmniGrip frame and a capstan pulley is attached to the motor shaft. Capstan cabling is routed from one of the lever arms, around the active capstan pulley, around the second passive capstan pulley, and to the second lever arm.

An Arduino Pro Mini is mounted on the OmniGrip and is used to control the motor torque, determine the OmniGrip lever angle, and communicate this grip angle through the Phantom Omni. The OmniGrip has a 1/4" female stereo jack connector that attaches to the male stereo connector on the Phantom Omni's distal link. When the standard stylus end effector is attached to the Phantom Omni, the two buttons on the stylus can send signals to open or close a grasping DOF. To encode the grip angle information in an analog form, the OmniGrip uses a 16 Hz pulse-width modulated (PWM) signal transmitted through the Phantom Omni stereo connector. Custom code on the Phantom Omni side samples this signal at 1600 Hz and counts the samples that are high. In this way, a duty cycle is measured and mapped to a desired grip angle.

B. OmniGrip Control

The control of the OmniGrip was implemented using the attached Arduino Pro Mini. The force rendered by the OmniGrip controller has two distinct regions. In the first region, which starts with the OmniGrip fully open, the force output increases proportionally to K_{p1}. At an angle of 20°, defined by the angle between the two lever arms of the OmniGrip,

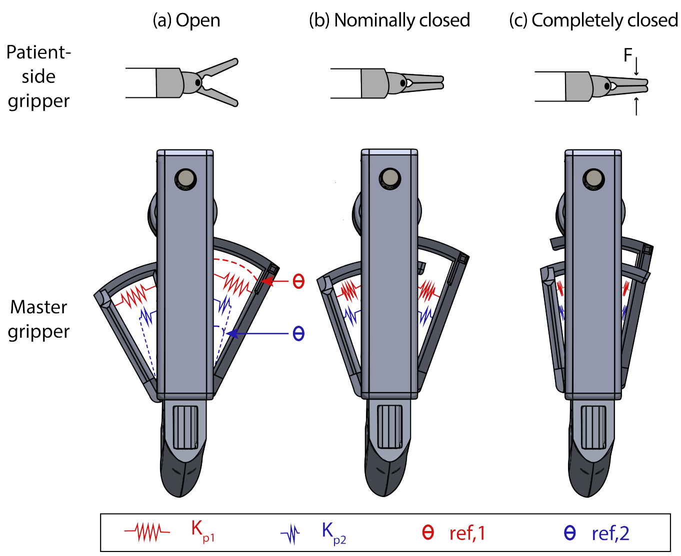


Fig. 3. Teleoperation mapping between the OmniGrip master manipulator and commanded slave-side gripper position. (a) OmniGrip fully open at 50° commands the slave-side gripper to fully open. (b) OmniGrip closed to 20° commands the slave-side gripper to fully close. (c) OmniGrip closed beyond 20° commands the slave to tighten its grip.

an additional stiffness of K_{p2} is included until the OmniGrip is fully closed. This angle was chosen based on the angle of transition between the two spring stiffness used in the design of the da Vinci Surgical System master manipulator grippers (30°) [16], and corrected to account for the limitations of the OmniGrip's motor. The force based on grip angle is calculated by

$$F_g = \begin{cases} K_{p1}(\theta_{ref,1} - \theta_g), & \theta_g < \theta_{ref,2} \\ K_{p1}(\theta_{ref,1} - \theta_g) + K_{p2}(\theta_{ref,2} + \theta_{offset} - \theta_g), & \theta_g \geq \theta_{ref,2} \end{cases} \tag{1}$$

where F_g is the commanded force to the motor and pushes the gripper levers open, θ_g is the grip angle, $\theta_{ref,1} = 50°$ is the fully opened grip angle, $\theta_{ref,2} = 20°$ is the angle at which the second spring stiffness is added, and θ_{offset} is a 2° pre-compression of the second spring stiffness designed to make the transition between the two stiffness regions more noticeable by the user. The OmniGrip motor is voltage controlled, and the force commanded assumes that the motor is in static equilibrium. Custom C/C++ code was used to interpret the signal sent by the Arduino Pro Mini on the OmniGrip. The code also determined the Cartesian position and orientation of the Phantom Omni. Data for analysis was recorded at 10 Hz.

