Wearable Haptic Feedback Actuators for Training in Robotic Surgery

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Abstract

The Intuitive Surgical da Vinci robot allows surgeons to perform minimally invasive surgery more fluently and comfortably, but it does not provide any touch feedback. This lack of haptic cues is especially challenging to those who are initially learning to use the da Vinci, because they must rely solely on their vision. Inexperienced users often unwittingly apply forces that injure the patient's tissue or break sutures. The solution analyzed in this project focuses on a haptic feedback system for surgical robotic training that provides users with the knowledge of the forces they are applying to the training task. It places a three-axis force sensor beneath the task materials and a custom servo-driven haptic actuator on each of the user’s wrists. A custom circuit, in combination with a conductive training tasks, determines which tool is touching the task.   The left and right actuators squeeze the user’s wrists in proportion to the magnitude of the force applied by the respective instrument. Initial tests were conducted to determine whether this system is beneficial. One expert robotic surgeon and several lay people used the developed system to complete a task called ring rollercoaster, in which one guides a metal ring along a curved track. Many participants understood how to interpret the provided haptic cues and had positive remarks on their utility. The expert surgeon was particularly enthusiastic about the system's potential as a training tool. Ongoing work centers on designing a human-subject experiment to quantify the impact of this system on the learning curve of surgeons in an actual training task.

Introduction

Over 50 million surgeries are performed on average per year [1]. Although surgery is a common medical treatment, it can have negative consequences such major scars and painful, long recoveries. These problems can be mitigated in part by minimally invasive surgery. Not only does it reduce scarring by requiring only small incisions, but studies have also shown that patients who have minimally invasive procedures often require a shorter hospital stay and fewer painkillers [2].

The Intuitive Surgical da Vinci’s improves on traditional minimally invasive surgery, making many procedures much easier for surgeons to accomplish. The da Vinci gives surgeons added dexterity and precision in tight spaces through the use of surgical instruments with a flexible wrist joint and the ability to scale down their movements. It also provides them with stereoscopic vision, resulting in much better depth perception.

Despite these advantages, robotic minimally invasive surgery with the da Vinci has a few drawbacks including the lack of haptic or touch-based feedback. This means that when the user touches or pushes on an object with the da Vinci arms, they do not feel how much force they are applying to that object, and must rely on their vision to estimate these forces. This is important when operating because surgeons do not want to apply forces that could potentially harm the patient or break equipment (such as needles for suturing) [3]. For novice robotic surgeons, understanding how much force is being applied through the robot is particularly challenging because this visual estimation ability is underdeveloped.

The solution addressed in this paper provides a potential solution to this problem in robotic minimally invasive surgery training by creating a haptic feedback system that alerts trainees to the forces they are exerting on the training task with the robot. The system consists of haptic feedback actuators that go on the user's wrists and a force plate that sits under the training task. We hypothesize that surgeons training with this system will gain a sense of how to visually estimate the force they are applying with the da Vinci, a result that should be transferrable into actual surgeries.

Background

Haptic feedback is diminished in minimally invasive surgery because surgeons are removed from the operation site [4]. Since robotic minimally invasive surgery removes the surgeons another step further, there is no haptic feedback. Surgeons who operate using the da Vinci describe this challenge as a "major limitation [5]."

Haptic feedback in robotic minimally invasive surgery has been proven to decrease the amount of force applied in training tasks [6] [10]. Due to its positive assessment, there are many proposed solutions to include haptic feedback in an actual surgical robotic system. One type of haptic feedback research has to do with textures. This type is especially important when analyzing patient tissue and trying to locate abnormalities under the skin [7]. Another type of feedback that many solutions aim to provide is the level of force being applied during surgical tasks. This type is important so that surgeons do not harm patient tissue.

In addition to the kinds of haptic data that is analyzed, there are also different kinds of ways to portray that haptic sensation to the surgeons. Some solutions propose using visual and auditory cues to let the surgeons know how much force they are applying [8]. Another method is to create a haptic display for surgeons. In this method, when the instrument comes into contact with something, the display will provide the user with a touch sensation in order to give them an idea of what the robot is feeling [9]. Examples of these touch sensations are vibrations, squeezes, or poking.

