Towards a ROS-based Modular Multi-Modality Haptic Feedback System for Robotic Minimally Invasive Surgery Training Assessments

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***Abstract*—Current commercially available robotic minimally invasive surgery (RMIS) platforms provide no haptic feedback of tool interactions with the surgical environment. As a consequence, novice robotic surgeons must rely exclusively on visual feedback to sense their physical interactions with the surgical environment. This technical limitation can make it challenging and time-consuming to train novice surgeons to proficiency in RMIS. Extensive prior research has demonstrated that incorporating haptic feedback is effective at improving surgical training task performance. However, few studies have investigated the utility of providing feedback of multiple modalities of haptic feedback simultaneously (multi-modality haptic feedback) in this context, and these studies have presented mixed results regarding its efficacy. Furthermore, the inability to generalize and compare these mixed results has limited our ability to understand why they can vary significantly between studies. Therefore, we have developed a generalized, modular multi-modality haptic feedback and data acquisition framework leveraging the real-time data acquisition and streaming capabilities of the Robot Operating System (ROS). In our preliminary study using this system, participants complete a peg transfer task using a da Vinci robot while receiving haptic feedback of applied forces, contact accelerations, or both via custom wrist-worn haptic devices. Results highlight the capability of our system in running systematic comparisons between various single and dual-modality haptic feedback approaches.**

I. INTRODUCTION

Robotic minimally invasive surgery (RMIS) is quickly becoming the gold standard of treatment for many surgical procedures due to improved visualization of the surgical field and enhanced range of motion it provides over other minimally invasive techniques [1], [2], [3], [4]. The Intuitive Surgical da Vinci is the most widely used RMIS platform for various routine and non-routine surgical procedures [5]. However, one feature the da Vinci lacks is haptic feedback of the surgeon's tool interactions with the surgical environment. Humans naturally rely on various tactile cues from mechanoreceptors in the skin to sense a range of mechanical stimuli such as contact forces and vibrations when performing dexterous tasks [6], [7]. Without these cues, surgeons using the da Vinci must learn to visually estimate the physical interactions between the surgical tools and the surgical environment, which can lead to significant increases in the learning curve necessary for novice surgical trainees to reach psychomotor skill proficiency.

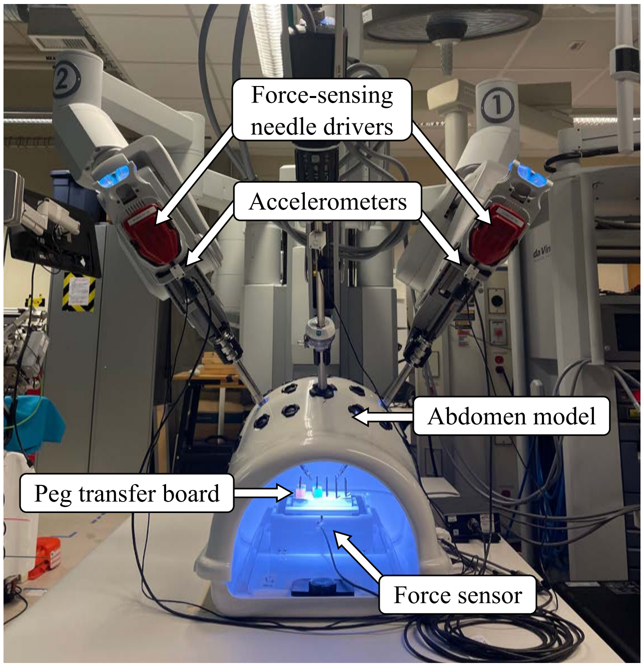

Fig. 1. Sensor module featuring ForceN surgical tools with accelerometers, inserted in abdomen model containing peg transfer board and force sensing platform.

