# Effect of load force feedback on grip force control during teleoperation: A preliminary study

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# Effect of Load Force Feedback on Grip Force Control During Teleoperation: A Preliminary Study

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**ABSTRACT**

During robot-assisted minimally invasive surgery, teleoperation systems allow surgeons to perform operations at a distance via instruments inserted through small incisions in the body, thereby minimizing patient pain and recovery time. While the patient-side manipulator allows precise, dexterous gripping and manipulation by the surgical tools, current clinical systems provide the surgeon with limited haptic feedback about tool-environment interactions. This differs from direct grasp and manipulation of hand-held objects, during which we receive feedback that provides cues regarding object surface properties, slip, and load force. We use a custom research version of the da Vinci Surgical System to study the control of grip force during teleoperated manipulation of an elastic environment. We tested a placement task that involved stretching of a rubber band, with and without feedback of the patient-side load forces to the user. We hypothesized that there is greater coupling between the applied grip force and the patient-side load force when force feedback is provided, as is observed during direct manipulation of hand-held objects. With an experienced surgeon user, coupling between the applied grip force and the load force was greater with force feedback than without.

**Index Terms:** L.1.0 [Haptics]: Human Haptics—Touch-based Properties and Capabilities of the Human User; L.2.0.r [Haptics]: Haptics Technology—Telemanipulation

## 1 INTRODUCTION

### 1.1 Motivation

Teleoperation systems, in which a user manipulates a master device that controls a slave robot, facilitate interaction with remote environments that are hazardous or difficult to access. Because teleoperation systems separate the user from the environment, the somatosensory feedback typically present during direct manipulation is now limited. One widespread application of teleoperation is robot-assisted minimally invasive surgery (RMIS), which allows surgeons to perform procedures via robotic instruments inserted through small incisions in the body. The da Vinci Surgical System (Intuitive Surgical, Inc.) is an example of a teleoperation system in which a surgeon grasps the master controllers with a precision grip, usually with the thumb and either the index or middle finger, and the surgeon's hand movements are used to command motion of the patient-side robot (Fig. 1A). The patient-side robot allows for highly dexterous, precisely controlled manipulation of tissue. Despite these benefits, the surgeon receives limited feedback about pressure, stiffness, slip, and texture during tool-tissue interaction. Tactile feedback is inaccurate, as the surgeon grasps the master controller rather than objects within the remote environment. Force feedback is essentially absent from RMIS systems, as

