A DEXTROUS MASTER FOR TELESURGERY

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Lara S. Crawford

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Abstract

Minimally invasive surgical techniques, in particular laparoscopy, have many advantages over traditional surgery, most notably more rapid patient recovery. Limitations of current instrumentation, however, can make laparoscopic surgery awkward for the surgeon. A teleoperative surgical workstation would improve the surgeon's dexterity and control during laparoscopy. This report first presents a brief background on laparoscopy, describes a proposed telesurgical workstation, and discusses design goals for the human interface, or dextrous master, for this workstation. It then describes a prototype glove-like master and presents preliminary performance and calibration data obtained with this device.

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1 Introduction

Minimally invasive surgical techniques are revolutionizing surgery. These techniques, which involve inserting surgical instruments into the body cavity without making large incisions, have several advantages over more traditional surgical methods, including more rapid patient recovery, but have disadvantages associated with the fact that the surgeon may observe the operation only via a video image and must operate with multiple single-purpose instruments which usually have only an open-close control. We are developing a teleoperative surgical workstation that is more dextrous and easier to use than are the instruments currently available. I have designed and built a prototype glove device which senses the positions of the surgeon's fingers and wrist. The glove is intended to provide a more natural means of control than do the current minimally invasive tools, and will be used as a master to drive a miniature robotic hand which will replace the instrument inside the patient.

2 Minimally Invasive Surgery

Minimally invasive surgery encompasses gastrointestinal endoscopy, laparoscopy (abdominal surgery), thoracoscopy, arthroscopy, angioscopy (blood vessel surgery), and pelviscopy. These techniques involve the insertion of instruments and viewing equipment (the endoscope) into the body, either through a natural body orifice, in gastrointestinal endoscopy, or through puncture wounds created by the surgeon, in the other types of minimally invasive surgery. Minimally invasive surgery is often an alternative to more conventional types of surgery involving large incisions, for example, laparotomy, which involves a large incision through the abdominal wall. The main advantage to the minimally invasive nature of the surgery is more rapid patient recovery ([13], pp. 1-3; [24], pp. 239-240; [5], p. 1); for example, using laparoscopic techniques for cholecystectomy (gall bladder removal) reduces the hospital stay by 2-4 days, and the patient can return to work within a week ([13], p. 2). I have focussed on laparoscopy because it is one of the more common types of minimally invasive surgery and because size constraints on laparoscopic instruments are not as stringent as those on the instruments for some of the other types of minimally invasive surgery.

Laparoscopy has been used, largely as a diagnostic technique, for several decades. In the early 1960s, fiber-optics technology permitted the development of "cold" light sources, which transmit light down a fiber-optic cable from a source outside the body. These replaced earlier laparoscopes fitted with distal light bulbs, which tended to cause burns and other complications when placed inside the body cavity. In the mid 1960s, more reliable equipment for insufflation (pumping gas into the abdominal cavity to create space in which to work) was developed. These two developments contributed to changing diagnostic laparoscopy from a non-standard technique used mainly by medical pioneers (many of whom were gynecologists) into a much more widely accepted diagnostic method ([24], Ch. 2; [13], p. 7). Many operative laparoscopic/pelviscopic techniques were pioneered by gynecologists as well, but only very recently (within the last five years or so) has operative laparoscopy been in common use ([24], p. 15; [13], p. 3).

2.1 Laparoscopic Procedure

There are several steps that all laparoscopic operations have in common. The patient can be given either local or general anesthesia, depending on the procedure to be done and the preferences of the surgeon and the patient ([13], Ch. 6; [24], pp. 37-39; [21], p. 28). The first major step of the procedure, and one of the most critical, is establishing the pneumoperitoneum. The pneumoperitoneum is a layer of gas (usually carbon dioxide) pumped into the peritoneal cavity (between the parietal peritoneum and the abdominal viscerae) in order to lift the abdominal wall and create space in which to work inside the patient. The surgeon inserts a Verres needle (a special spring-loaded needle) through the abdominal wall and the peritoneum into the abdominal cavity. Gas can then be pumped through a channel in the needle into the abdominal cavity. The surgeon must perform various tests both before inserting the needle and before beginning insufflation to ensure that the needle is inserted correctly and to avoid puncturing bowel or arteries. ([13], pp. 7-10; [24], pp. 132-171; [21], pp. 29-33.)

Next, the surgeon inserts the trocar, a metal rod with a sharp (usually conical) tip, through the abdominal wall. The trocar is placed in a cannula, or trocar sleeve, and both are inserted together, usually near the umbilicus. The trocar is then removed, leaving the cannula as a channel through which the laparoscope may be inserted. Cannulas have valves which prevent the gas from leaking out of the insufflated abdomen and a side lock for attaching insufflation tubing (see Figure 1). The cannulas come in different sizes (typically from five to ten millimeters in diameter) for use with different sizes of scopes or instruments. Additional cannulas may be placed in a similar manner at other locations on the abdomen for the insertion of various laparoscopic instruments. ([13], pp. 11-14; [24], pp. 144-146, p. 150; [21], p. 14, pp. 33-35.)

A laparoscope is essentially a rigid tube containing lenses and optical fibers with an eyepiece at one end. A light source cable is attached near the eyepiece. A video camera is usually attached to the eyepiece, allowing the image to be displayed on a monitor; before video endoscopes and laparoscopes became available (in the last few years), the surgeon had to place his or her eye up to the eyepiece. The field of view of a laparoscope is about thirty degrees ([28]). In some laparoscopes the view is centered around the axis of the tube, and in others it is at an oblique angle with respect to the tube. Although most laparoscopes are completely rigid, there are laparoscopes available with flexible ends (controlled by knobs outside the body). In contrast, gastrointestinal endoscopes are much longer than laparoscopes and must be completely flexible; only their tips are controllable. Gastrointestinal endoscopes also have narrow instrument channels in them since in a gastroendoscopic procedure there is no easy way to insert instruments except through the endoscope. ([13], pp. 14-16, Ch. 2; [21], pp. 9-12; [24], pp. 46-55.)

After the laparoscope is inserted into the body cavity, the main procedure can begin. The surgeon makes a preliminary survey of the abdominal cavity, then begins the diagnostic phase of the procedure. The operative phase of the laparoscopic procedure, if any, is done after the diagnostics are completed. The diagnostic phase includes a thorough examination of the area of suspected pathology, possibly including biopsies. Typical procedures performed in the operative phase include cholecystectomy, appendectomy, peptic ulcer surgery, adhesiolysis, tubal sterilization, puncture and excision of ovarian cysts, and many others ([13]; [24]). There are many instruments available for use in laparoscopic operations, including biopsy forceps, various types of graspers, scissors, tools for electrocautery, needleholders, and special suture loops for ligation. Most of the instruments are opened and closed via tendons attached to a handle that operates like the handle of a pair of scissors. (There are other instruments specific to gastrointestinal endoscopy, such as polyp snares.) ([13], pp. 19-28; [24], pp. 106-123; [21], pp. 9-25.) Some common laparoscopic equipment is shown in Figure 1.

After the operation is complete, the instruments are removed and the abdominal cavity is deflated. Closure of the puncture incisions is relatively easy; the surgeon can use either skin clips, staples, or a few stitches. ([21], p. 39; [24], p. 120, p. 142.)

2.2 Limitations of Laparoscopy

There are several limitations of the laparoscopic instruments and imaging equipment which make laparoscopy more awkward and difficult for the surgeon than traditional surgery. First, the view of the operative field through the scope is only two-dimensional, so the surgeon loses depth perception, making control of movements perpendicular to the viewing frame more difficult ([13], p. 39; [28]). Stereo endoscopes are currently being developed to address this problem. There are other disadvantages associated with the viewing system, including reduced angle of view, reduced resolution, and the lack of ability to scan a view by moving one's head ([28]; [13], p. 39, p. 85). There are also quite a few problems associated with the mechanical aspects of laparoscopy. Since the instruments pivot about a fulcrum in the patient's abdominal wall, the instrument moves left when the surgeon moves the handle right, and forward when he moves it back. This type of control does not exhibit stimulus-response compatibility, a natural correspondence between the movements of the operator and the movements of the tool; it is not very intuitive ([7]; [13], pp. 83-85). Also, the single access point to the abdomen makes it impossible for instruments to reach all positions and orientations; the instruments have only four degrees of freedom in position and orientation instead of six, which makes some tasks much more difficult. Since the instruments are rigid and unarticulated, they cannot bend around obstacles, so some areas of the abdominal cavity will be difficult to reach from any given entry point. The lack of dexterity when operating with these instruments makes some tasks especially difficult, like suturing and tying knots within the body

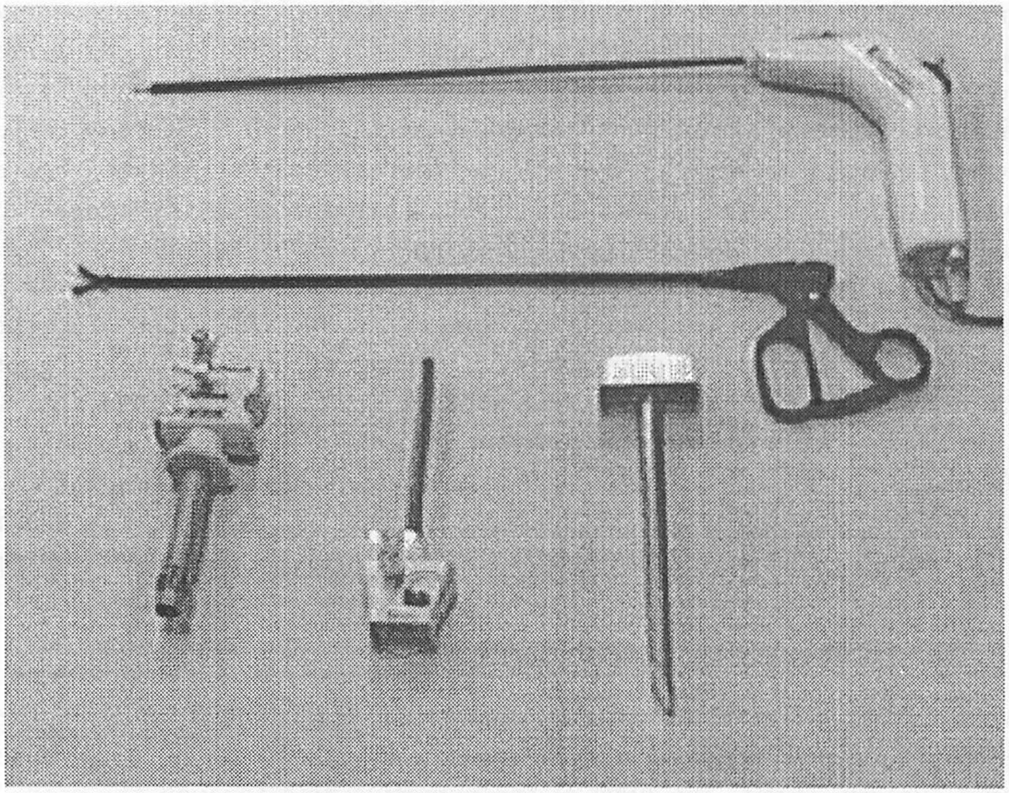

Figure 1: Laparoscopic equipment and instruments. From top to bottom: Electrocautery hook (for 5mm cannula), graspers (5mm), 10/11mm cannula, 5mm cannula, 10/11mm trocar.

cavity ([13], pp. 23-25; [24], p. 98). In addition, the instruments are single-purpose, so in order to change from grasping to cutting, for example, the surgeon must switch from one instrument to another.