Previous research has demonstrated that providing da Vinci users with haptic feedback has a significant impact on surgical training task performance. Brown et al. showed that wrist-squeezing haptic feedback of interaction force led to reduced contact forces in an inanimate ring rollercoaster training task [8]. King et al. demonstrated that tactile feedback significantly reduced grip forces of trainees completing a peg transfer task [9]. Wottawa et al. showed that tactile feedback significantly decreased grasp forces when running an *in vivo* porcine bowel. Regarding surgeons' preference in using haptic feedback, Koehn and Kuchenbecker showed that both surgeons and non-surgeons prefer vibration feedback (compared to no feedback) during robotic surgery [10]. However, when evaluating single-modality vibrotactile feedback of tool contact accelerations, McMahan et al. found that haptic feedback did not improve or impede performance in a variety of surgical training tasks [11]. Furthermore, the survey responses from this study were polarized; participants rated the haptic feedback both negatively and positively.

There have been several attempts at incorporating haptic feedback into RMIS training, using both single and multi-modality approaches [12]. In an effort to improve upon prior single-modality haptic feedback approaches, researchers have recently begun investigating the efficacy of using multiple modalities of haptic feedback simultaneously in surgical training. Abiri et al. for example, showed that multi-modality haptic feedback combining tactile and kinesthetic feedback allowed users to achieve significantly lower grip forces [13] in a peg transfer task than with single-modality approaches alone. Using pneumatic feedback and discrete vibrotactile cueing, Abiri et al. also demonstrated that dual-modality haptic feedback of applied normal forces resulted in significantly improved vessel localization and tumor detection in an artificial palpation task [14]. Note that Koehn and Kuchenbecker used both vibrotactile and audio feedback, however, these feedback modalities originated from the same data stream of tool accelerations.

Some studies, however, have shown no significant benefit when using multi-modality haptic feedback over single-modality approaches. For example, our preliminary results from a study comparing continuous single and dual modality haptic feedback in a virtual grasp-and-hold task with a da Vinci-like gripper showed no clear benefit of multi-modality approaches over single-modality approaches [15]. Likewise, Pacchierotti et al. demonstrated that fingertip deformation feedback significantly improved task performance for novice participants using the da Vinci to palpate a simulated soft tissue model [16]; however, when vibrotactile feedback was added, they found no significant difference in performance from the single-modality haptic approach. Although Abiri et al. [13] found significant benefits of using dual-modality haptic feedback, peak grip forces remained high enough to damage tissue regardless of the feedback modality used. Despite the fact that they achieved better results in this regard with tri-modal haptic feedback, to our knowledge, no other studies have reproduced this result. The results of this study provide further evidence that multi-modality haptic feedback merits additional investigation, but clearly the lack of standardized evaluation methods can make it complicated to replicate existing experiments.

Because of the mixed results on the utility of both single and multi-modality haptic feedback, there is no general consensus on the efficacy of haptic feedback for RMIS training. This, in large part, has precluded haptic feedback from being used for RMIS in training or clinical practice. The lack of adequate comparisons between haptic feedback modalities likely contributes to this ambiguity. Even if the same haptic feedback modalities are presented in different studies, the unique hardware and software architectures utilized by the various feedback approaches can make it complicated to properly evaluate and compare the effects of each modality. Currently, there is no standardized framework that supports the development and testing of any number of these modalities across the same surgical robotic platform with the same experimental task.