C. Teleoperation Setup

The Phantom Omni with an attached OmniGrip served as the master manipulator for the Raven II open-source surgical robot. The mapping between OmniGrip closure and slave-side gripper closure is shown in Figure 3. Closing the OmniGrip from fully open to 20° corresponds to closing the slave-side gripper from fully open to fully closed. Closing the OmniGrip past 20° to fully closed commands the slave-side gripper to tighten its grip.

When using the stylus, participants used the two buttons on the stylus to command open and close of the slave-side gripper. As participants held a button, the master manipulator sent commands to the Raven II to increment or decrement the slave grippers in steps of 0.05° at the rate of 1600 Hz.

The position, orientation, and grip angle information of the master manipulator using either the OmniGrip or the stylus was communicated to the Raven II at a rate of 1600 Hz using a TCP/UDP protocol. The Raven II computer determined the inverse kinematics of the desired position and orientation. A Robotics Operating System (ROS) node performed 1000 Hz hard-real-time control of the joints.

IV. Experimental Methods

A. Experiment Description

A total of 8 participants participated in the experiment after giving informed consent, in a protocol that was approved by the Stanford University Institutional Review Board. All of the participants were self-reported right-hand dominant. The mean age was 26.1 with a standard deviation of 2.1 years. Of the 8 participants, 7 had prior experience with haptic devices.

Participants used a SensAble Phantom Omni with an attached OmniGrip or stylus to control a Raven II open source surgical robot in a teleoperated pick-and-place task as shown in Fig. 2(b). Throughout the experiments, participants had full visibility of the Raven II workspace as well as an adjacent computer screen that displayed graphical instructions to guide the user through the experiment protocol. Participants were asked to pick up a physical fixture and move it to successive positions in the workspace as shown in Fig. 2(c). This fixture contained an Entran ELFS series load cell that was used to determine the grip force during movement of the fixture. Participants started by hovering over the *Home* position with the Raven II grippers. Then, they pressed a button on the computer keyboard to indicate the start of a reaching motion. The participants then moved to pick up the fixture from position *1* to position *2*. After completing the reach, the participants returned to hovering over the *Home* position and pressed a button on the computer keyboard to indicate the start of the next reaching motion. The participants continued with this pattern, moving through the sequence of positions *1, 2, 3* and *4*. Movement of the fixture through the entire sequence consisted of one trial.

The described task was performed under four different conditions for the master manipulator. The order of presentation of these conditions was determined according to a Balanced Latin Squares experiment design in order to mitigate the effects of learning on the results. For one condition, participants teleoperated the Raven II using their stylus. In this condition, each button on the stylus incrementally closed or opened the

Condition	K_{p1} (mNm/rad)	K_{p2} (mNm/rad)
A	210	900
B	280	1200
C	350	1500

TABLE I. Stiffness parameters for the OmniGrip. A, B, and C conditions were tested to determine the effect of gripper stiffness on grasping force.

Raven II gripper. For the other three conditions, participants used the OmniGrip with different gripper stiffness values as shown in Table I. Each set had two parameters: K_{p1} (soft spring) and K_{p2} (stiff spring). Gain set B was chosen by empirically matching it to the stiffness of the da Vinci Surgical System master console. Stiffness conditions A and C were chosen to be 25% lower and higher than the reference B. This difference in gripper stiffness is greater than the 5-10% Just Noticeable Difference (JND) of grip stiffness determined by previous research [17].

Each participant performed two training trials under each of the four experiment conditions. Then, participants began the main experiment which consisted of 10 trials under each of the four feedback conditions. The entire experiment took approximately one hour to complete.

B. Data Analysis

For each evaluated metric, data appeared normally distributed and a Chi-Square goodness-of-fit test was used to ensure normality. There were two main objectives of our data analysis. Firstly, we wanted to determine the effect of varying the stiffness of the OmniGrip on grasping force and task completion time. Additionally, we wanted to show that using the OmniGrip improved performance when compared to using the stylus.

To assess the efficacy of using each of the four experimental conditions, we examined two main metrics:

- *Mean Grasping Force (N)*: Calculated for each trial by evaluating the mean grasping force throughout the trial. Forces were only considered during the grasping portions so as not to weight the result on the time in between grasping motions.
- *Completion time (s)*: Calculated as the time in seconds that elapsed between participants starting their first reach to *position 1* and ending after returning to the *home* position after moving the fixture through all positions in the environment.

