Draft to be submitted to Journal of American College of Surgeons

Development of Infrared-Based Positioning Simulator for Endoscopic Carpal Tunnel Release Surgery

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Background: Surgical simulations are becoming an integral part of surgeon's training due to decreased cost and increased repeatability. However, there are no current models that interface a physical anatomical model with visual software for endoscopic carpal tunnel release surgery. Our goal is to create a realistic, cost-effective training simulation.

Study Design: The simulator prototype was designed to include infrared position tracking and a physiologically accurate hand model. This positioning system was integrated with an array of endoscope images captured a carpal tunnel surgery. We performed testing to determine the optimal range of which the LEDs are accurately detectable by the infrared receiver.

Results: The final prototype included a silicone-based hand containing a carpal tunnel and transverse carpal ligament. Proper haptic feedback was accomplished by the addition of a rapid prototype blade cap. An LED circuit board is attached to an endoscope, sending position coordinates to an infrared receiver. Results indicated that no significant difference in accuracy exists between the z-axis ranges of 20-60 cm.

Conclusions: The simulator prototype replicates the forces felt by the surgeon during a carpal tunnel procedure, and position accuracy allows realistic visual simulation.

Disclosure Statement: Funding made possible by a grant received by Dr. Ben Mandel, Dept. of Surgery, University of Wisconsin Hospital

The surgical field is moving towards using simulators to train for surgical procedures, which are more efficient and cost effective than cadavers. Simulators provide a solution to the problem because models are durable and repeatable, allowing a single simulator to be used to teach multiple surgeons how to do a surgical procedure. Here in lies the motivation for a simulator for endoscopic carpal tunnel surgery.

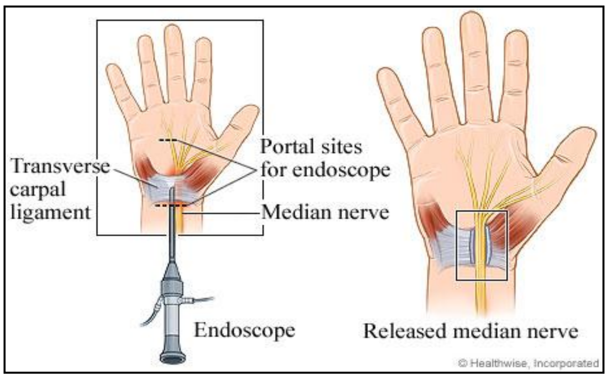

Figure 1: Placement of endoscope and cutting of transverse carpal ligament.
(http://www.health.com/health/library/mdp/0,,zm2464,00.html)

Surgical Procedure

Endoscopic carpal tunnel surgery is a non-invasive procedure that reduces the symptoms of carpal tunnel syndrome[1]. Before the endoscope is inserted, an incision is made on the distal wrist crease of the hand. Surgical tools are inserted into the incision to widen the carpal tunnel. During this time, the surgeon is able to feel the corrugations on the underside of the ligament, allows him or her to sense the location and borders of the transverse carpal ligament[2]. The endoscope also comes equipped with a camera, which allows the surgeon to see inside of the wrist.

The surgeon uses a visual display to verify the endoscope position in the tunnel. Once the end of the transverse carpal ligament is located, the blade is deployed and used to cut the transverse carpal ligament[3].

Current Devices

Many different systems are available with open source technology packages meant to interface existing simulation instruments with visual processing software specific to a surgery of interest. Tracking devices can be categorized into three general types: mechanical, optical, and electromagnetic. Simulation systems such as TrEndo[4] and SIMENDO offer haptic feedback and virtual visualization, but lack a physical anatomical model.

Hybrid surgical simulators allow for interaction between virtual and physical models. The surgeon views images on a monitor, but uses real instruments and has the option of studying a physical structure. Most hybrid systems, such as ProMIS simulate laparoscopic surgery. No device currently exists for the simulation of carpal tunnel release surgery.

METHODS

Prototype Design

A prototype was developed containing a hand model made of silicone rubber, a force feedback mechanism, and an LED circuit tracked by an IR (infrared) receiver. A few specifications were followed in order to create a realistic simulator. For instance, the tracking system needed to interface with the array of carpal tunnel images captured by the client. It must relay information relating the position of the instrument to the position within the carpal tunnel. The system should detect movement along and rotation about the z-axis and have a precision of 1 mm. External devices, such as wires and receivers, should not interfere with the surgical procedure.