Laparoscopic surgery offer the advantages of minimal invasiveness to the patient, but there is much room for improvement on the instruments and imaging techniques. Laparoscopy is often a preferable alternative to a traditional laparotomy, but the surgeon's lack of access and lack of dexterity in the abdominal cavity become severe disadvantages in an emergency, such as accidental puncture of a large artery. When complications occur, or even if upon examination of the abdominal cavity the surgeon decides the planned procedure cannot easily be performed laparoscopically, the operating team must switch to performing a standard laparotomy ([13], p. 79; [24], pp. 16-17, pp. 225-227).

3 Telesurgery

Teleoperation simply means remote operation. Since during a laparoscopic procedure the surgeon operates through the medium of the endoscopic instruments and observes the operation through the medium of the video equipment, laparoscopic procedures are essentially teleoperative. The first modern teleoperation system was created in 1945 by Raymond Goertz at Argonne National Laboratory to handle radioactive material in a sealed room. Teleoperative devices are now being used in diverse applications such as space exploration, undersea oil operations and scientific research, and toxic waste cleanup ([26]). Teleoperative systems are most effective when they encourage telepresence, the operator's feeling that he or she is at the site of the remote operation performing the task directly. Many of the problems with laparoscopic surgery discussed above can be considered to be facets of the lack of telepresence experienced by the surgeon performing the surgery with the currently available equipment.

In order to create a more natural-feeling link between the surgeon and the laparoscopic operation we envision a surgical workstation (*cf.* [23]). The surgeon will use a master device to drive a remote miniature robotic tool or hand. The robotic hand will replace current endoscopic instruments in the patient's body. The surgeon will receive visual, tactile, and force feedback from the operative environment. The visual feedback will be presented in a way that mimics what the surgeon would see if he or she were actually present inside the patient's body; the scene will move as the surgeon turned his or her head, for example. Similarly, the force and tactile feedback will be presented in such a way that the surgeon would feel as if it were actually his or her hand that was inside the patient.

A workstation like this would enhance the telepresence of the surgeon, improving his or her control of the operation. The robotic hand will be designed to have many degrees of freedom, including a wrist and elbow, for example, which will allow the hand to move more freely inside the body cavity and permit the surgeon to reach areas that are difficult to access with standard instruments. The surgeon will then also have more dexterity at his or her disposal, and so will be able to perform a wider range of procedures easily. Laparoscopic suturing and knot-tying inside the body cavity are particularly difficult with current endoscopic instruments, and there are times when suturing is preferable to using absorbable clips or electrocautery, such as when closing large wounds after the removal of an ovarian cyst, a tubal pregnancy, or an appendix ([13], p. 23; [24], p. 113). According to Anderson and Romfh ([1], pp. 43-58), completing even one stitch in a traditional suture using a needleholder involves ten distinct steps: positioning the needle in the holder (usually perpendicular to the holder), grasping the needle-holder, positioning the free end of the suture, placing the needle point, pushing the needle through the tissue, releasing the needle, regrasping the needle on the other side of the tissue, extracting the needle, pulling the desired length of suture through the wound, and repositioning the needle in the holder for the next stitch. All of these steps need to be completed smoothly for clean, accurate stitches, but manipulating the needle inside the body with current laparoscopic instruments is quite awkward. We intend to use suturing and knot-tying as representative tasks with which to test our prototype surgical workstation.

4 Hand Controllers/Masters

4.1 Types of Controllers

Many types of input devices have been used throughout the history of teleoperation; a survey and comparison of many of these can be found in Brooks and Bejczy ([7]). Switches, knobs, joysticks, and, more recently, spaceballs, are the simplest types of controllers. Other devices Brooks and Bejczy discuss include replicas, master-slave systems, anthropomorphic controllers, nongeometric analogic controllers, and universal controllers. A replica control input device is one which has the same geometry/kinematics as the manipulator but at a different scale. According to Brooks and Bejczy a master-slave system is a replica system whose scale is 1:1, but the term "master" is often used more generally to refer to almost any type of input device except the simplest ones mentioned above. An anthropomorphic input device derives signals directly from the arm and hand positions of the operator. A nongeometric analogic controller has a different configuration from the manipulator, but has some spatial correspondence with the manipulator or correspondence between its joints and those of the manipulator. A universal controller is one that can be used to control a manipulator with any configuration. ([7])

For a surgical application, we are interested in anthropomorphic controllers, since the surgeon is already extremely trained and dextrous with his or her hands and with hand-held tools. To make use of the surgeon's expertise, we also require stimulus-response compatibility between the controller and the surgical tool; as discussed section 2.2 above, standard laparoscopic instruments do not have this compatibility.

Some degree of universality in the controller is desirable, in order for the controller to be usable with several different surgical tools, but all of these will have similar structures, so the controller should not be so general that it sacrifices features useful for the surgical task. Our idea of a surgical workstation includes a miniature robotic hand to be used as the laparoscopic tool, and this hand will have sufficent dexterity that very few other tools would be required in any case (perhaps only scissors and electrocautery tools). In order to be an effective controller for surgery, the input device will have to have many degrees of freedom, not only to take advantage of this increased dexterity in the laparoscopic tool, but also to be able to distinguish between the many grasps the surgeon uses during the course of an operation. The controller should be usable with a single hand, so that the surgeon would have the option of using one in each hand or of having one hand free. From these considerations, we decided upon a glove-like input device. A glove device has clear stimulus-response compatibility with an articulated robotic hand, has many degrees of freedom, and can be used with other, less dextrous, teleoperative surgical tools as well by devising a suitable joint or position correspondence.

4.2 Grasps

The glove device must have the ability to distinguish between many different surgical grasps. Since suturing is one of the more difficult procedures to do laparoscopically and is a goal for our teleoperative workstation, I will concentrate on the grasps the surgeon uses in a (non-laparoscopic) suturing task. For a typical suture, the surgeon holds a curved needle with a needle-holder, an instrument similar in structure and size to a pair of scissors, but with a gripping surface at the end instead of a blade. There are four common grasps used in holding a needle-holder, depending on the precise nature of the suturing task: the palmed grasp, the thenar grasp, the thumb-ring finger grasp, and the pencil grasp ([1], pp. 46-50). The palmed grasp is an extremely stable grasp, and is used for tasks like pushing the needle through tough tissue, for which a lot of pressure is required. The thenar grasp is good for continuous suturing, since the surgeon can use this grasp for all the steps in suturing, and thus need not change grasps ([1], pp. 47-48). The thumb-ring finger grasp is used for more delicate suturing work ([1], pp. 48-49). The final grasp, the pencil grasp, is used with a Castroviejo needle-holder, which is similar to a pair of tweezers in shape. The needle can be locked into the jaws of this needle-holder and then released by applying finger pressure on the lock mechanism. The pencil grasp (also called the dynamic tripod) is the most sensitive of the four and is used with the Castroviejo needle-holder for delicate suturing ([1], pp. 49-50).

For some suturing tasks, the surgeon may use a hand-held straight needle. This needle is grasped with the thumb on one side and the index and middle fingers on the other ([1], pp. 58-60). This thumb-two finger grasp also permits precise, dextrous manipulation.

The most common knot used in surgery is the square knot ([1], p. 79), but there are others used as well. In traditional surgery, knots are usually tied with the fingers directly. When the ligature is held and manipulated while tying a half-hitch (half of a square knot), the right hand usually holds the ligature between the thumb and index finger (for a right-handed knot; a left-handed knot is done in reverse) ([1], pp. 81-85). The left hand grips the ligature between the palm and the last three fingers while using the thumb and index finger for manipulation ([1], pp. 81-85). If the free end of the suture is too short to be grasped in the right hand, the surgeon may use the instrument tie technique, in which the short end of the suture is held in a needle-holder or clamp ([1], pp. 100-102). Current laparoscopic techniques for tying knots inside the patient's abdomen are an adaptation of the instrument tie, using two instruments instead of one instrument and one hand.

Since the master device we have chosen is an anthropomorphic glove, and since it is designed to control a miniature robotic hand, it is more relevant to consider the grasps the surgeon employs when using the hand-held needle and when tying knots with the hands directly. Thus the most important grasps for our controller to be able to identify are the thumb-two finger grasp for holding the needle and the thumb-index finger grasp used in tying a square knot. The grasp used by the left hand while tying the half-hitch is extremely complicated and involves all five fingers and the palm (though only three virtual fingers plus the palm; the last three fingers function as one), so although it is important for tying square knots, it is too difficult to implement in a first prototype. To test the prototype workstation in the future, we will have the robotic hand play the role of the surgeon's right hand during knot tying, but will have a human hand play the role of the left.