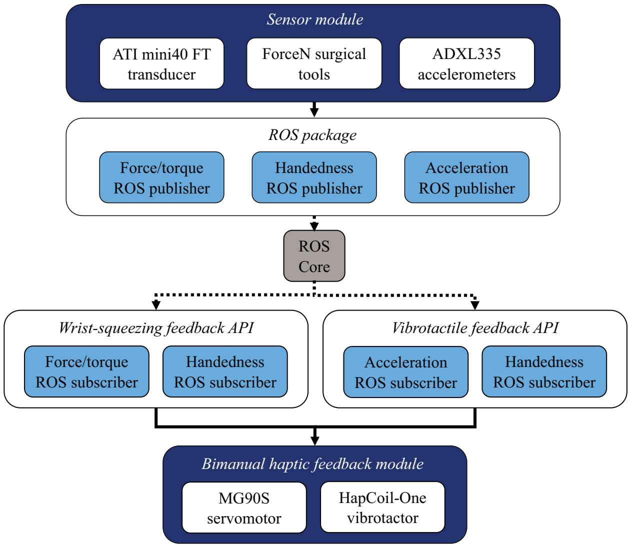

Fig. 2. The modular ROS system consists of four major components: the sensors, the ROS publishers, the ROS subscribers, and the haptic feedback devices. The sensors are sampled and published to ROS topics. The subscriber nodes compute the amount of haptic feedback and the handedness before generating the wrist-squeezing or vibrotactile signals directly to the haptic feedback device.

In this manuscript, we present the development and evaluation of a generalized multi-modality haptic feedback hardware/software architecture for robotic surgery research that leverages the real-time capabilities of the Robot Operating System (ROS) for data acquisition, collation, and streaming. Although ROS has been used in the past to bridge communication between sensors and actuators in other teleoperation studies, our system provides a modular interface that is capable of incorporating existing APIs across multiple coding languages. While our current efforts focus on RMIS training with the clinical da Vinci, the ubiquitous use of ROS in robotics make this architecture easily portable to other robotic surgery platforms such as the da Vinci Research Kit [17]. In what follows, we outline the specific details of our ROS-based framework (including links to our active, open-source Git repository), along with preliminary results from a user-study comparing single and dual modality haptic feedback for RMIS training that makes use of the ROS-based framework to achieve real-time control of two previously developed haptic feedback approaches for RMIS training, vibration [11] of contact acceleration and wrist-squeezing of contact force [8].

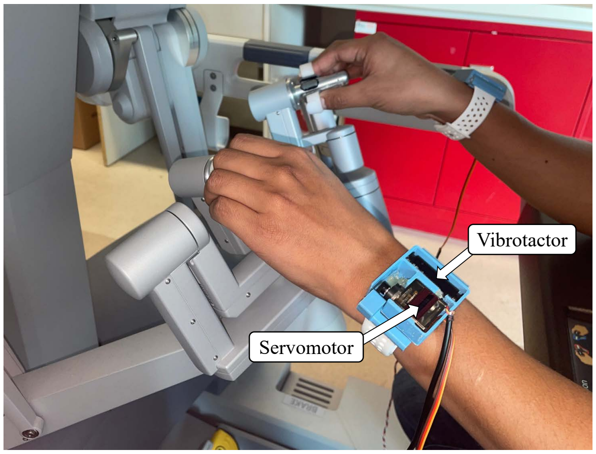

Fig. 3. Multi-modality haptic feedback devices featuring MG90s servomotor for wrist-squeezing feedback (via smartwatch wrist bands) and Tactile Labs HapCoil-One voice coil actuator for vibrotactile feedback. Both actuators are fixed in a custom 3D printed housing and are powered and controlled externally.

II. MATERIALS AND METHODS

In the following subsections, we describe our da Vinci Si surgical robotic setup and the structure of our ROS-based framework, including the sensor module, data acquisition module, and bimanual haptic feedback module.

A. *da Vinci Si surgical robot*

The da Vinci Si consists of three subsystems: 1) surgeon's console, 2) patient cart, and 3) vision cart. In our study, we use the left instrument arm, right instrument arm, and the endoscopic camera arm. As seen in Figure 1, these arms are positioned into the ports of a plastic abdomen model through 12 mm cannulas.

B. *ROS framework*

The ROS framework, via subscribers and publishers, can communicate asynchronous messages using non-blocking functions. This structure allows multiple machines to share separate components of the process without the additional overhead of implementing synchronized or time-consuming communication protocols between them. As seen in Figure 2, our ROS framework incorporates three sensor modules. Each module consists of a ROS node receiving raw signals from a physical sensor and publishing those signals as individual ROS topics, all in real time. Each ROS node is developed by wrapping existing sensor APIs in a ROS publisher using standard ROS message types (e.g. `geometry_msgs`) to publish, for example, a three-axis accelerometer signal as one ROS topic. The wrist-squeezing and vibrotactile feedback APIs then subscribe to the published topics and use these signals to perform real-time control of tactile actuators in the bimanual haptic feedback module.