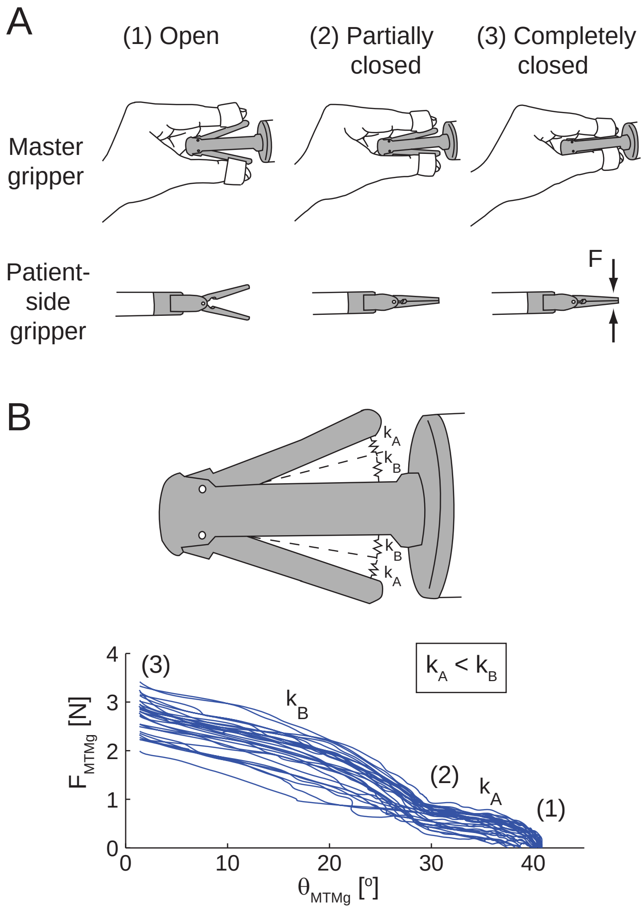


Figure 1: Custom mapping between the master tool manipulator (MTM) and patient-side manipulator (PSM) grippers. (A) Initial closure of the MTM gripper, which compresses a physical spring (stiffness $k_A$), controls PSM gripper movement (1). Partial closure of the MTM gripper to the interface of the two springs ($k_A < k_B$) commands complete closure of the PSM gripper (2). Additional closing of the MTM gripper commands a negative desired angle to the PSM gripper, enabling higher grip force to be applied at the patient-side (3). (B) The measured MTM gripper angle $\theta_{MTMg}$ and force applied to the MTM gripper $F_{MTMg}$ were used to estimate the two spring stiffnesses.

the integration of force sensors on surgical instruments is restricted by cost, size limitations, sterilization, and bio-compatibility; estimating environment interaction forces is also challenging due to the substantial dynamics of the patient-side robot.

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The lack of haptic feedback in RMIS systems causes surgeons to rely heavily on visual feedback when grasping tissues and sutures. Excess grip force can be detrimental, resulting in tissue damage for the patient [2] and hand fatigue for the surgeon [14]. Insufficient grip force, on the other hand, can cause the object to slip. This has been shown during laparoscopic grasping, in which surgeons received distorted haptic feedback of tissue-tool interactions [16]. Thus, it is important to understand how users control grip force when manipulating objects via a teleoperation system.

### 1.2 Previous Work

Previous work on grip force control has focused on direct manipulation of hand-held objects. People have been shown to alter their grip force, effectively adjusting the friction force between their skin and the object, to prevent the object from slipping from their fingers. When grasping an object, a person's applied grip force (normal to the object's surface) is typically tightly coupled with the load force acting at the hand (tangent to the object's surface) [6].

Sensory feedback is crucial in the precise control of grip force during direct object interaction. During initial object contact, vision allows for anticipatory grip force control based on visual estimation of object properties, such as weight [5]. Somatosensory feedback, which provides information about object surface properties, slip, and load force, becomes more important than visual feedback upon object contact. Previous studies have demonstrated that feedback from mechanoreceptors in the fingertips is crucial in grip force control [6], [8], [12], while the role of proprioceptive muscle and joint receptors is not as clear [9], [11].

Several studies have also explored grip force control during indirect object manipulation with teleoperation systems. Since somatosensory feedback to the operator is usually limited, researchers have explored ways to provide haptic feedback. Verner and Okamura [17] had subjects perform a peg-in-hole task with a 4-degree-of-freedom (DOF) teleoperator (three translational plus grip), providing either full force feedback, translational force feedback only, grip force feedback only, or no force feedback. Subjects decreased their applied grip force when they received grip force feedback from the slave side, but their grip was not significantly affected by translational force feedback. Other studies have focused on the effect of tactile feedback, rather than force feedback, on grip force control [7], [10], [13], [15]. King et al. [7] mounted a balloon tactile display on the da Vinci master gripper to relay grip force at the slave manipulator back to the user. This feedback allowed subjects to reduce their grip force during a peg transfer task. These studies suggest that grip force control of the user is affected more by feedback of grip force rather than translational forces. In the peg transfer tasks of the previously mentioned studies, the load force while moving the peg (due to the its low inertia) was likely small. During object manipulations that cause greater load force, such as pulling on tissue or tightening a suture, translational force feedback may have a larger effect on grip force control.

### 1.3 Research Question

We examine the relationship between load and grip force during a teleoperated task with a custom da Vinci, both with and without feedback of load force. We hypothesized that there is greater coupling between the grip force and load force when feedback of the load is provided. In a preliminary experiment with an experienced surgeon da Vinci user, we found that modulation of the applied force varied more with the load force when force feedback was present, compared to when force feedback was absent.