4.3 Desired Features

There are several features that are important for a master device for telesurgery. The master must be comfortable, lightweight, and easy to use so the surgeon will not become fatigued ([18]; [7]). It must be easy to put on and remove, since the surgeon may need to use his or her hands in a hurry. Low cost is also important, so that hospitals will be more willing to try the new equipment. Most other desirable design features fall under the requirement that the system be "transparent" to the operator; in other words, that the glove should not interfere with but rather enhance his or her perception that he or she is actually at the site of the operation ([4]). In order to achieve transparence, the controller needs to have feedback from the slave device, including force feedback and tactile feedback. Force feedback gives the operator information about the magnitude of contact forces, while tactile feedback gives the operator information about texture and vibration. The importance of force feedback has been stressed by many authors ([3]; [4]; [8]; [25]; [26]), and studies have shown that simple teleoperative tasks are completed faster when the operator has force feedback available ([14]; [15]); more complicated tasks, although they may take slightly longer, are completed more accurately with force feedback ([25]). Force feedback will help the surgeon avoid injuring tissues by indicating when the robot hand comes up against an obstacle. Although there are many controllers available with force feedback, and have been for many years, dextrous controllers (those having many degrees of freedom, like a glove) with force feedback are still an area of ongoing research. Implementing tactile feedback would also be extremely difficult at present; tactile sensing and display systems have not yet been developed sufficiently to be used effectively with a dextrous control device.

For transparent operation, we also require that the joint movements of the controller correspond closely to the joint movements of the slave, so that stimulus-response compatibility is preserved as far as possible. It would be very difficult to achieve exact joint correspondence, for several reasons. First, the human hand (not including the wrist) has twenty degrees of freedom ([8]) and robotic hands typically have fewer. Second, the joints along one human finger do not bend strictly in the same plane, as do robotic joints, and the lengths of human finger segments change slightly as the joints bend ([18]). This complexity of the human hand structure makes it difficult to measure the joint angles accurately as well as difficult to create a glove and robot hand with corresponding joints.

For the control system to seem transparent to the operator, it also needs to have sufficient informational bandwidth. According to Brooks ([6]), the human hand can output information at a maximum rate of 5-10Hz (1-2Hz for unexpected signals, 2-5Hz for periodic signals, about 5Hz for "internally generated or learned trajectories," and about 10Hz for reflexes). It can receive information at 20 to 30Hz for force (kinesthetic) and position feedback and up to about 320Hz for tactile feedback. Sharpe claims that for skilled teleoperations, the forward position control loop needs to have a bandwidth of up to 20 or 30Hz and the force feedback loop needs to have a bandwidth of at least 300Hz and preferably 5-10kHz ([25]). Fischer, *et al.*, suggest position and force bandwidths of 50Hz ([12]). Comparing these numbers, it is clear that 50Hz should be sufficient for position information, as well as for most force information, though Sharpe found that some significant force information is present in the 500Hz to 5kHz range.

Other features affecting the transparence of the system include the friction, backlash, and inertia (and thus backdriveability) of the controller ([4]; [19]; [12]), and the impedance at the human/machine interface ([8]). Discussions of design criteria for teleoperative controllers can be found in McAffee and Fiorini ([19]), Fischer, *et al.* ([12]), Brooks ([6]), and Brooks and Bejczy ([7]).

4.4 Examples of Dextrous Controllers

One of the dextrous controllers most commonly used in research on dextrous teleoperative systems is the VPL DataGlove.. This glove uses flexible optical fibers on the back of the glove to sense the amount of bending of the finger joints; the more the joint flexes, the less light is transmitted through the optical fiber (see [11]). It measures the flexion and extension of two joints on each finger (including the thumb), abduction and adduction on the thumb, index, and middle fingers, and thumb-palmar abduction and adduction (see [26]; [16]; [20]). The glove can be coupled with a Polhemus sensor to give the position and orientation of the whole hand. The readings from the glove sensors, however, do not correspond directly to the joint angles of the hand and may be extensively correlated with each other, necessitating extensive calibration procedures to recover the actual joint angles from the glove readings ([16]; [20]; [26]).

Another dextrous controller that is gaining popularity is the Exos Dextrous Hand Master (DHM). The DHM is an exoskeleton that attaches to the joints of the hand and uses Hall-effect sensors to measure joint angles. It is more accurate than the DataGlove but is somewhat bulkier. The DHM measures four joint angles each on the thumb, index, middle, and ring fingers. ([18]; [11]; [26]; [20])

Neither these nor any other commercially available dextrous masters that I am aware of have force feedback. Various prototypes exist, however, and several are discussed by Burdea and Zhuang in [9]. Jones' and Thousand's 1966 glove provides force feedback via pneumatic bladders fixed underneath the glove's fingers. Another glove-like master is Zarudiansky's 1981 device, which implements force feedback through actuators connected on one end to a rigid external support and on the other to a ring around a finger segment or another portion of the hand. In 1989, Burdea and Speeter created a one-degree-of-freedom portable master that uses a "pneumatic micro actuator" to provide force. This master is used in combination with a position control system which can be switched between types of task control (pinching or rotation, for example). The final type of master discussed by Burdea and Zhuang is the kinematically identical master-slave system. An exoskeletal master of this type being designed at the University of Utah uses hydraulic actuators to provide force feedback, while one being designed at the Jet Propulsion Laboratories uses backdriveable pulleys.

5 Glove Design

Based on the considerations discussed above, I have designed and built a prototype glove for the telesurgery workstation described earlier. The glove was designed to control a miniature hydraulic robotic hand being developed in our laboratory by M. Cohn. Both of these prototypes will be incorporated into a testbed surgical workstation using the Robotworld platform (see Figure 2). Robotworld is a platform for industrial robotics applications. It can be used with a variable number of independent modules, each of which has four degrees of freedom: x, y, and z positioning and rotation about the z axis (angle θ). The glove will be attached to one of the modules and the slave to another, and we will make use of an already implemented master/slave controller with force feedback for these modules to drive the slave's z and θ. We do not currently have force feedback for the x and y positions, but will in the future. The master will thus have force feedback in the z and θ global positioning axes, but

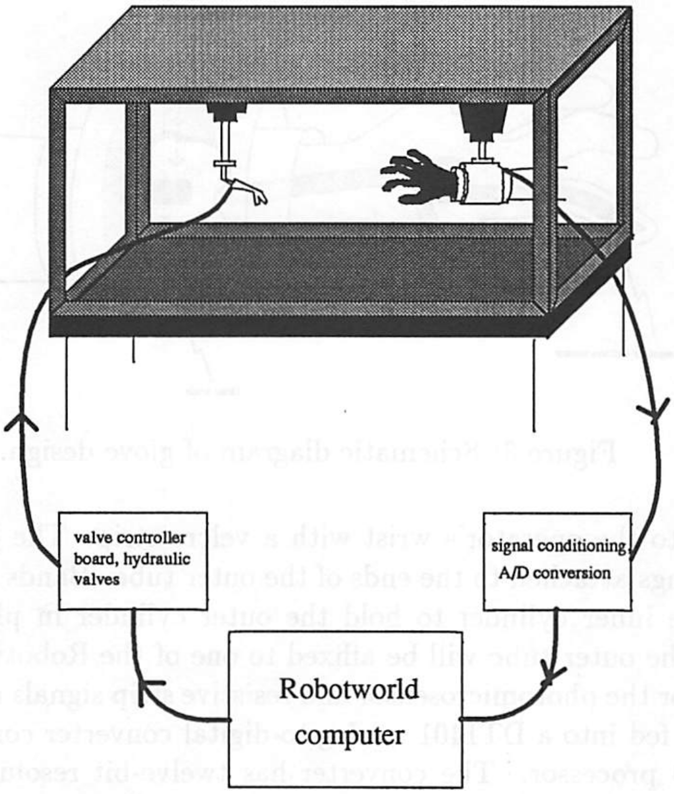

Figure 2: Testbed surgical workstation setup.

the prototype glove does not incorporate force feedback at this time. We decided to build a glove rather than purchase one of the commercially available dextrous masters because they are quite expensive, do not incorporate wrist rotation sensors, and have many more degrees of freedom than we need for controlling the initial prototype robotic hand.

The glove senses thumb, index finger, and wrist flexion and wrist rotation. It thus has sufficient degrees of freedom to control the miniature robotic hand prototype, which currently has a flexible wrist and a simple gripper (but will have more degrees of freedom in the future). The flexion sensors are made from resistive strips from a Nintendo Power Glove. The three strips are attached to a lycra glove on the dorsal side of the hand. The strips change resistance when bent, from the 100KΩ range for the unbent strip to the 200-300KΩ range for flexion in the preferred direction corresponding to a fully bent finger. The strips respond only slightly to bending in the non-preferred direction; their resistance decreases with bending in this direction. The wrist rotation sensor is made from two concentric plastic tubes (see Figures 3 and 4). The inner tube has a photomicrosensor (Omron EE-SF5) mounted in it, and the outer tube has a grayscale attached to its inner surface. When the two cylinders are rotated with respect to one another, the photosensor moves along the grayscale. The inner tube is hinged to allow the operator to insert his or her gloved wrist,

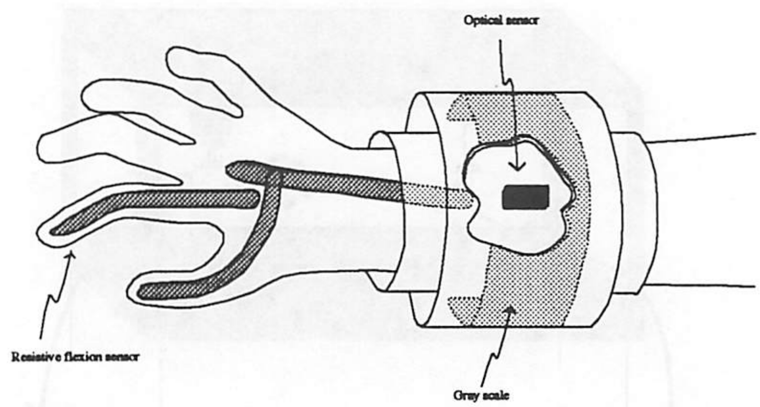

Figure 3: Schematic diagram of glove design.

and is secured to the operator's wrist with a velcro strip. The inner tube then fits snugly inside rings attached to the ends of the outer tube. Bands are fastened around each end of the inner cylinder to hold the outer cylinder in place but allow it to rotate freely. The outer tube will be affixed to one of the Robotworld modules. The circuitry used for the photomicrosensor and resistive strip signals is shown in Figure 5. The signals are fed into a DT1401 analog-to-digital converter communicating with a Motorola 68040 processor. The converter has twelve-bit resolution and, when the data presented here were taken, was operating with an input range of -10 to 10 volts.