In order to determine the effectiveness of the OmniGrip when compared with using the stylus with buttons of the Phantom Omni, we performed paired t-tests between each of the gripper stiffness conditions and the stylus condition for each of the performance metrics. The Bonferroni correction for multiple comparisons was used to control family-wise error.

We evaluated the effect of the OmniGrip stiffness on performance by performing one-way ANOVA with repeated measures on the data from the OmniGrip conditions, with each metric as the dependent variable, OmniGrip stiffness as a continuous fixed effect factor, and participants as a random effect factor. We used the Greenhouse-Geisser correction to account for any violations of sphericity. In addition, we calculated a regression between the metrics of interest and the normalized gripper stiffness and found a confidence interval bound on the slope to further show the correlation between OmniGrip stiffness and the metrics.

All statistical tests were performed at the 0.05 level of significance.

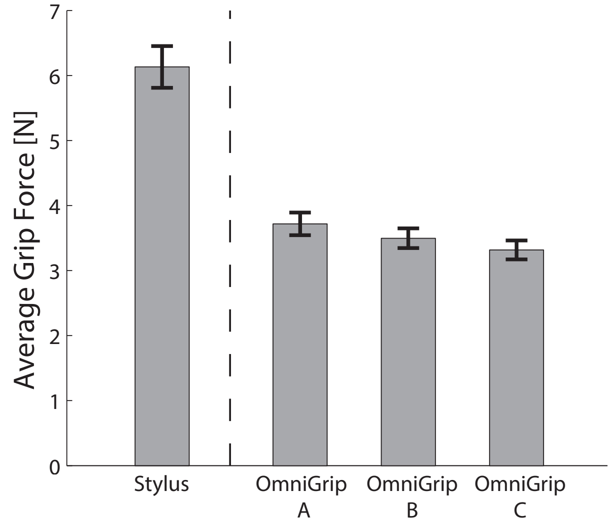


Fig. 4. Average force applied to the fixture on the slave-side measured from the force sensor inside the fixture. Error bars indicate 95% confidence intervals. Force sensor data obtained in conditions OmniGrip A, B and C were compared with a linear regression and showed that increasing OmniGrip stiffness decreased the average slave-side grip force. Additionally, paired t-tests with Bonferroni correction for slave-side grip force between stylus and each of the OmniGrip conditions showed that participants exerted significantly more grip force in the slave-side environment when using the stylus as compared to the OmniGrip in all stiffness conditions (A, B and C).

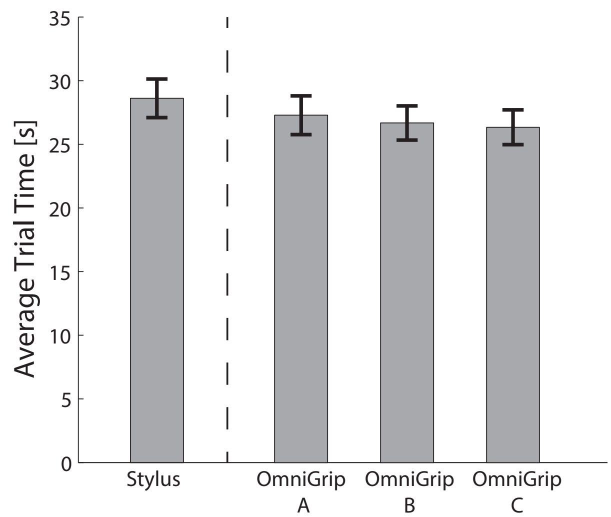


Fig. 5. Average completion time for each trial was evaluated by determining the mean completion time of all trials for each experiment condition. Error bars indicate 95% confidence intervals. There was no significant effect of the OmniGrip stiffness on the trial completion time as determined by a one-way ANOVA. Paired t-tests with Bonferroni correction for trial completion time between the stylus and each stiffness condition, revealed that the OmniGrip with stiffness B and C enabled participants to complete experiment trials significantly faster than when using the stylus.