## 2 Custom Research Version of the da Vinci Surgical System

The teleoperation system consists of a custom research version of the da Vinci Surgical System, which uses first-generation da Vinci hardware and our own control system. We used the da Vinci Research Kit, developed by researchers at Johns Hopkins University, Worcester Polytechnic Institute, and Intuitive Surgical. A detailed description of the electronics, firmware, and software is provided in [1]. The master tool manipulator (MTM) has 8 DOFs (with redundancy), enabling 3-DOF translation, 3-DOF rotation, and grip. While only the first seven joints are actuated (grip is not), every joint position is measured. The patient-side manipulator (PSM) is a 7-DOF manipulator with actuation at every joint. The update rate was about 750 Hz. Only the right-hand MTM and PSM were used.

### 2.1 Custom Teleoperation Controller

The movement of the MTM, as driven by the human operator while grasping the MTM gripper, is tracked and used to compute control commands to the PSM. All mappings between the MTM and PSM were of our own design, and are not what is used in a clinical da Vinci system. However, we did attempt to emulate the behavior based on observation of the clinical system.

The Cartesian position of the PSM was controlled by:

$$F_i = K_p(0.4p_{\text{MTM}i} - p_{\text{PSM}i}) - K_d\dot{p}_{\text{PSM}i} \tag{1}$$

where $F$ is the commanded force, $p_{\text{MTM}}$ is the position of the MTM wrist, and $p_{\text{PSM}}$ is the position of the PSM wrist in the $i$ = $x$, $y$, $z$ directions. The control gains were set to $K_p$ = 750 N/m, $K_{d_{x,y}}$ = 700 Ns/m, and $K_{d_z}$ = 400 Ns/m. The scaling between master and patient-side movement was 0.4. The orientation of the PSM wrist was controlled by:

$$\tau_i = K_p(\theta_{\text{MTM}i} - \theta_{\text{PSM}i}) - K_d\dot{\theta}_{\text{PSM}i} \tag{2}$$

where $\tau$ is the commanded torque, $\theta_{\text{MTM}}$ is the angle of the MTM wrist, and $\theta_{\text{PSM}}$ is the angle of the PSM wrist for $i$ = roll, pitch, and yaw. The control gains were set to $K_p$ = 1 Nm/rad and $K_d$ = 0.1 Nms/rad for smooth tracking and stability.

### 2.2 Controller Design of Gripper

The MTM gripper contains two physical springs of different stiffnesses (Fig. 1). Partial closure of the MTM gripper, from approximately 40° to 30°, compresses the weaker spring (approximately 9.4 N-mm/rad). When the weaker spring of the MTM gripper is fully compressed, the PSM gripper (Cadiere forceps) is commanded to be completely closed (Fig. 1). Subsequent closing of the MTM gripper, from 30° to 0°, compresses the stiffer spring (approximately 37 N-mm/rad). When the MTM gripper is within this region, we commanded a negative angle to the PSM gripper:

$$\tau_g = K_p(\alpha(\theta_{\text{MTM}g} - \Theta_{\text{MTM},\delta k}) - \theta_{\text{PSM}g}) - K_d\dot{\theta}_{\text{PSM}g} \tag{3}$$

$$\alpha = \begin{cases} \frac{\Theta_{\text{PSM,max}}}{\Theta_{\text{MTM,max}} - \Theta_{\text{MTM},\delta k}}, & \theta_{\text{MTM}g} > \Theta_{\text{MTM},\delta k} \\ -\frac{\Theta_{\text{PSM,min}}}{\Theta_{\text{MTM,max}}}, & \theta_{\text{MTMg}} \leq \Theta_{\text{MTM},\delta k} \end{cases} \tag{4}$$