C. *Sensor module*

Within the abdomen model, a square acrylic platform houses an ATI mini40 force/torque sensor. As seen in Figure 1, the peg transfer task board is magnetically attached to the top of the platform, aligned with the x, y, z axes of the mini40 sensor. For the surgical instruments, we used EndoWrist needle drivers with custom ForceFilm force sensing technology (ForceN, Inc.) that measure the deflection of the tools to calculate applied forces. Finally, we clip high-bandwidth accelerometers (ADXL345) to the shafts of the surgical instruments using custom 3D printed housings. The mini40 and accelerometers have been used in our prior work [8], [18].

D. *Data acquisition module*

The accelerometers and mini40 sensor send analog voltage signals to a Sensoray 826 PCIe data acquisition board via a custom external PCB, which also provides power for each sensor. The Sensoray 826 C++ API sets the voltage range to ±10V for each analog input channel and sets the sampling rate using a $20\mu s$ settling time for analog to digital conversion (ADC). We modified the API to convert the incoming voltage signal to SI units of force (N) and acceleration (m/s^2) in real time. The ForceN tools connect to our central PC over USB serial communication. Using a ROS wrapper, we publish the stream of force/torque data to a `wrench` node and the stream of acceleration data to three corresponding nodes: `accel1` for the accelerometer on the left surgical instrument, `accel2` for the accelerometer on the endoscope, and `accel3` for the accelerometer on the right surgical instrument.

E. *Bimanual haptic feedback module*

The individual haptic feedback modalities we implement are 1) wrist-squeezing feedback of applied forces [8], [19], and 2) vibrotactile feedback of the resulting contact accelerations [11], [20]. We developed a custom wrist-worn device which houses an MG90s servomotor for wrist-squeezing and a Tactile Labs HapCoil-One voice coil actuator for vibrotactile feedback, as seen in Figure 3. For wrist-squeezing, a watch strap is attached to the frame of the wrist-worn device and is looped around the wrist to attach to the servo horn on the other side of the wrist. The servos are both controlled by a Python wrist-squeezing script running on our PC which subscribes to the `wrench` topic, extracts the force data, and takes the Euclidean vector norm of the three force axes to produce a single-axis force magnitude F according to

$$F = k \cdot \sqrt{f_x^2 + f_y^2 + f_z^2} \tag{1}$$

where f_x, f_y, f_z are the forces in the x,y,z axes, respectively, and $k = 0.1$ is a linear gain (determined heuristically through pilot studies). We then use this signal to control the amount of wrist-squeezing by changing the servo angle according to

$$\theta = \theta_{min} + c \cdot (F^2 - F_{th}^2) \cdot (\theta_{max} - \theta_{min}) \tag{2}$$

where $\theta_{\max} = 140°$ for the left wrist and $40°$ for the right wrist, $\theta_{\min} = 90°$ for both left and right wrists, and $c = 6.0\,\mathrm{N}^{-2}$ is a linear scaling factor that maps force to position. These parameters were all chosen heuristically through pilot