5.1 Rotation Sensor

With a linear gray scale, the photosensor responds exponentially, so logarithmic grayscales were tested. Based on data from the linear scale, a scale predicted to produce linear output was generated by

$$f(t) = \frac{\log[(kt+\delta)/A]}{\log B}, \quad 0 \le t \le 1$$

with A=.121, B=58, δ=.2, and k=8. This grayscale did produce a nearly linear response from the sensor circuitry. However, the best linear fit to the data differed somewhat from the best 3rd or 5th degree polynomial fit, so new grayscales with small polynomial components were tested. The best of these was generated by

$$f(t) = c_1 \ln[t + .01] + c_2 + c_3 t + c_4 t^2 + c_5 t^3 + c_6 t^4, \quad 0 \le t \le 1$$

with the c's given in Table 1. This grayscale is shown in Figure 6, and the generating function is shown in Figure 7a. The scale was printed on a 400 dpi laser printer. Figure 7b shows the data generated with this grayscale when the sensor output was sampled every .5 inches along the circumference of the outer tube. This corresponds to sampling about every 16.2 degrees or .28 radians. The four different tests shown in the figure were designed to test the amount of play in the device. In the first

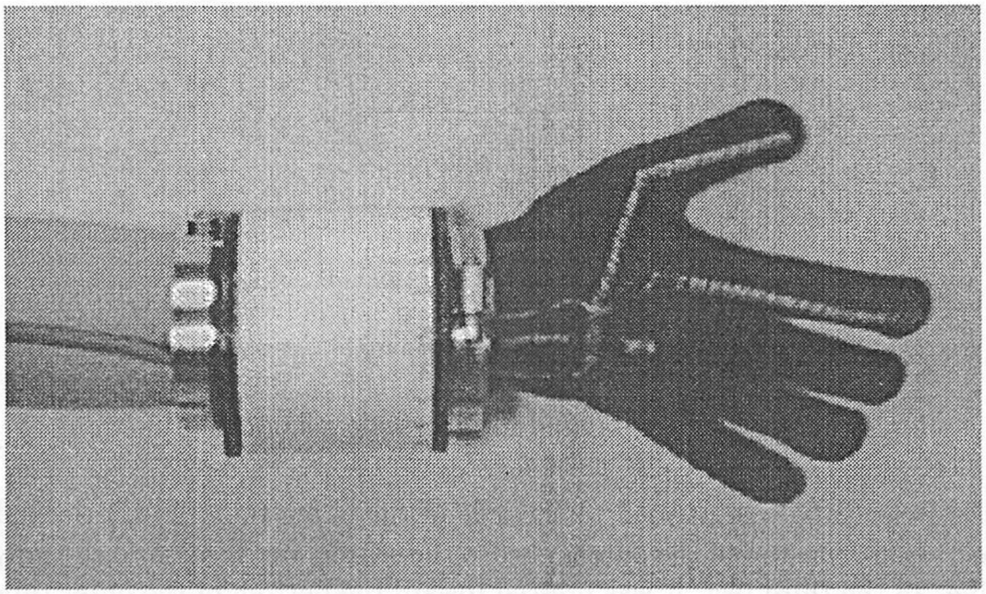

Figure 4: Prototype glove device.

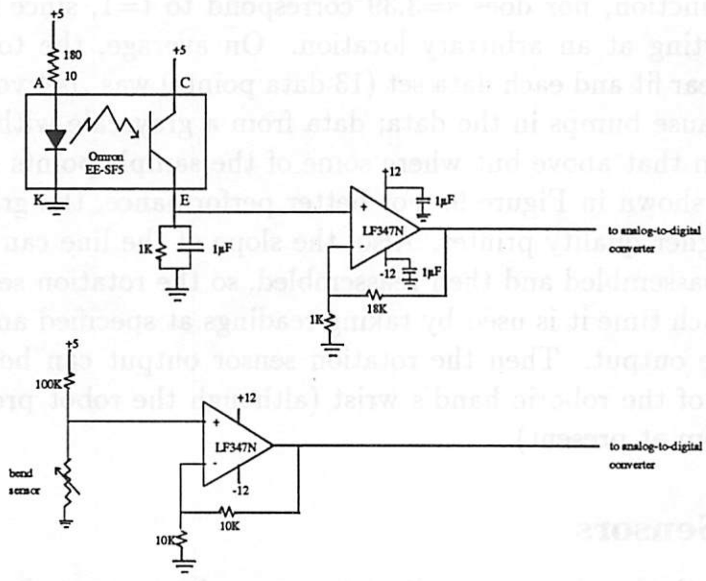

Figure 5: Circuitry for photomicrosensor and resistive strip signals. The top diagram is the photomicrosensor circuit; the bottom diagram is the circuit used for each of the three resistive bend sensors.

i	c_i
1	0.1479
2	0.8261
3	0.0408
4	0.9523
5	-1.3894
6	0.5687

Table 1: Coefficients used for grayscale generating function.

test the inner tube was pressed to the side of the outer tube. In the second, it was pressed toward the top of the outer tube, so the sensor was as close to the grayscale as possible. In the third test, it was pressed toward the bottom of the outer tube, so the sensor was as far from the scale as possible. In the fourth test, it was allowed to fall naturally. The data is very nearly linear; the best linear and fifth degree polynomial fits to the data are shown in Figure 8. The best linear fit was $1.9405s + 1.7696$, where $0 \leq s \leq 3.39$ radians. S=0 in this expression does not correspond exactly to t=0 for the grayscale function, nor does s=3.39 correspond to t=1, since the data samples were taken starting at an arbitrary location. On average, the total squared error between the linear fit and each data set (13 data points) was .144 volts^2. Flaws in the grayscale can cause bumps in the data; data from a grayscale with slightly different parameters from that above but where some of the sample points are lined up with printer flaws is shown in Figure 9. For better performance, the grayscale should be printed on a higher quality printer. Also, the slope of the line can change when the apparatus is disassembled and then reassembled, so the rotation sensor may need to be calibrated each time it is used by taking readings at specified angles to determine the slope of the output. Then the rotation sensor output can be mapped directly to the rotation of the robotic hand's wrist (although the robot prototype lacks this degree of freedom at present).

5.2 Flex Sensors

In order to map the bend sensor readings to appropriate output signals for the miniature robotic hand, the glove device needs to be calibrated. There are two issues involved: determining how the joint angles of the human hand map to sensor readings, and determining how to map the joint angles of the hand to the joint angles of the robotic hand. Hong and Tan ([16]) addressed the first issue for a VPL DataGlove; they determined the function mapping each joint angle to sensor response, keeping the other joints fixed, and then they eliminated the cross-correlation between sensors. Pao and Speeter ([20]) addressed the second issue at a functional level; they defined a set of matching human and robot hand positions and used this set to develop a

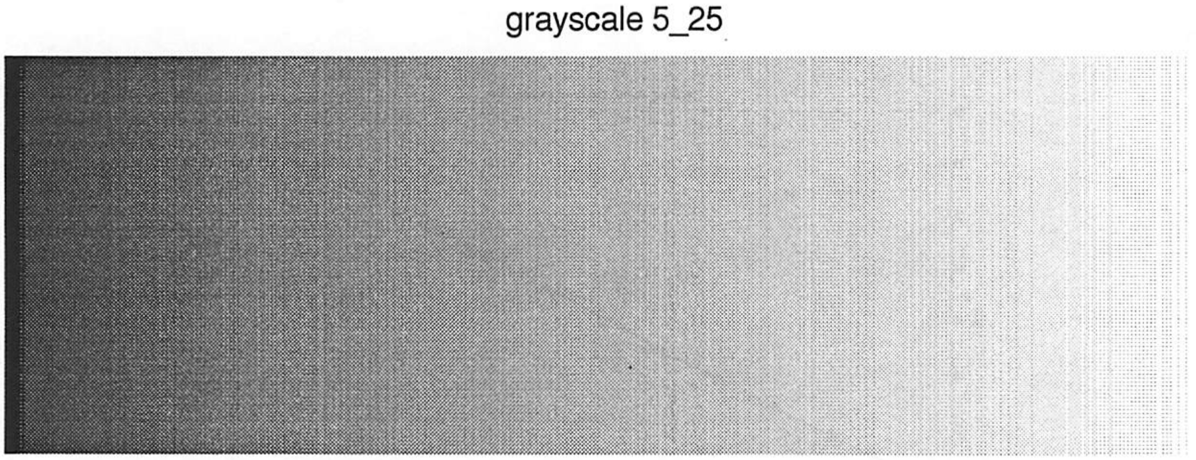

Figure 6: Grayscale.