For the hand model, corrugations must be present on the top of the tunnel to reflect the texture on the underside of the transverse carpal ligament.

Measurements of anatomical structures (Figure 2):

1. Transverse carpal ligament length: 3.5cm
2. Ligament corrugations ~1mm height by 1mm width
3. Carpal tunnel diameter: 1cm at proximal end with taper towards the distal end
4. Incision location: 5mm proximal to distal wrist crease

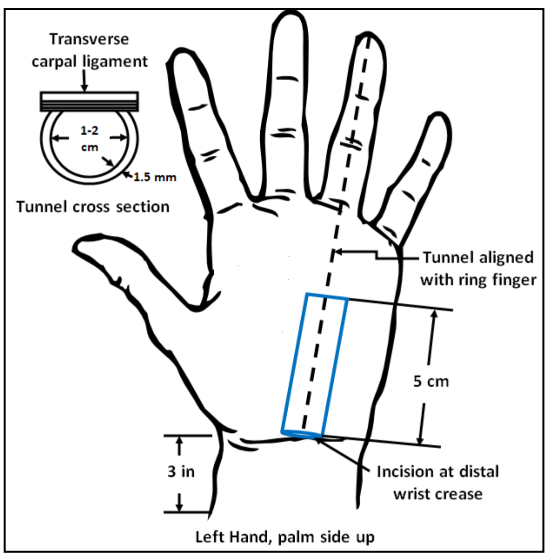

Figure 2. Schematic of carpal tunnel placement within hand model. The carpal tunnel is highlighted in blue and is aligned with the ring finger.

An additional force feedback mechanism was incorporated into the prototype design to replicate the forces felt by the surgeon when the blade mechanism is deployed and the transverse carpal ligament is cut in the simulation.

Fabrication

Circuit Board

The printed circuit board was fabricated using a toner transfer technique. . The completed product is then drilled to make room for the components' leads which are soldered into place to complete fabrication (see Figure 3).

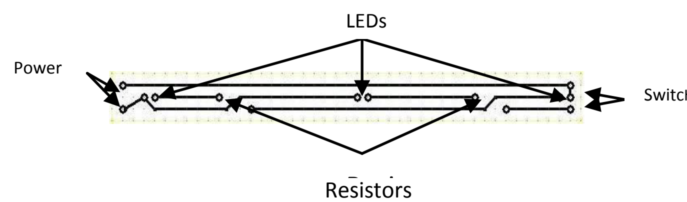

Figure 3: Circuit board schematic.

Blade Caps

SolidWorks models of the five blade caps were submitted as stereolithography files to the SLA-Viper si2 printer. This machine was chosen because it can create small models with high resolution and a fine surface finish. These caps were fitted on the blades and secured with Epoxy.

Testing Method

The objective of testing this prototype involved determining the optimal range of LED detection by the receiver and using this information to choose the final dimensions of the platform. This was accomplished by testing how the accuracy of the positioning system changed with distance and determining the horizontal motion of the circuit board that remained in the range of the receiver. By determining the distance between the Wii remote and infrared LEDs that results in the lowest percent error, the accuracy of the prototype can be optimized.

Also, recording the detectable horizontal motion of the LEDs at different initial differences will help determine if the LED-Wii mote separation with the highest positioning accuracy allows for adequate movement throughout the simulation.

Procedure for testing positioning accuracy:

1. The starting distances between the Wii remote and the infrared LEDs were chosen at 20, 30, 40, 50, and 60 cm.
2. At each starting distance, the position of the Wii remote remained constant.
3. The circuit board containing the LEDs was moved away from the Wii remote a total of 5cm in 1cm increments (see Figure 4). 5cm was chosen because this is the approximate length of the carpal tunnel.
4. At each increment, distances were recorded by the processing software and compared to the set experimental distances, which were measured with two fixed metric rulers.
5. Three repetitions were executed for each starting distance data set.
6. The average deviation and percent errors were calculated for each data set.

Procedure for determining detectable horizontal distance:

1. The starting distances between the Wii remote and the LEDs were 30, 40, 50, 60, and 70 cm.
2. The LED circuit board was placed at the above initial distances (see Figure 4).
3. The circuit was then moved perpendicular to the z-axis under the positioning program indicated it was out of range.
4. At each starting distance, the horizontal motion of the circuit board before moving out of range was recorded.