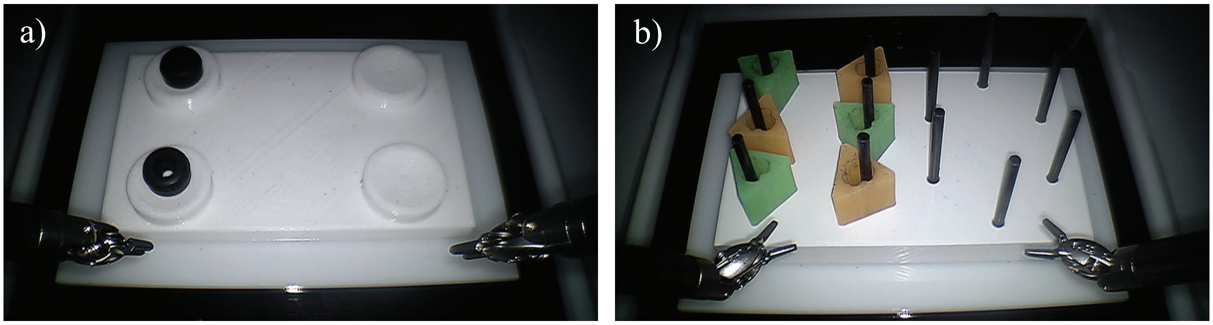

Fig. 4. a) Simplified task board - users pick up black pieces and place them into any of the four circular wells. b) Peg transfer task - users pick up triangular pieces on the left side of the board with the left surgical tool, handoff to the right surgical tool in midair, and position the pieces onto pegs on the right side. This process is repeated until all pieces are transferred to the right side; then, the procedure is reversed until all pieces are transferred back to the left side.

studies. This rendering approach is similar to the one used by Brown et al. [8].

To appropriately drive the haptic feedback in accordance with the hand(s) being used by operator, we must determine which tool (or combination of tools) is contacting the task materials. To predict this, we measure the bending force on both force-sensing surgical tools compared to a heuristically chosen threshold value. If the force exceeds this threshold, we label that tool as generating the force. The appropriate haptic signal is sent only to hands we predict are generating force; this may be either left, right, both, or neither. Without handedness detection, the user would feel haptic feedback on both hands regardless of the tool they were using at the time, which could confound the user's interpretation of the haptic signals.

When handedness is determined for the wrist squeezing feedback, the computed servo angle from equation 2 is clamped between minimum and maximum servo angle values (i.e, $\theta_{min} \leq \theta \leq \theta_{max}$) for each wrist as discussed above. The angle commands are sent to both servos using a Phidgets 1061_1B PhidgetAdvancedServo servomotor control board communicating with the PC over USB.

For vibrotactile feedback, we subscribe to the individual `accel` topics, process the accelerometer data in the customized Sensoray API and generate an analog output signal. While signals from the accelerometers are in three dimensions, the voice-coil vibrotactors are only capable of generating oscillations along their major axis. As such, the haptic rendering algorithm must resolve these three axes into a single component. To this end, we used the DFT321 algorithm [21], implemented in real-time in Python 3.8 using the NumPy Fast Fourier Transform (FFT) algorithm, to preserve the temporal and spectral information of the 3D acceleration signal while projecting into a 1D signal. Finally, we use a Syntacts amplifier board (https://www.syntacts.org) to amplify the output signal and drive both of the HapCoil-One actuators.

III. SYSTEM EVALUATION

A. *Preliminary study design*

We ran a preliminary study to evaluate basic functionality of our system. To this end, we recruited N=7 novice participants (3 male, 4 female) from the adult (18 years of age or older) population at Johns Hopkins University and The University of Maryland Baltimore County. All participants provided informed consent according to a protocol (HIRB00011569) approved by the Johns Hopkins University Homewood Institutional Review Board. The experiment lasted approximately 60 minutes and participants were compensated $15 for their participation. In our data analysis, we did not use data from Participants 1 and 2 since we made changes to the experimental setup after their trials.

Participants were first provided with an introduction of the da Vinci surgical system and received instructions on how to operate the controls. They were then instructed to sit at the console. Then participants received a description of the peg transfer task, with images of the task provided for visual support, and were instructed to perform the task as quickly as possible while minimizing the force they apply on the task board and pegs. Following the instructions, participants were given five minutes to practice on a simplified task board as seen in Figure 4a. They were encouraged to explore the entire work space with the surgical instruments.