where $\tau_g$ is the commanded torque to the PSM gripper, $\theta_{\text{MTM}g}$ is the angle of the MTM gripper, and $\theta_{\text{PSM}g}$ is the angle of the PSM gripper. $\Theta_{\text{MTM,max}} = 40°$ is the maximum angle of the MTM gripper, $\Theta_{\text{MTM},\delta k} = 30°$ is the MTM gripper angle at the interface between the two springs, $\Theta_{\text{PSM,max}} = 30°$ is the maximum angle of the PSM gripper, and $\Theta_{\text{PSM,min}} = -10°$ is the negative angle commanded to the PSM gripper when the MTM is fully closed. The control gains were set to $K_p$ = 0.95 Nm/rad and $K_d$ = 0.05 Nm-s/rad. This mapping allowed the user to command the PSM gripper to apply varying amounts of grip force to the grasped object. The values of $K_p$, $K_d$, and $\Theta_{\text{PSM,min}}$ were chosen to allow successful gripping under different load conditions, while maintaining stability.

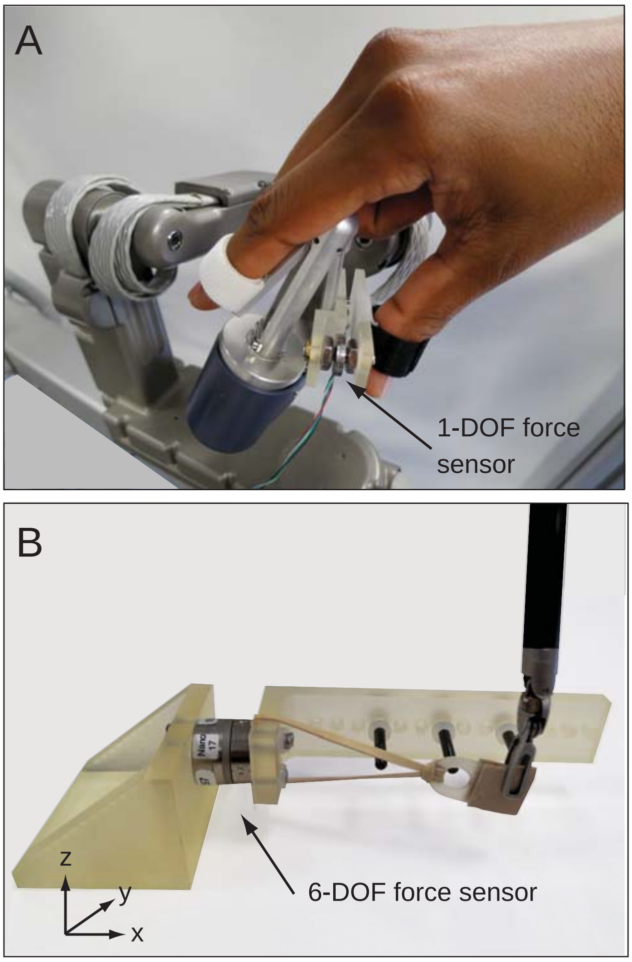


Figure 2: (A) MTM gripper equipped with a 1-DOF force sensor to measure the user's grip force. (B) As the PSM interacts with the patient-side environment, a 6-DOF force sensor measures the elastic load, which can be used to provide force feedback to the user.

### 2.3 Force Measurements and Feedback

A 1-DOF ELFS-T3 force sensor (Entran Devices) was mounted on the MTM gripper to measure the user's grip force (Fig. 2A). Our custom da Vinci can be operated with and without force feedback. The PSM interacted with a custom-built environment, further explained in Section 3.1, that was mounted to a Nano17 six-axis force/torque transducer (ATI Industrial Automation). Bilateral position forward/force feedback control was used, based on the forces measured from this transducer, to provide feedback of the PSM-environment forces to the user:

$$F_{\mathrm{FB}_i} = -F_{\mathrm{meas}_i} \quad (5)$$

where $F_{\mathrm{FB}}$ is the force fed back to the user and $F_{\mathrm{meas}}$ is the force measured at the slave side for the $i = x, y, z$ directions. The torque measured by the Nano17 was not used to provide feedback, nor was any torque feedback provided to the user. A unilateral position forward controller (Eq. 1, 2, and 3) was used when there was no force feedback. Regardless of whether force feedback was rendered, gravity compensation was included on the master side.