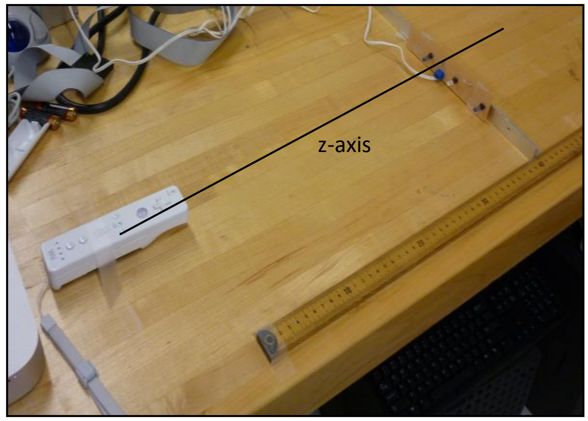

Figure 4: Testing set-up. The Wii remote is aligned with 0 on the metric ruler, and the circuit board with LEDs was moved along in 1 cm intervals.

RESULTS

Final Design

The final prototype incorporates a blade cap in order to provide force feedback, an improved silicone-based hand model, an endoscope fitted with an LED circuit board, and a remote infrared receiver (see Figure 5). The positioning data corresponds to a series of carpal tunnel images that provide visualization during the surgery. Finally, all the components are positioned on an acrylic platform, creating consistency throughout simulations.

Blade Cap

In order to increase the resistance inside the carpal tunnel when the transverse carpal ligament is "cut" in the simulation,

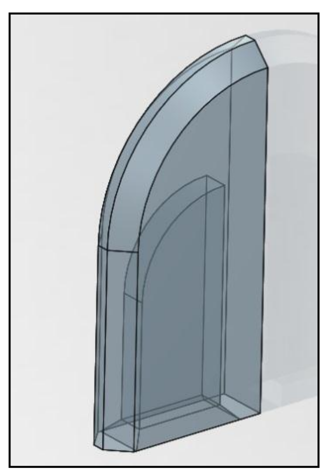

Figure 6. SolidWorks representation of the blade cap prototype.

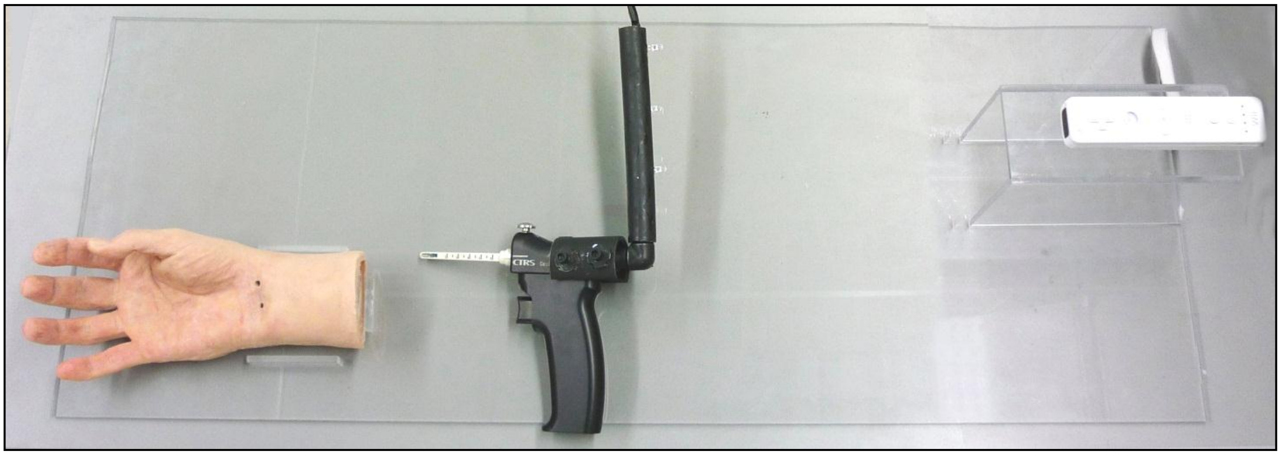

Figure 5. Final prototype with the acrylic platform housing (from left to right) the hand model, the endoscope with blade attachment, the LED circuit, and the receiver.

blade caps were created to cover the current blade (see Figure 6). Five caps were created with heights of 0.250, 0.275, 0.300, 0.325, and 0.350 inches, and each contained a pocket to fit around the current blade. This blade cap design did not interfere with the surgical mechanism already in place, allowing the user to obtain a realistic training experience during the simulation.