Once the practice session was completed, trial sessions began. Participants were given headphones playing white noise to mask any potential auditory cues from the feedback devices or robot actuators and were asked if the volume was comfortable. Participants then completed the peg transfer task (Figure 4b) in the following three conditions in the same order: 1) wrist-squeezing feedback, 2) vibrotactile feedback and 3) both wrist-squeezing and vibrotactile feedback. Participants completed a total of 9 trials total, three for each feedback condition. Before each trial, the experimental set-up was re-adjusted to its initial position; the camera view and da Vinci instruments were also re-aligned. Participants had the option to take a 5-minute break after each feedback condition. After each trial, participants were asked to complete a survey consisting of seven Likert scale (1-10) and two open-ended questions related to task difficulty and perceived task performance, as shown in Table I.

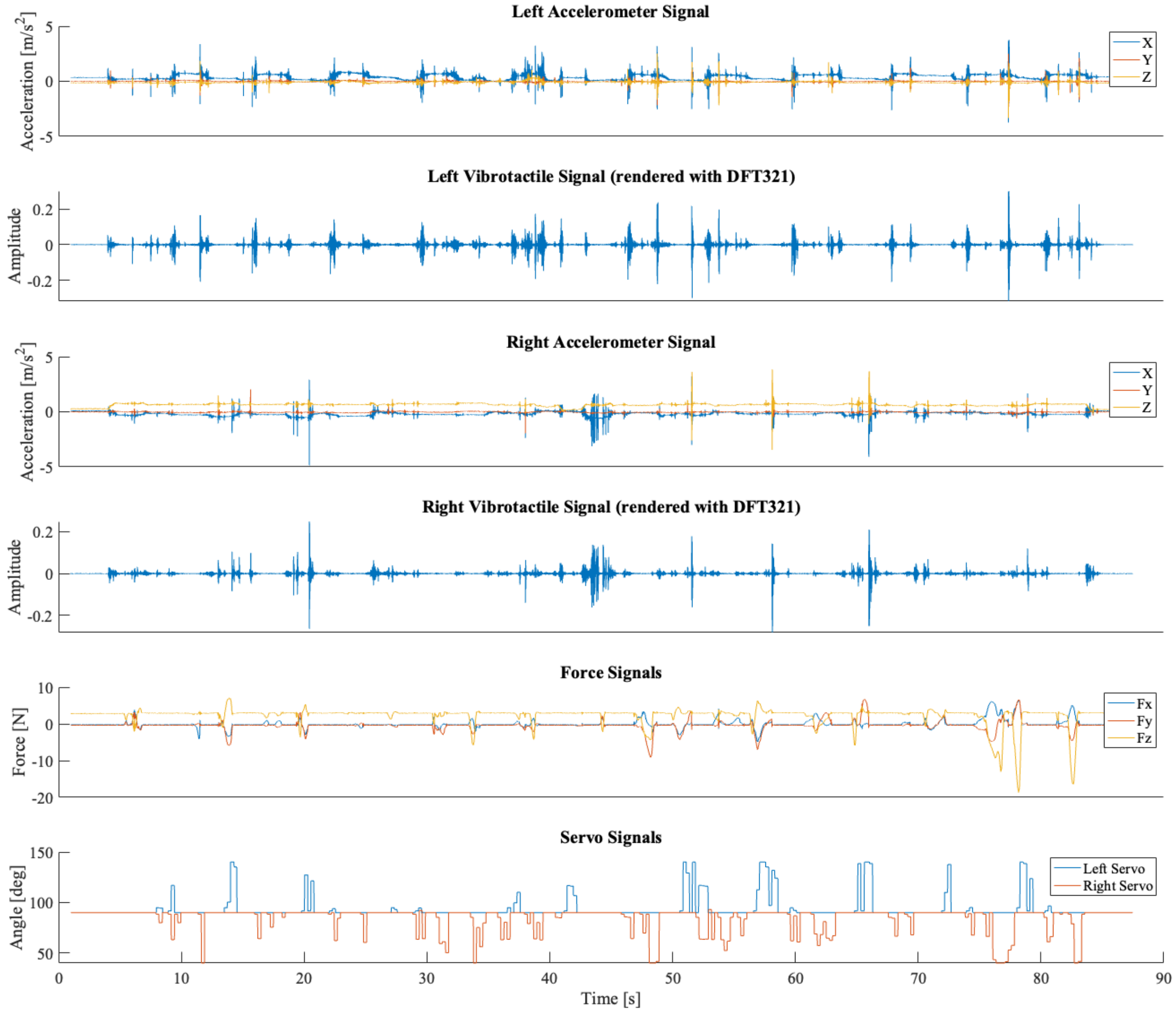

Fig. 5. Visualization of force and acceleration sensor signals, servo angle output, and DFT321 output for each accelerometer.

IV. PRELIMINARY RESULTS

We recorded the accelerations of the surgical tools, as well as the forces applied on the task board, as participants completed each trial of the peg transfer task. The resulting average accelerations of the left and right surgical tools as well as the average force applied by each participant are shown in Figure 6. Furthermore, Figure 5 shows a sample visualization of all signals collected during the trials, including force, acceleration, DFT321/vibrotactile output, and servo angle for wrist-squeezing output.