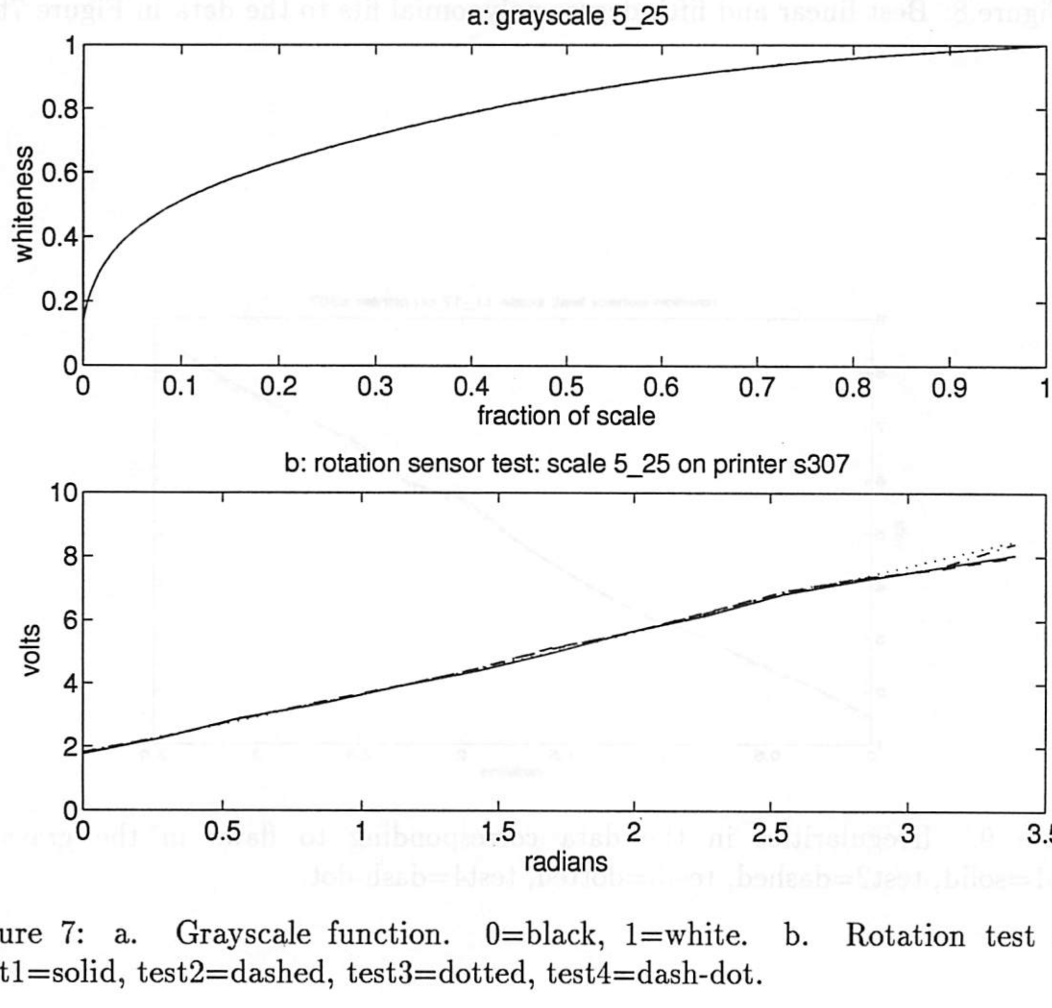

Figure 7: a. Grayscale function. 0=black, 1=white. b. Rotation test data. Test1=solid, test2=dashed, test3=dotted, test4=dash-dot.

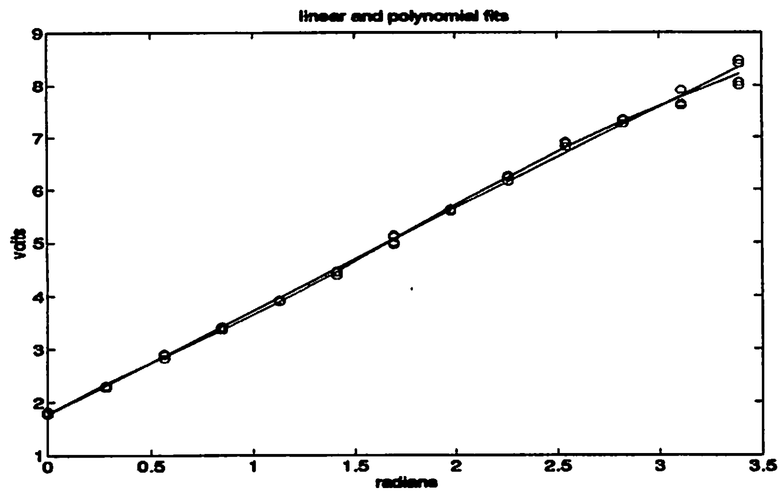

Figure 8: Best linear and fifth degree polynomial fits to the data in Figure 7b.

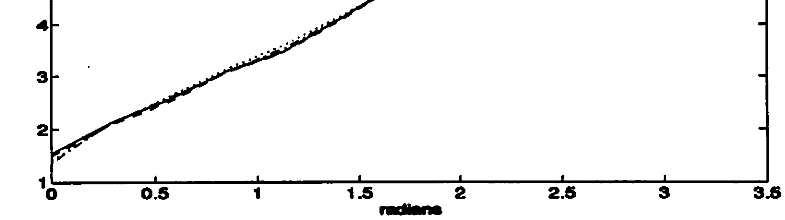

Figure 9: Irregularities in the data corresponding to flaws in the grayscale. Test1=solid, test2=dashed, test3=dotted, test4=dash-dot.

transformation matrix mapping human joint angles to robot joint angles. In our system, however, there is considerable degeneracy in both the mapping of joint angles to sensor readings and the mapping of human joint angles to robot joint angles, since there is currently only one bend sensor each for the index finger, thumb, and wrist, and the robot currently has only a wrist and a jawlike gripper corresponding to the human index finger and thumb. Also, the glove fits people with different sized hands differently, and thus gives slightly different readings for the same hand positions. The sensor readings can be functionally mapped to the robotic joint positions, however, by mapping the sensor readings taken from standard hand poses to similar standard poses of the robotic hand. Each subject would have a slightly different map.

I developed a simple calibration procedure to take sensor readings from subjects' hands in standard poses and took some preliminary data to assess the consistency and relevance of these readings. Four subjects, including myself, were tested, all of whom are right handed (the prototype glove is for the right hand). For the calibration procedure, the subject was asked to put his or her hand in a series of standard poses and the sensor readings for these poses were recorded. The standard poses used were relaxed hand position, wrist held flat, wrist maximally flexed (downward), maximally open hand position (index finger and thumb spread as far as possible), and pincing position. The pincing position used was the thumb-two finger grasp surgeons use for a hand-held straight needle, as described above (see Figure 10). This position was chosen since the current prototype of the miniature robotic hand has a gripper whose motion corresponds to a pincing motion of the thumb and fingers. I alternated the relaxed position with the other poses in the series of recorded hand positions (see Table 2). Each subject went through this calibration procedure twice, once before and once after a series of short tests in which sensor readings were taken while the subject moved his or her hand in a specified manner. For these tests, a timer was started that beeped every second, and the subject was asked to perform movements synchronized with the timer. First, the subject moved his or her wrist smoothly up and down, from a comfortable flexed position to a comfortable flat position (not necessarily as far apart as those used for the first part of the procedure), with the peaks and valleys of the movement coinciding with the beeps. The sensor readings were sampled at 50Hz (but were only recorded every tenth of a second for this experiment) for ten to eleven seconds. Second, the subject was instructed to move smoothly between a comfortable open position (not necessarily as far open as in the open position for the first part of the procedure) and the pincing position, again with the endpoints of the movement falling on the timer beeps. This movement was also recorded for ten to eleven seconds. Each of these two tests was then repeated. The relaxed hand position was sampled 18 times in each of the calibration runs (except for subject AC, for whom it was only sampled 17 times in the second run), the flat wrist position 3 times in each, the flexed wrist procedure 3 times each, the open position 3 times each, and the pincing position 9 times each.

The calibration data for subject DM are shown in Figures 11 - 13. The level

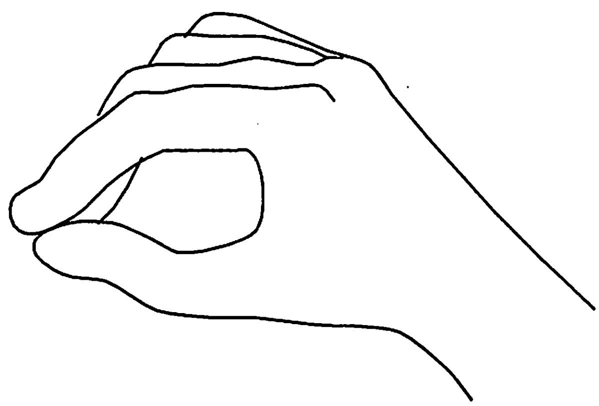

Figure 10: Diagram of pincing position used in calibration and movement tests.

relaxed	flexed wrist	flat wrist	open	pincing
1,3,5,7,9,11	2	4	6	8,10,12

Table 2: Order of hand positions for the calibration test. This series of twelve positions was repeated three times in each calibration run.

of consistency of the readings for this subject are fairly typical. Note that for the flexed and flat wrist positions, only the wrist sensor values were recorded, and for the open and pincing positions, only the thumb and index sensor values were recorded. The timed movement data from all four subjects is shown in Figures 14 - 25. In these plots, the calibration values for each subject have been averaged over both calibration runs and shown as horizontal lines. The average calibration values for all four subjects on each position are shown in Table 3. Although there are differences between subjects, the overall pattern of values for the different positions is fairly consistent across subjects.

subject	relaxed wrist	flat wrist	flexed wrist	relaxed index	open index	pinced index	relaxed thumb	open thumb	pinced thumb
DB	5.2535	5.1260	6.6220	5.8293	5.6568	7.3228	5.9545	6.1145	6.6692
AC	6.0906	5.1448	7.0632	5.8815	5.6417	7.0279	5.9973	6.1987	6.3333
LC	5.4614	5.0608	6.8823	5.8439	5.6758	7.4572	5.9522	5.9433	6.6938
DM	6.0651	5.2130	7.3697	5.7276	5.6737	7.2751	5.9551	6.2717	6.3184

Table 3: Average calibration values for all subjects, in volts.