Circuit Board Endoscope Attachment

The housing used to cover the LED circuit in the final design consists of rigid plastic tubing and a plastic elbow joint of diameter approximately equal to the inner diameter of the tubing[5]. To accommodate the housing, the circuit was miniaturized to a width approximately equal to the inner diameter of the tubing. The housing was fixed to the endoscope via a PVC collar with a slot for the endoscope and four tee nuts. Screws in the tee nuts fastened the housing to the collar and the collar to the endoscope.

Communication between Positioning System and Surgical Images

The Java program of the final design uses a subset of classes from the moteJ utility package[6]. For the final design, the Wii Remote was used solely as an infrared detector[7]. The information gained from the Wii Remote's infrared detector comes in the form of pixel coordinates on the Remote's photosensitive array. Using trigonometry and the widely available Wii Remote

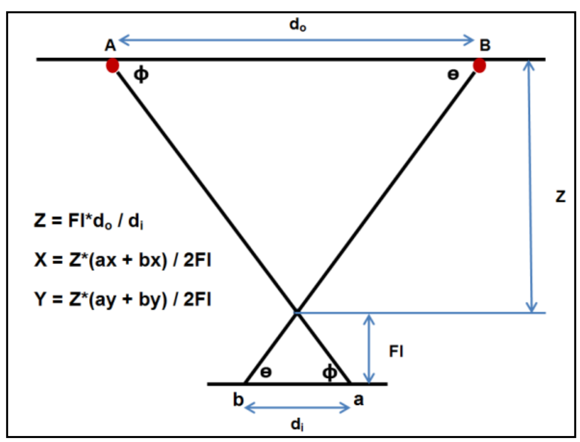

Figure 7: Trigonometry used for translating pixel coordinates to real world coordinates

specifications, these pixel coordinates are translated into real world coordinates of the center point between two sources of infrared light (see Figure 7). Two IR sources also allow for detection of rotation. Once the real world Z coordinate and rotation are calculated, a simple look-up table of images is manipulated in sequence to produce the simulation video. A third, variable IR source is also employed to signal the program when the blade is to be deployed. When the source emits light, the blade remains down in the video. When it stops emitting, the program exchanges the "blade down" overlay with a "blade up" overlay. Furthermore, when the "blade up" overlay is visible and the Z coordinate decreases, images of the intact carpal ligament in the look-up table are replaced with images of the cut carpal ligament in order to simulate ligament cutting and facilitate checking for a successful cut.

Platform

A platform was created to house all the components (hand model, endoscope, and receiver) and increase the aesthetics of the simulator. The platform was fabricated out of 0.220 inches thick clear acrylic sheeting, and all pieces were secured together using an acrylic solvent. The receiver and LEDs were spaced at a constant distance of 50 cm. This distance was chosen because it fits within the z-axis accuracy range and provides adequate horizontal freedom of motion (see Testing). The purpose of choosing a constant distance is to easily calibrate and set an absolute zero point in the positioning software. Overall, the platform combines all elements of the prototype into a simple display that is visually pleasing to the user.

Testing Results

An optimal distance between the Wiimote and the LEDs was expected to exist and become evident through trends in the testing data. Upon testing the system at initial distances ranging from 20 cm to 60 cm, a span that reflects possible simulator set-ups, no such trend was found. Average interval distances ranged from 0.97 cm to 1.02 cm, however, there was no consistent increase or decrease in the data that related to the specific starting position (Figure 8). These results indicate that there is not a significant difference in the accuracy of the system over the tested range of initial positions.