The results of the survey are shown in Table I. Overall, responses to our Likert scale questions suggest that participants did not find the task mentally or physically demanding, nor did they feel hurried or rushed. However, they did feel somewhat frustrated by their inability to complete the task to their expected level of performance, likely because they felt that the haptic feedback did not assist them in this regard. Likewise, when analyzing the open-ended questions, four main themes were extracted. First, many participants commented that there were challenges in depth perception with using the robotic system. Second, a few participants mentioned that the presence of the haptic feedback devices restricted their movement when performing the task. Third, the majority of participants felt that the vibrotactile feedback was distracting and at times uncomfortable. Finally, some participants commented that the multi-modality haptic feedback made the task more stressful.

V. DISCUSSION AND FUTURE WORKS

We developed a ROS-based, modular multi-modality haptic feedback system for RMIS training assessments. We implemented this system with the da Vinci Si, using various modules including a sensor module, data acquisition module, and a bimanual haptic feedback module - all communicating in real time over ROS. Results showed the capability of this system to gather and process relevant force and acceleration data for RMIS training assessment through our preliminary study. Prior studies had shown mixed results when assessing the

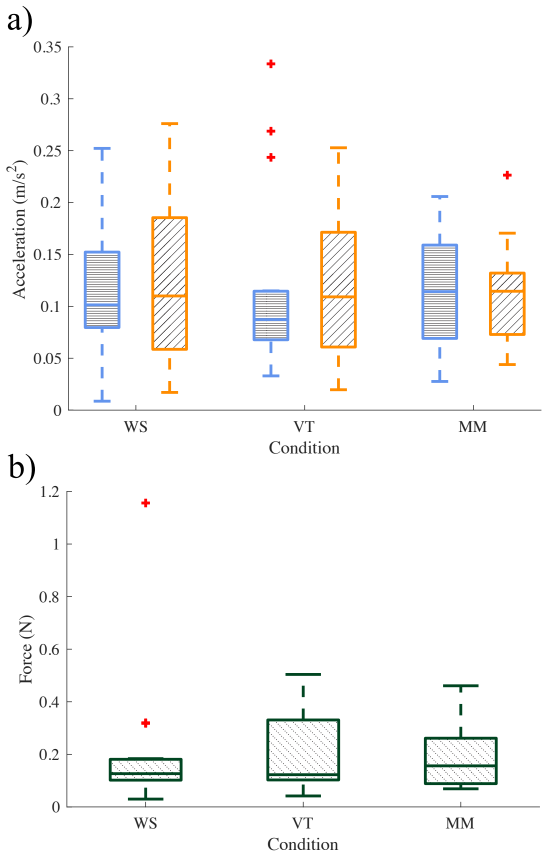

Fig. 6. a) Accelerations of left (blue, horizontal hatches) and right (orange, diagonal hatches) surgical tools averaged across all participants, b) Applied forces averaged across all participants. Both are shown for wrist-squeezing (WS), vibrotactile (VT), and multi-modality (MM) haptic feedback conditions.

efficacy of multi-modality haptic feedback, which is perhaps due to the lack of proper comparisons between haptic feedback modalities since there was no generalized framework for developing and testing these modalities.