## 3 Effects of Load Force on Grip

### 3.1 Manipulation Task

The patient-side environment consisted of a series of pegs, separated by 6 mm, mounted on a 3D-printed platform that was fastened to the Nano17 (Fig. 2B). A rubber band attached to one end of the platform acted as an elastic actuator, providing a varying load force when stretched. A small tab with a circular cutout was attached to the end of the rubber band to provide the PSM with a surface to grip and maneuver. With this design, the Nano17 measured forces exerted by the PSM on the environment during manipulation of the rubber band. The teleoperation task was to grasp the tab and dock it at various pegs. The forces of the rubber band ranged from 0-4 N. The load forces used in this experiment are within the range of pulling forces measured during laparoscopic surgery [3].

An expert surgeon, with seven years of experience and over 100 cases using a clinical da Vinci system, performed the manipulation task. The protocol was approved by the Stanford University Institutional Review Board, and the surgeon signed a consent form prior to participating. The surgeon was instructed to grasp the tab and move it in a continuous motion to the designated peg. He was told to use the da Vinci gripper as he would during an operation. There was an initial practice period during which he became familiar with the task. The recorded experiment consisted of five movements to six different pegs. The experimenter manually moved the tab back to the starting position between trials. The task was first performed without force feedback (NoFF), similar to normal system operation, then with force feedback (FF). Since the surgeon was experienced in using the da Vinci without force feedback, it was assumed that any effects of this prior experience would overshadow potential short-term order effects of the two conditions; thus, we chose to perform the NoFF trials first. The surgeon operated the MTM while directly watching the PSM move in the patient-side environment. The surgeon confirmed that the addition of the force sensor on the MTM gripper did not impede normal usage of the manipulator.

### 3.2 Data Analysis

The recorded da Vinci variables of interest were position, velocity, and grip angle of the MTM and PSM, and commanded torque to the motors that control the PSM gripper. Force data from the Nano17 and the 1-DOF transducer were also stored. Data were recorded at 1 kHz and smoothed using a fifth-order, zero phase lag, low-pass Butterworth filter with a cutoff frequency of 10 Hz. We focused our analysis on the portion of the task during which the user pulled the rubber band towards the desired peg (Fig. 3). The starting point was determined when the measured load force exceeded a threshold of 0.15 N. The ending point was determined when the PSM velocity was below a threshold of 0.15 mm/s. Subsequent manipulation involving transfer of the tab to the peg is not included in the current analysis.

Although PSM grip force was not measured, other variables can be used as a proxy. Since the grasped object had a deformable surface, the PSM gripper angle provided quantitative information about the applied force (i.e., smaller grip angle corresponds to firmer grasp). We examined coupling between the patient-side load force and the following signals: (1) applied grip force to the MTM gripper, (2) MTM gripper angle, and (3) PSM gripper angle. In future studies, we would like to measure the grip force of the PSM gripper and the load force on the user from the MTM. This would allow a direct comparison of the grip and load force at the master side (and slave side).

### 3.3 Results

Control of the gripper differed for the FF and NoFF conditions, as reflected by both MTM and PSM variables. Figure 4A (1st and 2nd columns) shows how the angle of the MTM gripper $\theta_{\mathrm{MTM}g}$ varied

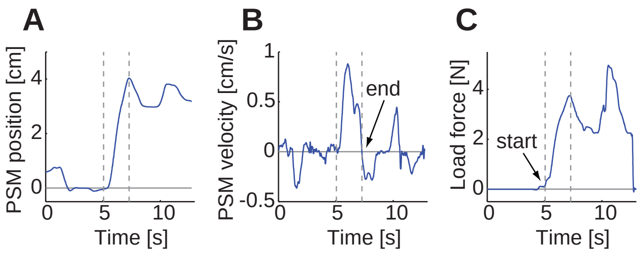


Figure 3: (A) PSM position, (B) PSM velocity, and (C) load force in the x-direction during one movement. The start and end of the time range of interest (while the user pulls the rubber band towards the desired peg) is determined by load force and velocity threshold values, respectively.