V. EXPERIMENTAL RESULTS

The average slave-side grip force applied to the fixture during grasping is shown in Fig. 4. A one-way ANOVA with repeated measures on all four conditions showed a significant effect of experiment condition on measured grip force after the Greenhouse-Geisser correction for violation of sphericity

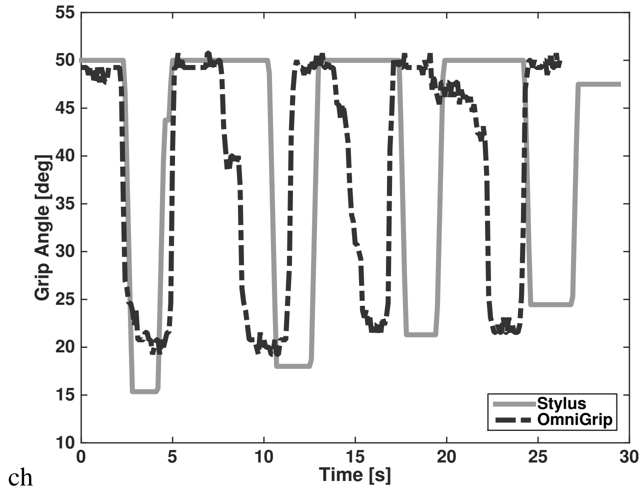


Fig. 6. Grip angles for a typical participant over the course of a trial using the stylus and OmniGrip. While the participants grasp in a similar manner during each reach using the OmniGrip, the commanded grip angle using the Omni stylus has much larger variance and a smaller ending grip angle.

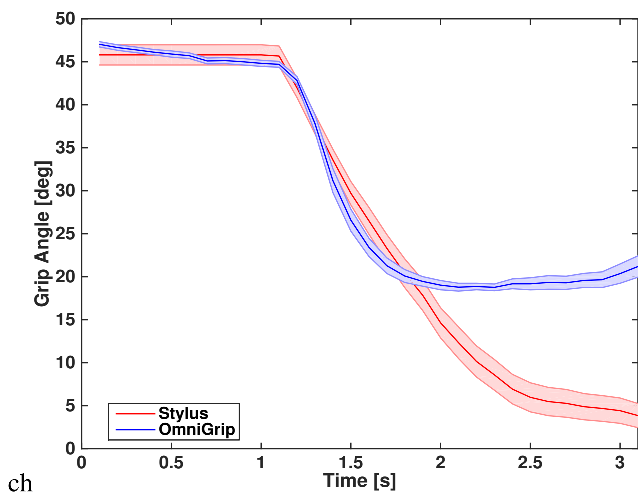


Fig. 7. Representative grasping profile for a typical participant using the stylus and the OmniGrip. Line and shading represents average grip angle and 95% confidence intervals respectively, based on the rising edge of 40 grasp motions. Grasps using the stylus (red) and the OmniGrip (blue) are overlaid on the same plot. Both curves have similar slopes, indicating that participants' grasping profiles are comparable between both the OmniGrip and stylus.

(p=0.004). We then calculated a linear regression between the three OmniGrip stiffness and average slave-side grip force. The confidence interval of the slope was [-1.248, -0.354], indicating a decrease in average slave-side grip force with increasing OmniGrip stiffness. In addition, we compared the effect of using the OmniGrip and using the stylus. Paired t-tests for grip force were performed between the stylus and each OmniGrip stiffness using the Bonferroni correction for multiple comparisons. The results are summarized in Table II and indicate that for all OmniGrip conditions participants applied less force at the slave gripper than when using the stylus.

Average trial completion time is shown in Fig. 5. A one-way ANOVA with repeated measures did not show a significant effect of OmniGrip stiffness on trial completion time. Paired t-tests for trial completion time applied between the stylus and each OmniGrip stiffness with a Bonferroni correction revealed that the OmniGrip with stiffnesses B and stiffness C allowed participants to complete experiment trials significantly faster than when using the stylus.

Sample commanded OmniGrip angles for a representative participant over the course of a trial are shown in Fig. 6. The dips in closure angle correspond with closing the slave-side gripper on the environment fixture at each of the four positions in the environment. A one-way ANOVA with repeated measures comparing minimum commanded grip angle of each of the OmniGrip stiffness and stylus revealed a statistically significant difference between groups. A multiple comparison test showed that minimum commanded grip angle was significantly higher when using the OmniGrip compared to when using the stylus. The OmniGrip's mean minimum commanded grip angle was approximately the same for all stiffness conditions (16.7 $\pm$ 3.5 degrees). In the stylus condition, mean minimum commanded grip angle was lower (4.6 $\pm$ 5.8 degrees), indicating that participants closed the gripper further and with greater variance when using the stylus than when using the OmniGrip. A detailed depiction of the commanded grip angle angle over the time of a single grasping motion is shown in Fig. 7.