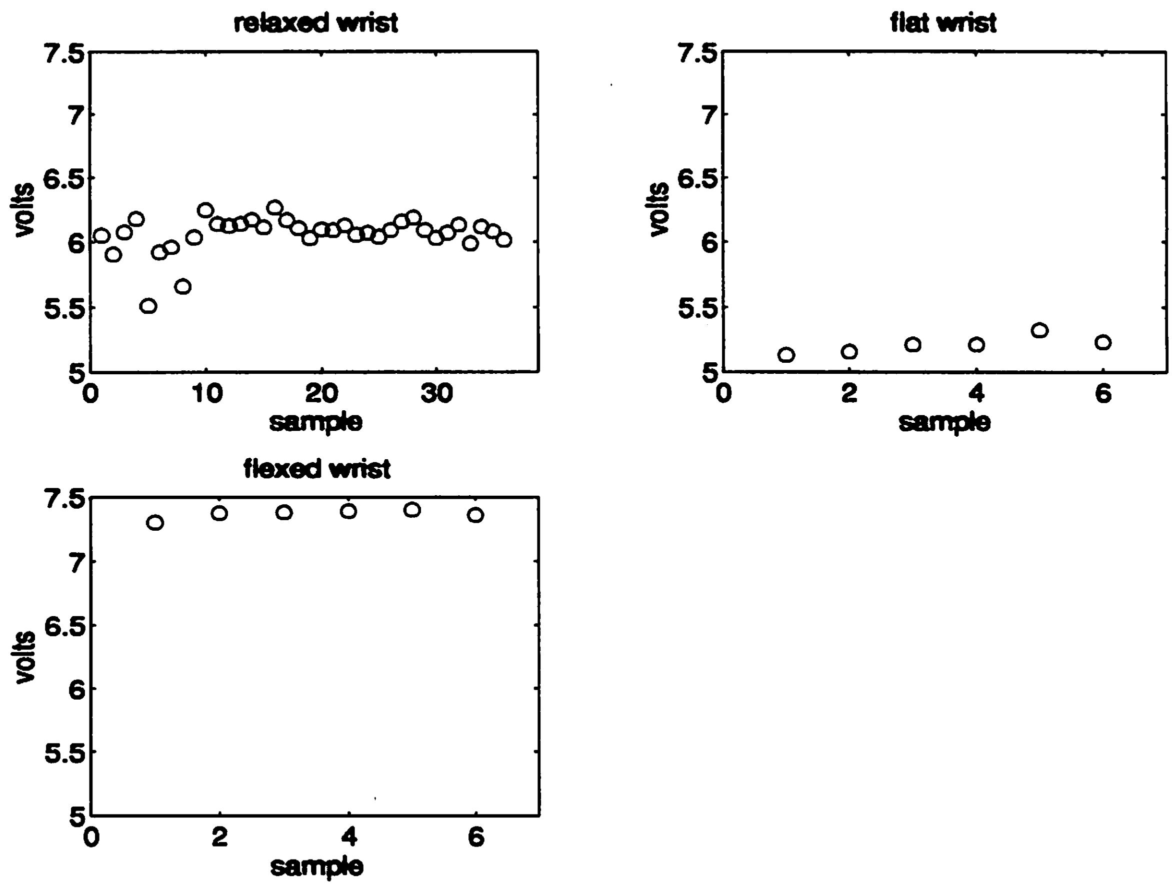

Figure 11: Wrist position calibration data for subject DM. The first half of the samples in each plot are from the first calibration run, and the second half are from the second run.

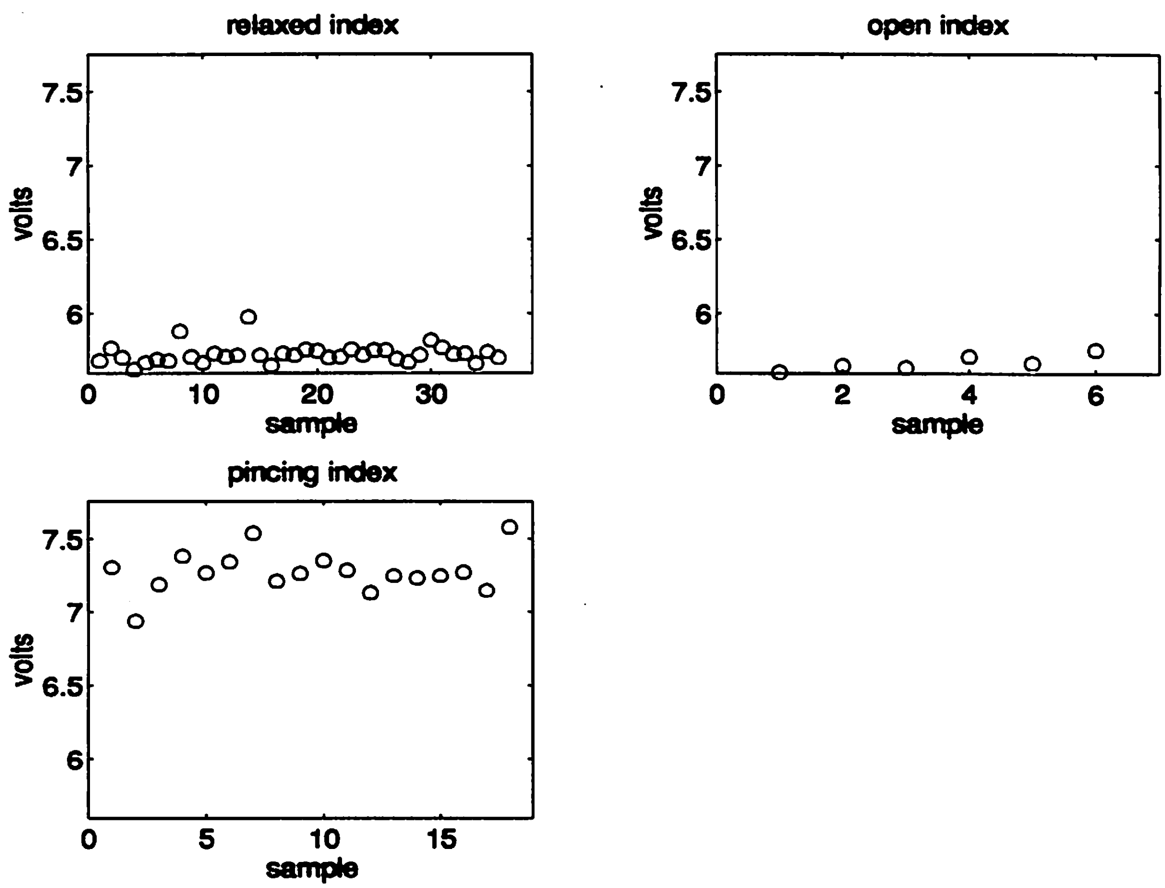

Figure 12: Index position calibration data for subject DM. The first half of the samples in each plot are from the first calibration run, and the second half are from the second run.

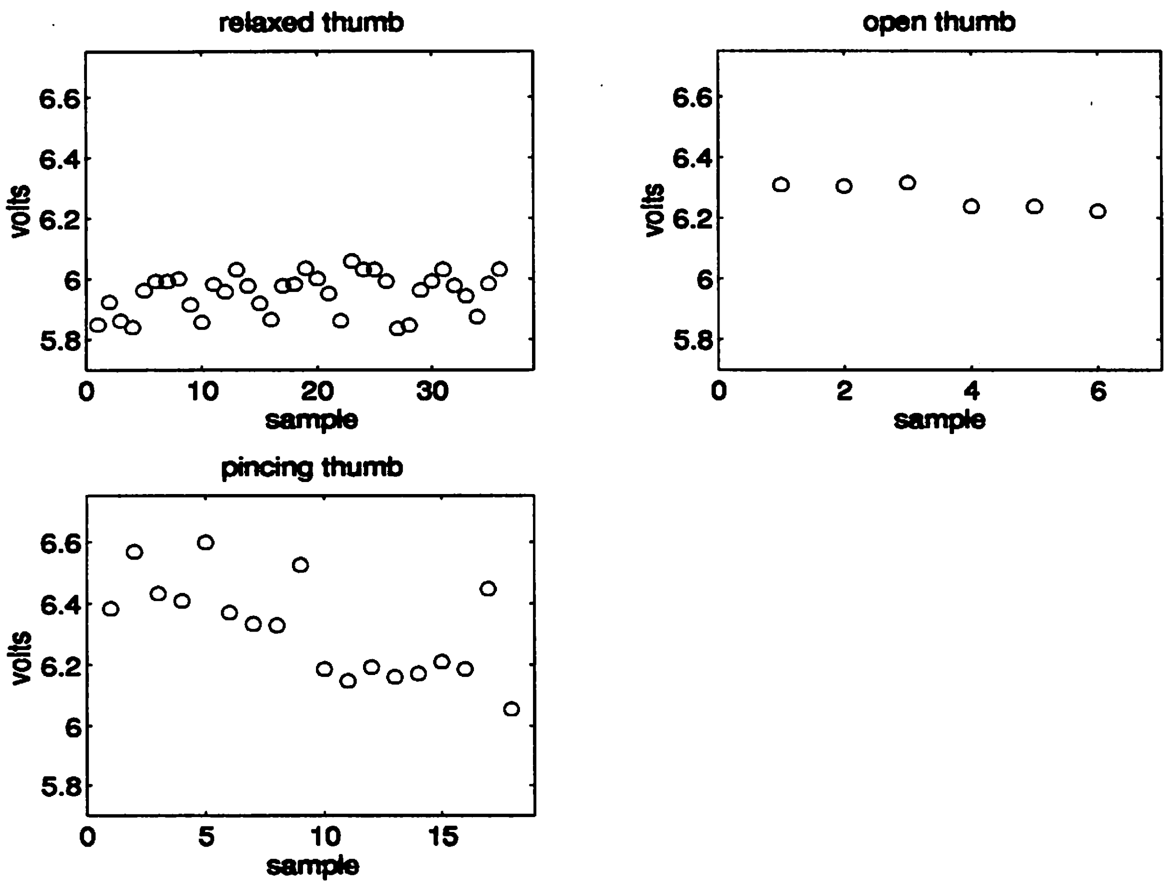

Figure 13: Thumb position calibration data for subject DM. The first half of the samples in each plot are from the first calibration run, and the second half are from the second run.

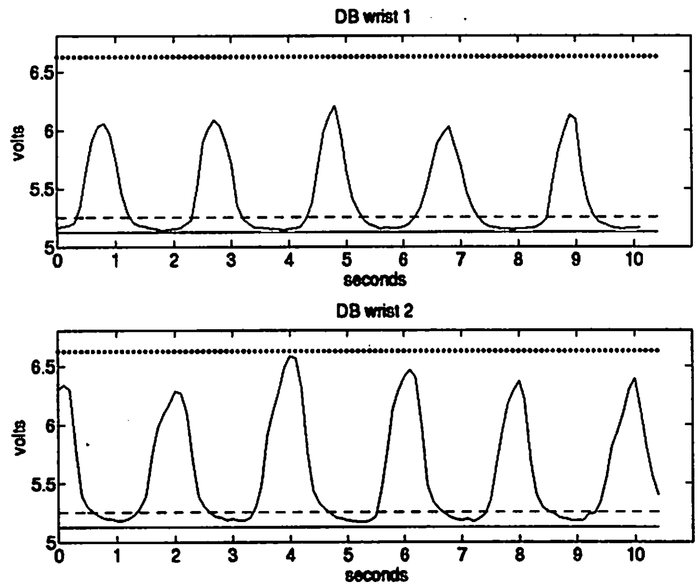

Figure 14: Wrist movement data for subject DB (two trials). Calibration data averages are shown as horizontal lines (flat=solid, relaxed=dashed, flexed=dotted).