with load force, for each movement. All 30 trials in each condition were successfully completed, i.e., the tab never slipped from the PSM gripper. Because the majority of the movement analyzed occurred in the x-direction, the load force was taken as the force measured along this axis. For the FF condition, the MTM gripper was typically at an angle less than $0.25°$, essentially closed. For the NoFF condition, the MTM gripper was also sufficiently compressed, but had a slightly larger range, from $1.25°$ to fully closed. Figure 4A (3rd column) shows the mean value of $\theta_{\mathrm{MTM}g}$ over increments of 1 N load force for each movement, averaged across trials. For both conditions, $\theta_{\mathrm{MTM}g}$ remained fairly constant, regardless of the load forces experienced. At the point of maximum load force (typically at the end of the movement), a near-zero value of $\theta_{\mathrm{MTM}g}$ indicates that the MTM gripper was completely compressed (Fig. 4A, 4th column). This behavior was observed regardless of the distance of the peg for the FF condition, and occurred more often for farther pegs in the NoFF condition. The small offset from zero is explained by error in the position calibration of the MTM gripper angle.

For the FF condition, we observe a slight coupling of the grip force applied by the surgeon and the load force (Fig. 4B), particularly with higher load forces. This is reminiscent of the behavior observed during direct manipulation of handheld objects. However, this coupling in the FF condition also caused a higher grip force to be used, compared to the NoFF condition; in the NoFF condition, grip force remained around 6 N (Fig. 4B, 3rd column).

Similar to $\theta_{\mathrm{MTM}g}$, the angle of the PSM gripper $\theta_{\mathrm{PSM}g}$ was slightly smaller for the FF than the NoFF condition (Fig. 4C). This implies that the PSM gripper was more tightly closed for the FF condition, applying a firmer grip to the tab.

## 4 Discussion

Our preliminary results suggest that a user will control the teleoperated gripper differently depending on whether force feedback is present. The surgeon user tended to apply more grip force during the FF condition; perhaps the addition of grip force feedback (in addition to load force feedback) can help users reduce their grip force. Our findings complement those of a previous study that examined changes in grip force during object lifts with laparoscopic graspers [16], a different type of indirect object manipulation. Use of a laparoscopic tool resulted in increased grip force and abnormal modulation of the grip force with respect to the load force, as compared to direct lifts with a hand-held object.

The difference in the magnitude of grip force between the NoFF and FF conditions may be explained by the fact that people naturally grip an object harder when there are greater load forces [4]. In the FF condition, when the load force was applied to the surgeon's hand, the surgeon may have used a firmer grasp to prevent the MTM gripper from slipping from his fingers. However, the finger straps on the MTM would most likely prevent the gripper from actually slipping from the user's fingers (Fig. 2A). On the other hand, when the load force was not present in the NoFF condition, less grip force was necessary to prevent the feeling of slip of the MTM gripper. Additionally, under normal operation (akin to the NoFF condition), surgeons are trained to grasp the MTM gripper as gently as necessary to accomplish the task, in order to reduce fatigue.

Interestingly, a previous study from our group showed that users applied higher grip force in the NoFF condition when using a different haptic device to interact with an object in a virtual environment. In [4], subjects grasped a rigid force transducer, rather than a spring-loaded gripper. In a way, subjects received direct grip force feedback as they grasped the force transducer, which measured their applied grip force that was then used to control the virtual object interaction. In our current study, the grip force applied by the surgeon to the MTM gripper differed from the grip force applied by the PSM gripper to the grasped remote object. These distinctions in the physical setups may account for the differences in results.