VI. DISCUSSION

When manually interacting with an environment through direct interaction, we are naturally aware of the forces we apply on the environment. However, in teleoperation, this feedback is not present and the user must rely on visual sensory information to modulate force. In our experiment, participants were told that the primary objective of the task was to minimize the grip force applied to the fixture on the slave side, but they did not receive direct force feedback based on environment forces. Rather, the OmniGrip rendered a linear spring force with two regions - starting off at a lower stiffness and continuing to a greater stiffness once the gripper was partially closed.

The mean minimum commanded grip angle when grasping was approximately the same among all stiffness conditions. Thus, participants exerted higher grip force on the OmniGrip when the stiffness was higher. We also determined that with higher OmniGrip stiffness, participants applied less force when grasping the fixture on the slave side.

A possible explanation for the decrease in slave-side grip force is that higher grip force interaction with the OmniGrip increases frictional forces between the user's fingers and the surface of the OmniGrip. The increase in friction could change the user's internal model for grip force control and provide a

Comparison	Force		Time	
	t_{79}	p	t_{79}	p
Stylus, Stiffness A	12.821	**< 0.001**	2.004	0.146
Stylus, Stiffness B	16.015	**< 0.001**	2.455	**0.049**
Stylus, Stiffness C	15.106	**< 0.001**	3.239	**0.005**

TABLE II. Paired t-tests results for average grasping force and trial completion time using the Bonferroni correction for multiple comparisons. Bold results indicate significance at the 0.05 level.

more precise modulation of grip force. This would be consistent with the findings by Cole and Johansson [10]. This relationship between master-side gripper stiffness and slave-side grip force could serve as general design guidelines for setting the master-side gripper stiffness in future teleoperated setups. However, it must also be considered that increasing gripper stiffness could result in increased participant fatigue. While increasing gripper stiffness lowered slave-side grip force, it would be interesting to determine the effect of changing the angle at which the increase in stiffness for each condition occurred.

While the OmniGrip did not render true environment force feedback, it successfully reduced the slave-side grasping force of participants when compared with using the stylus buttons, regardless of the stiffness conditions used. Most participants held the fixture at the slave-side by maintaining a grip angle of about 20° on the OmniGrip, which corresponds to commanding a nominally closed grip at the slave side. This is also the angle at which the OmniGrip stiffness transitions between the softer spring and the stiffer spring. This cue was not present in the stylus condition, and is likely the cause for the increased variability in the grip angle maintained during fixture grasping using the stylus. The reduced force on the slave side and reduced variability in grip angle when using the OmniGrip could be also attributed to the similarities in gripper movement of the OmniGrip and the slave-side gripper. In contrast to using the stylus, participants using the OmniGrip could find it more convenient to interface with the teleoperation setup from a proprioceptive point of view and, thus, perform better in terms of slave-side grip force modulation.

VII. CONCLUSIONS AND FUTURE WORK

The OmniGrip, an affordable open source gripper, was designed and implemented with a Phantom Omni to control the Raven II surgical robot. Human participant experiments demonstrated that increasing the stiffness of the OmniGrip resulted in decreased slave-side grip force. Moreover, results showed that the OmniGrip helped participants apply less slave-side grip force performing a teleoperated pick-and-place task when compared to the stylus.

This work not only introduces a new piece of hardware available open source to the research community, but also provides some design guidance on the implementation of future master manipulator grippers. By changing the force-angle relationships of master manipulator grippers, it may be possible to alter the way that users interact with teleoperated systems. The open source availability of the OmniGrip also allows the research community the freedom to optimize the design of the device. One problem that needs to be addressed is to move the center of gravity of the OmniGrip closer to the center of the user's hand, since the weight of the device is currently centered at the position of the motor.

Future work is needed to determine whether the trends observed in this experiment extend to wider stiffness ranges, including a zero stiffness condition. This would require adding finger straps in the OmniGrip design to be able to open the levers. Additionally, we would like to test whether changing the angle at which the OmniGrip switches between the stiffer and softer stiffness has an effect on the way that users interact with the slave-side environment. We would also like to investigate the possibility of updating the OmniGrip stiffness depending on the environment the slave-side robot is interacting with.

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