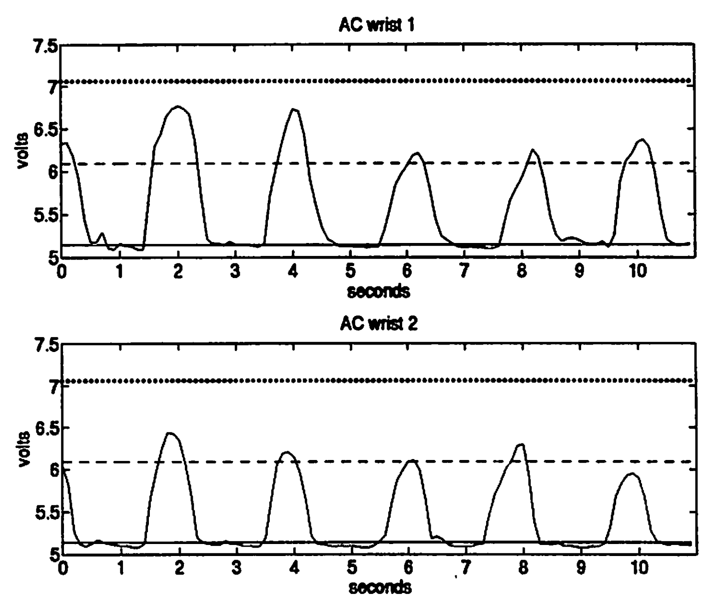

Figure 15: Wrist movement data for subject AC (two trials). Calibration data averages are shown as horizontal lines (flat=solid, relaxed=dashed, flexed=dotted).

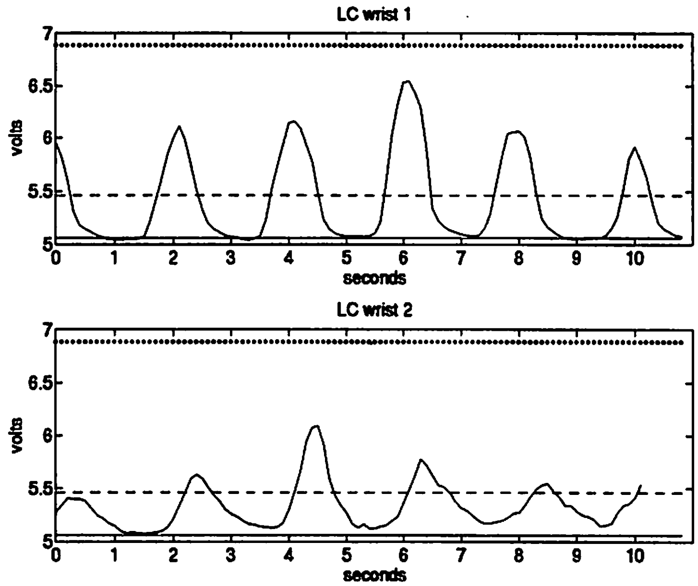

Figure 16: Wrist movement data for subject LC (two trials). Calibration data averages are shown as horizontal lines (flat=solid, relaxed=dashed, flexed=dotted).

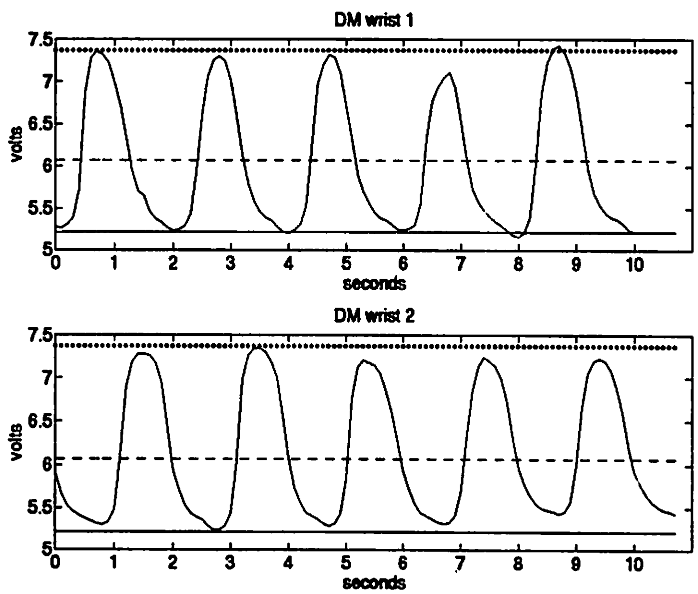

Figure 17: Wrist movement data for subject DM (two trials). Calibration data averages are shown as horizontal lines (flat=solid, relaxed=dashed, flexed=dotted).

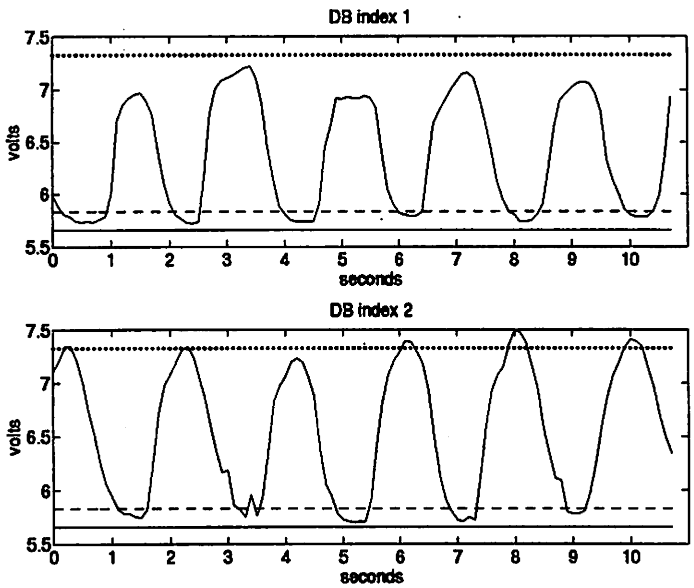

Figure 18: Index movement data for subject DB (two trials). Calibration data averages are shown as horizontal lines (open=solid, relaxed=dashed, pincing=dotted).

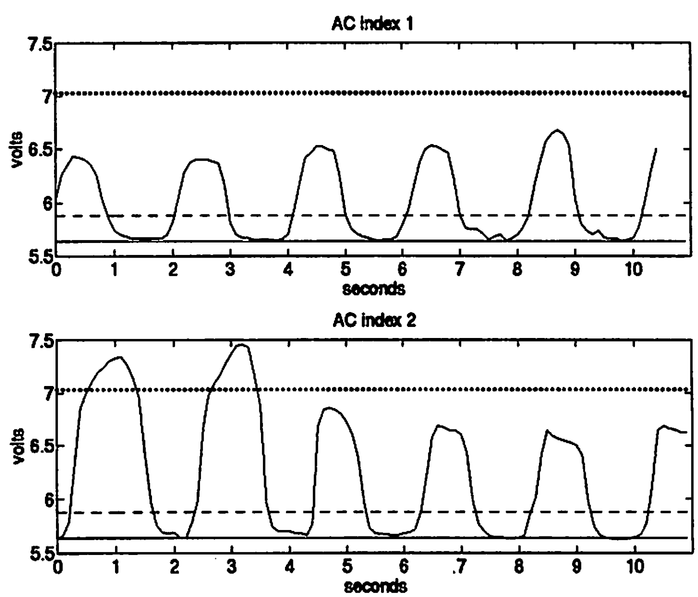

Figure 19: Index movement data for subject AC (two trials). Calibration data averages are shown as horizontal lines (open=solid, relaxed=dashed, pincing=dotted).

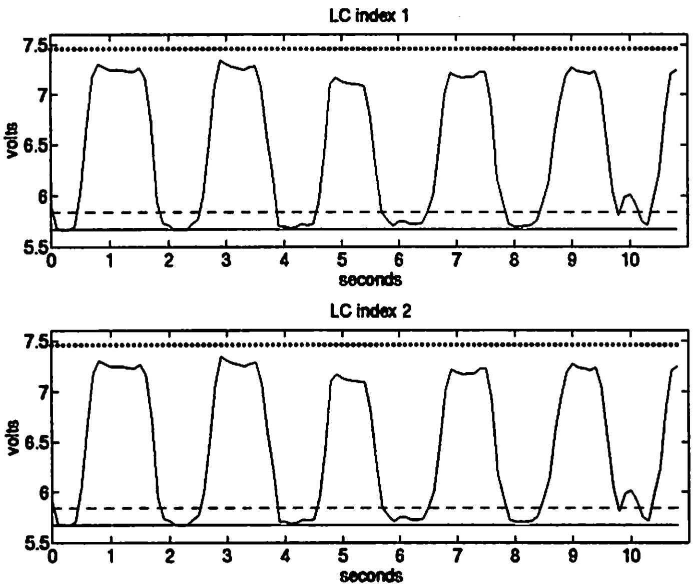

Figure 20: Index movement data for subject LC (two trials). Calibration data averages are shown as horizontal lines (open=solid, relaxed=dashed, pincing=dotted).

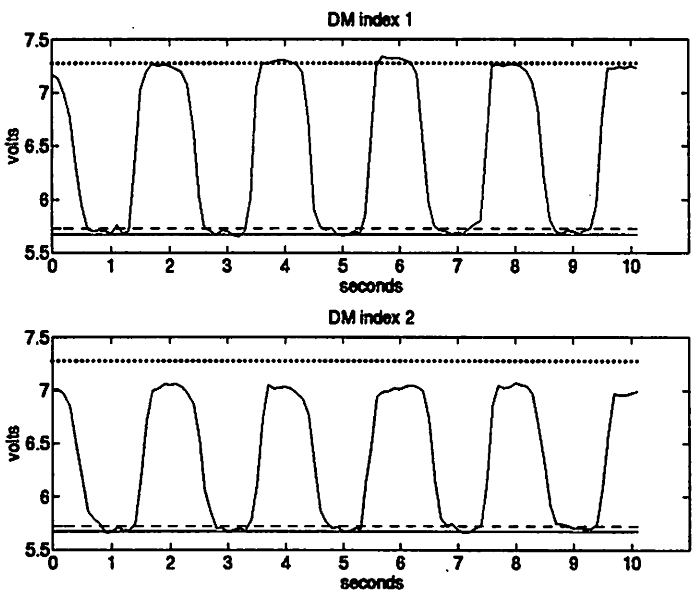

Figure 21: Index movement data for subject DM (two trials). Calibration data averages are shown as horizontal lines (open=solid, relaxed=dashed, pincing=dotted).