Although haptic feedback does seem to improve training tasks for minimally invasive surgery, some still question its usefulness during an actual operation [10]. In some studies, haptic feedback for users with experience using the da Vinci resulted in little-to-no difference. Only when inexperienced users were analyzed, was it evident that haptic feedback was a benefit [11]. The reason for this is because experience surgeons can pick up on visual cues that indicate how much force they are applying. Novice da Vinci users cannot do this due to their inexperience [10]. In addition to this, haptic feedback is difficult to incorporate in actual surgery because it would require either a force plate to go under the patient or force sensors be attached to the da Vinci arms. The force plate under the patient could decrease stability during an operation and force-sensors on the da Vinci arms could add bulk to the slim design of the arms necessary for insertion under the skin. More research should be done on methods and benefits of haptic feedback in actual surgeries, but it seems that for training purposes it is remarkably valuable.

Methods

The haptic feedback system discussed in this paper is a modified solution of a design created by Sean Cohen, a 2015 Rachleff Scholar in the Penn Haptics Group. His solution, as is the one in this paper, focuses on haptic feedback in training with the da Vinci. A key difference is that his design squeezes the fingertips of the users when they apply a large enough force, whereas the solution in this paper squeezes the user’s wrist.

As seen in Figure 1, the haptic feedback actuator was adapted from a wearable tactile actuator meant to emulate human interaction [12] [13]. The actuator is made of two parts that are 3D printed using polylactic acid. It is composed of a mount that holds a Futaba s3114 servo motor and an attachment that turns when the motor turns. The mount sits on the user’s wrist, and a

Velcro strap is wrapped around the wrist and connects to the attachment that turns. When the servo motor turns, the Velcro strap squeezes the user's wrist.

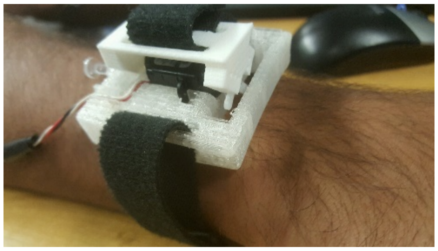

Figure 1. A picture of the haptic feedback actuator. The mount is the portion that sits on top of the wrist. The servo motor is under the attachment that pulls on the Velcro.

When force is applied with the da Vinci, the feedback device squeezes the user's wrist. The forces that the da Vinci applies are taken in as voltages by an ATI Mini40. These voltages are then analyzed by a custom smart task board which turns these voltages into a force using a calibration matrix. The magnitude of these forces is then calculated, and the position of the servo changes to match this magnitude. As seen in figure 2, the position of the servo increases linearly with the increase in magnitude until it reaches a maximum position. The larger the position of the servo, the harder the haptic feedback actuator squeezes.

$$\text{Position of the Servo} = \Theta_i + (F_{mag} * ((\Theta_i - \Theta_f)/F_{scale})))$$

Figure 2. This Equation defines where the position of the servo is with depending on force magnitude. Θ_i denotes the minimum possible value of the servo in the mount in degrees. Θ_f is the maximum possible position of the servo in the mount in degrees. F_{mag} stands for the force magnitude and is in Newtons. F_{scale} is a constant that is in Newtons that can be adjusted to increase or decrease sensitivity of haptic feedback system.

Since the da Vinci has two arms that can apply variable forces, there are two separate haptic feedback actuators for each of the user's wrists. To squeeze the appropriate wrist, a custom circuit was used that consisted of a bread board, wires, and resistors. As seen in figure 3, 3.3 volts are applied to each of the da Vinci arms. When the da Vinci arm is touching the task, which is grounded, the circuit is completed and a current is allowed to flow. When it is not, the resistance is infinite and no current can flow. If current is flowing through both arms because both arms are touching the task, then both servos on each of the user's wrist respond accordingly. The haptic feedback actuators only squeeze the user's wrists if a current flows through its corresponding da Vinci tool. In order for this system to work the task must be conductive. In doing this, the user will know which arm is applying a force and be able to adjust accordingly.