Our results motivate future studies on the effect of force feedback, training, and accuracy demands on grip force control with novice users and expert da Vinci surgeons. Since the surgeon did not have experience with force feedback on the da Vinci, as clinical systems do not offer such feedback, grip force control with load force feedback may change with additional practice. Particularly for novices, altering the accuracy demands required to place the tab on the peg may elicit a change in applied grip force. In future experiments, a stereo vision system will also be used to provide visual feedback via the surgeon's console, creating a more realistic setting.

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## References

[1] Z. Chen, A. Deguet, R. H. Taylor, S. DiMaio, G. S. Fischer, and P. Kazanzides. An open-source hardware and software platform for telesurgical robotics research. In *MICCAI Workshop on Systems and Arch. for Computer Assisted Interventions*, 2013.

[2] S. De, J. Rosen, A. Dagan, B. Hannaford, P. Swanson, and M. Sinanan. Assessment of tissue damage due to mechanical stresses. *International Journal of Robotics Research*, 26:1159–1171, 2007.

[3] H. de Visser, E. A. M. Heijnsdijk, J. L. Herder, and P. V. Pistecky. Forces and displacements in colon surgery. *Surgical Endoscopy*, 16:1426–1430, 2002.

[4] T. L. Gibo, A. J. Bastian, and A. M. Okamura. Grip force control during virtual object interaction: effect of force feedback, accuracy demands, and training. *IEEE Transactions on Haptics*, 2013. ePub ahead of print. DOI: 10.1109/TOH.2013.60.

[5] A. M. Gordon, H. Forssberg, R. S. Johansson, and G. Westling. Integration of sensory information during the programming of precision grip: comments on the contributions of size cues. *Experimental Brain Research*, 85:226–229, 1991.

[6] R. S. Johansson and G. Westling. Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects. *Experimental Brain Research*, 56:550–564, 1984.

[7] C. H. King, M. O. Culjat, M. L. Franco, C. E. Lewis, E. P. Dutson, W. S. Grundfest, and J. W. Bisley. Tactile feedback induces reduced grasping force in robot-assisted surgery. *IEEE Transactions on Haptics*, 2(2):103–110, 2009.

[8] V. G. Macefield, C. Hager-Ross, and R. S. Johansson. Control of grip force during restraing of an object held between finger and thumb:

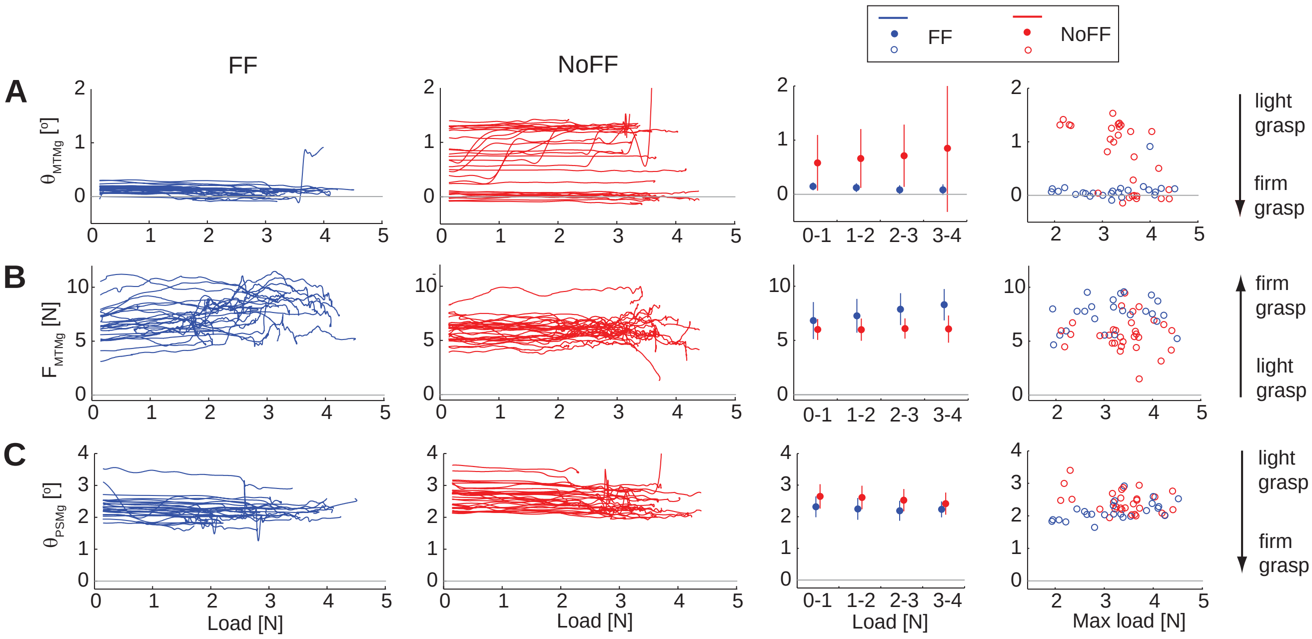


Figure 4: Variation in grip variables with load force. (A) Angular position of MTM gripper $\theta_{\mathrm{MTM}g}$ with patient-side load force for each of the 30 FF (1st column) and NoFF (2nd column) movements. Force was averaged over increments of 1 N load force for each movement (0-1 N, 1-2 N, 2-3 N, 3-4 N), then averaged across FF or NoFF trials (3rd column). Mean $\pm$ SD values are shown at the midway point of each force increment. The value of $\theta_{\mathrm{MTM}g}$ at maximum load force is shown in the 4th column. Data is similarly displayed for (B) force applied to the MTM gripper by the user $F_{\mathrm{MTM}g}$ and (C) angular position of PSM gripper $\theta_{\mathrm{PSM}g}$.

response of cutaneous afferents from the digits. *Experimental Brain Research*, 108:155–171, 1996.

[9] V. G. Macefield and R. S. Johansson. Control of grip force during restraing of an object held between finger and thumb: response of muscle and joint afferents from the digits. *Experimental Brain Research*, 108:172–184, 1996.

[10] K. Minamizawa, H. Kajimoto, N. Kawakami, and S. Tachi. A wearable haptic display to present the gravity sensation - preliminary observations and device design. In *World Haptics*, pages 133–138, 2007.

[11] D. A. Nowak, S. Glasauer, and J. Hermsdorfer. How predictive is grip force control in the complete absence of somatosensory feedback? *Brain*, 127:182–192, 2004.

[12] D. A. Nowak, J. Hermsdorfer, S. Glasauer, J. Philipp, L. Meyer, and N. Mai. The effects of digital anaesthesia on predictive grip force adjustments during vertical movements of a grasped object. *European Journal of Neuroscience*, 14:756–762, 2001.

[13] C. Pacchierotti, F. Chinello, M. Malvezzi, L. Meli, and D. Prattichizzo. Two finger grasping simulation with cutaneous and kinesthetic force feedback. In *Haptics: Perception, Devices, Mobility, and Communication*, pages 373–382, 2012.

[14] L. Santos-Carreras, M. Hagen, R. Gassert, and H. Bleuler. Survey on surgical instrument handle design: ergonomics and acceptance. *Surgical Innovation*, 19(1):50–59, 2012.

[15] E. P. W. van der Putten, J. J. van den Dobbelsteen, R. H. M. Goossens, J. J. Jakimowicz, and J. Dankelman. The effect of augented feedback on grasp force in laparoscopic grasp control. *IEEE Transactions on Haptics*, 3(4):280–291, 2010.

[16] E. P. W. van der Putten, J. J. van der Dobbelsteen, R. H. M. Goossens, J. J. Jakimowicz, and J. Dankelman. Force feedback requirements for efficient laparoscopic grasp control. *Ergonomics*, 52(9):1055–1066, 2009.

[17] L. N. Verner and A. M. Okamura. Effects of translational and gripping force feedback are decoupled in a 4-degree-of-freedom telemanipulator. In *World Haptics*, pages 286–291, 2007.