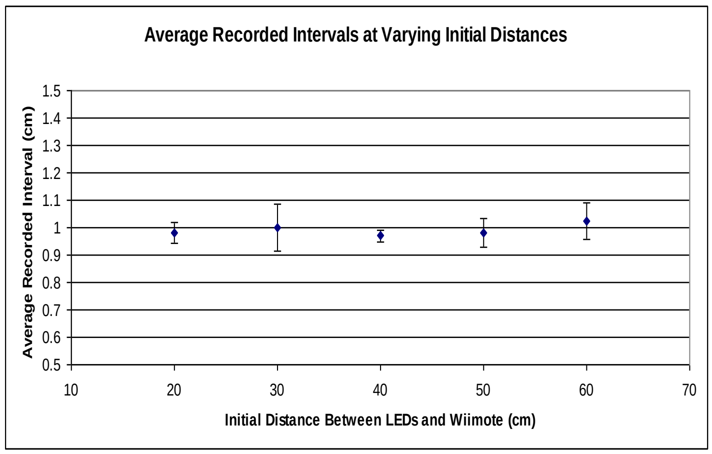

Figure 8. Graph of the average interval distances recorded by the Wii remote at initial starting distances of 20, 30, 40, 50, and 60 cm. All averages are centered on 1 cm because that was the experimental increment chosen. Error bars represent the standard deviations between the trials.

As expected, the horizontal range of motion detected by the receiver increased with increasing z-distance. A fairly linear trend was observed, increasing from r = 6 cm at a starting distance of 30 cm to r = 20 cm at a starting distance of 70 cm (Figure 9). These results allow the final dimensions of the prototype to be balanced between keeping the platform small enough to avoid access bulk but large enough to accommodate the horizontal motion of the endoscope during the simulation.

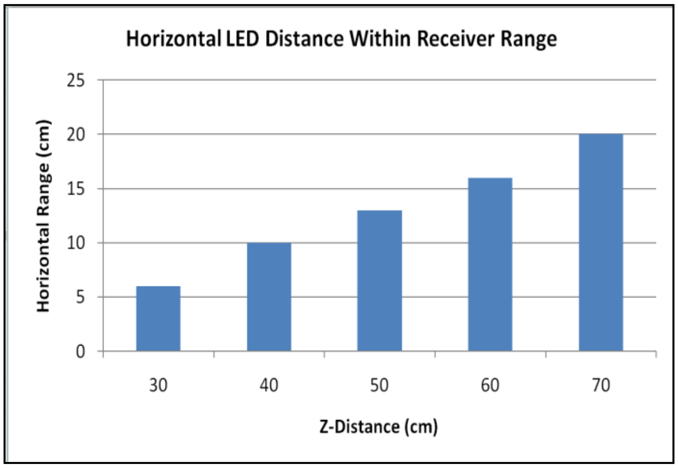

Figure 9: Graph showing the horizontal movement of the LED circuit detectable by the receiver at the following starting z-axis positions: 30, 40, 50, 60, and 70 cm.

DISCUSSION

To optimize both testing procedures, a better calibrated positioning system would reduce human testing error. One possibility would be using a digital caliper system to set and record distances instead of a ruler. Another method would be to utilize a linear motor moving at a constant velocity.

Future Work

Future work on the existing prototype includes lowering the height of the receiver platform in order to optimize the receivers connection with the LEDs based on the angle the endoscope is held when it is inserted into the carpal tunnel area. Also, although the mechanism connecting the endoscope to the circuit board is functional, a more ergonomic, streamlined design should be incorporated in order to increase the efficiency of simulation set-up and general aesthetics of the prototype.

In order to further optimize the haptics of the hand model and the general design of the simulation, a detailed survey should be developed and administered to a group of experienced surgeons. This survey would contain questions regarding the carpal tunnel width, the carpal tunnel depth, the transverse carpal ligament size, and the resistance supplied by the blade cap. More general questions would also be included to gain feedback on ease of use and overall aesthetics. Results from this survey would be used to optimize the complete prototype, ensuring that the simulation offers a realistic experience.

The aim of this prototype is to offer a more regulated, cost effective educational experience for developing surgical skills. With this in mind, future work includes integrating the carpal tunnel simulation into a greater learning tool that would contain step-by-step procedural instructions, pictures and descriptions of surgical instruments, and testing parameters to assess improvement. This package would then be a marketable, stand-alone teaching process that would incorporate all aspects of the surgery.

Acknowledgements

The team would like to thank our advisor, Professor Thomas Yen, Greg Gion from Medical Art Prosthetics, LLC., and our clients, Dr. Robert Radwin and Dr. Ben Mandel for their support of this project.

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