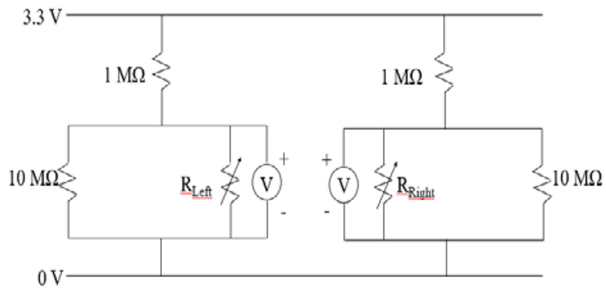

Figure 3. This is the circuit diagram that was used to determine which hand was in contact with task. The R_{Left} and R_{Right} represent the da Vinci arms which can provide variable resistance

The python code that runs this system says that while current flows through one or both of the arms, the position of the servo can be adjusted by how much force is applied. The function in figure 2 determines how much the servo turns. If the position of the servo is less than or equal to the minimum position of the servo, then it rests at its minimum. If it is between its maximum and minimum, the position of the servo is set by the function. If the position of the servo is greater than its maximum, then it will stop at its maximum.

Results/ Discussion

In order to tests this system's potential for training purposes, participants with little-to-no prior use using the da Vinci were asked to complete a task called ring rollercoaster, in which they must guide a ring along a bar with multiple curves, as shown in figure 4. Participants were asked to complete this task with and without the haptic feedback actuators. The first trial run was without haptic feedback and users were allowed to practice the task before being recorded. The second trail run was with haptic feedback, and users were again allowed to practice before being recorded in order to get a feel for the haptic feedback actuators.

Many of the participants struggled with this task. A major problem that most of the participants encountered was that the ring was constantly being pulled out of their graspers. The reason for this was that they would inadvertently be pulling the ring against the bar with a large amount of force, which would rip the ring from the da Vinci's forceps. Once the haptic feedback actuators were introduced to the task, the participants remarked that it was easier to tell how much force they were applying to a task. Although some participants still struggled with this task, the others ultimately benefitted by completing the task with much smaller force magnitudes. A representation of the group's average magnitude and root mean square of magnitude are shown in figure 5.

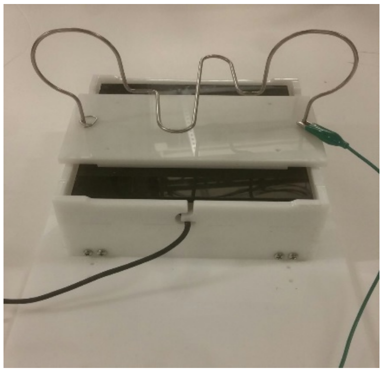

Figure 4. This is the ring rollercoaster. The ring that users grab with their forceps is resting at the bottom left of the task. The green alligator clip on the bottom right of the rollercoaster grounds task.

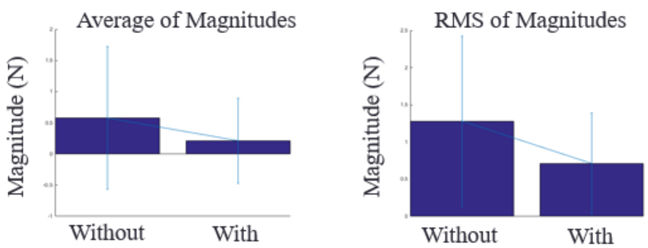

Figure 5. The average and the root mean square of the force magnitude applied by each participant was calculated with and without the haptic feedback actuators. Then these calculations were averaged to represent the group as a whole with and without haptic feedback.

In addition to the inexperienced users, an experienced robotic surgeon, who works at the Hospital of the University of Pennsylvania, was asked to evaluate the system. He tried the ring rollercoaster with the actuators and was impressed. He believed that with some practice using the haptic feedback displays, he would definitely be able to reduce the forces he applies to the task. He also mentioned that he liked how it squeezed the wrist, which he considered to be more comfortable than the finger.

More research should be done to determine how beneficial this system will be for novices training to use the da Vinci. A human-subject experiment, using medical students who are novice da Vinci users, is currently in process. These users are better suited participants because they are the users who this system aims to help. If this system proves to enable medical students to apply lower forces while doing a task, then it should be incorporated into the mainstream training for the da Vinci.

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