Regarding the quantitative results of our preliminary study, there are no clearly visible trends so far; these results are expected due to the small sample size. As seen in Figure 6a, the median accelerations are within 0.1 m/s^2 of each other across wrist-squeezing, vibrotactile, and multi-modality haptic feedback conditions. Closer still are the median applied forces, as seen in Figure 6b, across all feedback conditions. In our current study, no statistical analyses were relevant due to the small number of participants; future studies may show significant differences between conditions by fitting linear mixed effects models to the data, with feedback condition and trial number as fixed effects and participants as random effects. Although prior literature has shown that using haptic feedback can significantly improve RMIS training task performance over not using haptic feedback, our future study could also include the no-feedback condition as a control. Finally, outliers may be less prevalent as the variance in performance will likely increase with more participants of different experience levels with the da Vinci.

TABLE I

SURVEY QUESTION RESULTS FOR WRIST-SQUEEZING (WS), VIBROTACTILE (VT), AND MULTI-MODALITY (MM) FEEDBACK.

#	Question	Answer options	Feedback modality	μ	σ
1.	How physically demanding was the task?	1-10	WS	2	0.9
			VT	2	1.1
			MM	2	1
2.	How mentally demanding was the task?	1-10	WS	3	1.8
			VT	3	2
			MM	3	1.3
3.	How hurried or rushed was the pace of the task?	1-10	WS	2	1.6
			VT	2	1.3
			MM	2	1.3
4.	How insecure, discouraged, irritated, stressed, or annoyed were you?	1-10	WS	2.5	1.2
			VT	5	3.5
			MM	4.6	3.5
5.	How successful were you in accomplishing what you were asked to do?	1-10	WS	8	1.5
			VT	6	2.5
			MM	6	2.6
6.	How hard did you have to work to accomplish your level of performance?	1-10	WS	3.5	1.9
			VT	4	2
			MM	3.7	2.9
7.	How useful was the feedback?	1-10	WS	7	2.1
			VT	5	3.8
			MM	5.6	3
8.	What prevented you from performing the task as successfully as possible, if anything?	-	-	-	
9.	Do you have any comments, suggestions, and/or concerns?	-	-	-	

As a result of the user feedback obtained through our surveys, future works are focused on improving the quality of our experiment design and multi-modality haptic feedback. To improve visualization of the task board, we will devise a more consistent method of setting the da Vinci camera angle and brightness. Regarding issues with the vibrotactile feedback, we noticed some potential issues with our implementation. Since the accelerometers were clipped directly to the surgical tools, they sensed the accelerations due to the rotation of the tools about their long axis. These accelerations were particularly noisy and large in amplitude, most likely due to vibrations from the gear mechanisms close to the accelerometer. There may have been additional noise from the unshielded portion of the accelerometer cables, or, since the accelerometers are in motion throughout the study, from the mechanical interaction of these cables with the surgical tools or abdomen model. To increase the quality of the acceleration signals and corresponding vibrotactile feedback, we plan to use wireless, digital accelerometers with onboard filtering and DFT321 processing. Next, to improve wrist-squeezing feedback, we plan to use a geared DC motor to minimize jitter and backlash, which were limitations of our hobby servomotor. We will also investigate a new tendon-driven wrist-squeezing actuation principle to replace our current clamping-based method with radial forces around the wrist. Finally, we think that future studies could be informative by robustly investigating the contribution of dual modality haptic feedback with a greater number of participants.

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