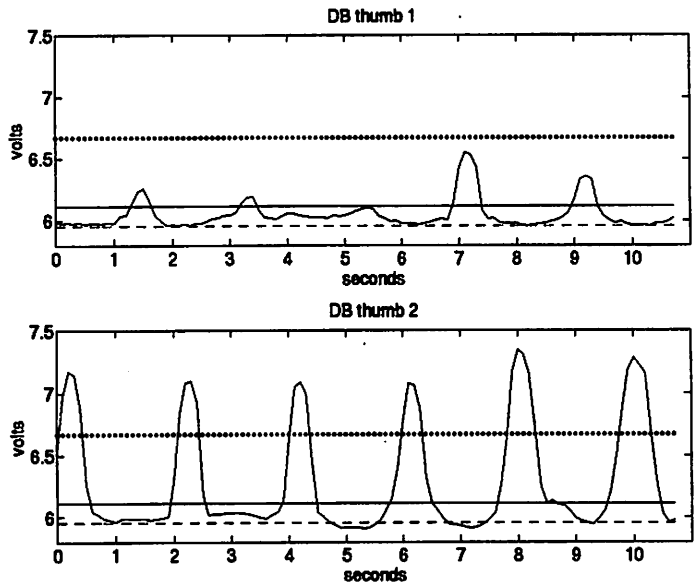

Figure 22: Thumb movement data for subject DB (two trials). Calibration data averages are shown as horizontal lines (open=solid, relaxed=dashed, pincing=dotted).

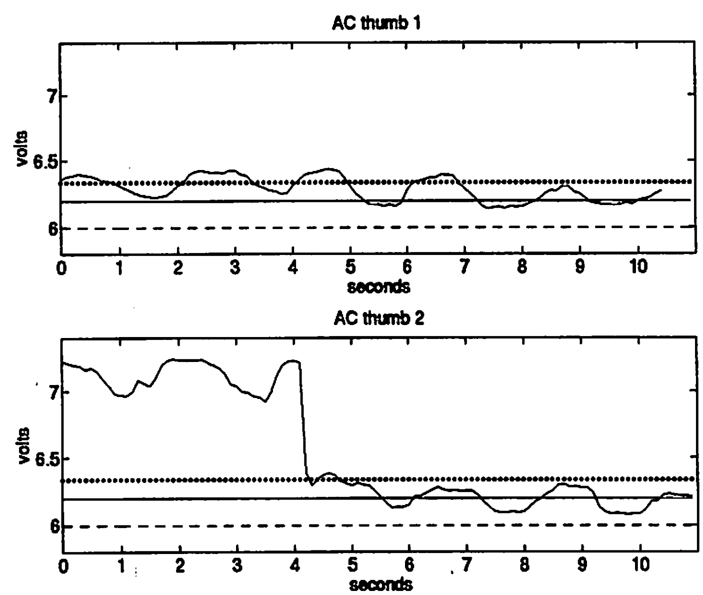

Figure 23: Thumb movement data for subject AC (two trials). Calibration data averages are shown as horizontal lines (open=solid, relaxed=dashed, pincing=dotted).

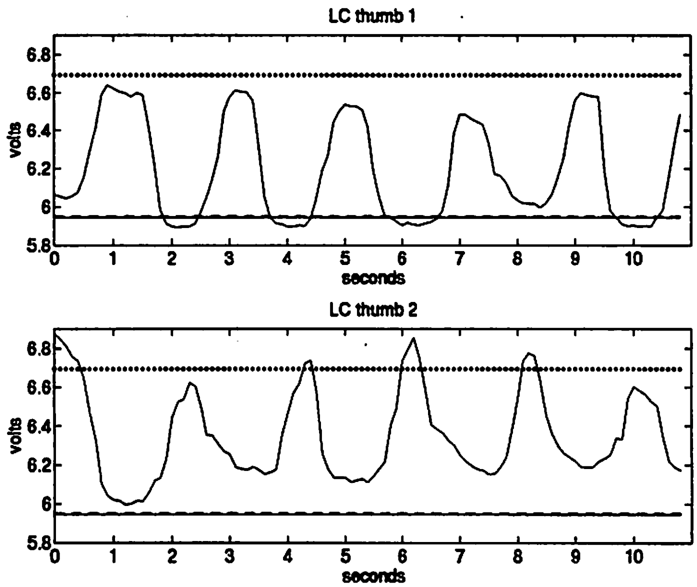

Figure 24: Thumb movement data for subject LC (two trials). Calibration data averages are shown as horizontal lines (open=solid, relaxed=dashed, pincing=dotted).

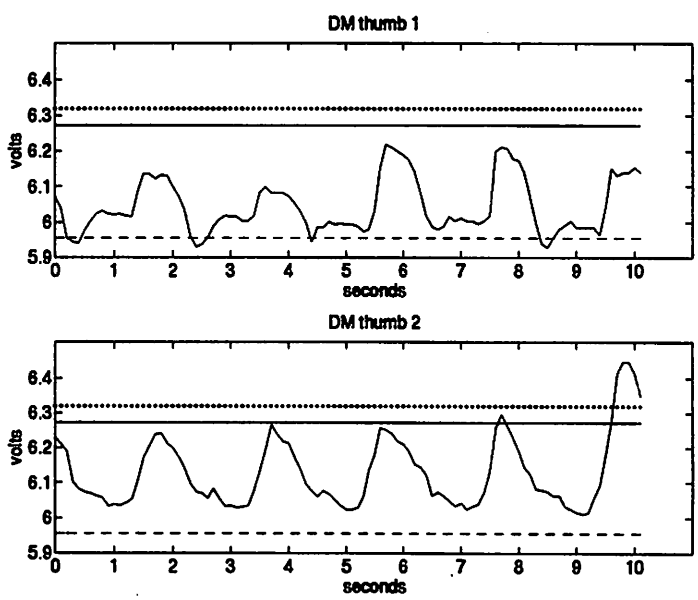

Figure 25: Thumb movement data for subject DM (two trials). Calibration data averages are shown as horizontal lines (open=solid, relaxed=dashed, pincing=dotted).

From the data in Figures 14 - 25, one can see that subjects were fairly consistent in their movements, at least within each trial, and that for the stylized movements tested, the calibration values appear to be fairly consistent with the values recorded during movement for both the index finger and the wrist. The thumb values vary widely; the value of a thumb reading does not seem to give a consistent indication of how far open or closed the pincing movement is. Unfortunately, since there is only one strip on the thumb and one on the index finger, individual joint angles in these fingers cannot be detected; a pincing position in which the thumb and finger are more rounded will give a higher sensor reading than one in which the fingers make contact on the pads of the fingers (rather than the tips). This problem could explain the differences in subjects' traces from trial to trial; a subject might adopt a slightly different pincing pose for each trial. The thumb values seem to be more variable in this respect, possibly because the carpometacarpal joint at the base of the thumb is so complex, or possibly because thumb movement was not as important as index movement for the subjects' pincing motions; the index finger traces have larger amplitudes than the thumb traces and differ much less between trials and among subjects. This variability would probably be lessened by using more (shorter) bend sensors, perhaps one for each finger joint. For the current design, though, when mapping the sensor values to the robot gripper position, the thumb sensor reading should not contribute strongly; how far the gripper is open should be determined mainly by the index reading. For the index finger, the movement values rarely go above the pincing calibration value or below the open calibration value, so a plausible mapping would map the open sensor value (and anything below it) to a fully open gripper and the pincing value (and anything above it)to a fully closed gripper. The intermediate values would correspond to intermediate states of the gripper. The valleys of the index finger movement are pretty consistent for each subject, falling at a value between the open and relaxed calibration values. The peaks are less consistent, as discussed above, but come fairly close to the calibration value in most subjects, and rarely overshoot it, so this mapping would be fairly reliable. Similarly, the valleys of the wrist movement are fairly consistent for each subject, falling between the relaxed and flat calibration values. The subjects were told not to flex their wrists completely to the calibration position during the movement if it was not comfortable to do so, so the difference between the peaks and the flexed calibration value represents the difference between comfortable wrist flexion and absolute maximum flexion. Since the wrist values rarely go below the flat calibration value or above the flexed calibration value, the flat value could be mapped to the flat robot wrist and the flexed value to the fully flexed robot wrist. The variation across subjects in the separation between the relaxed wrist value and the flat value is probably due to subjects resisting the effects of gravity on their hands different amounts.

The subjects were instructed not to bend their wrist upward past the flat position, since, especially for subjects with small hands, the wrist flex sensor tended to buckle when the wrist was bent upward, producing anomalous readings (see Figure 26). A

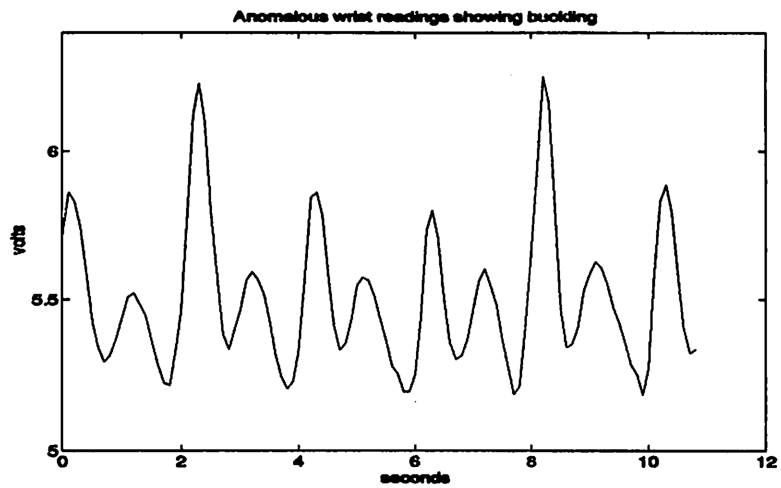

Figure 26: Anomalous readings in wrist movement tests due to buckling in the wrist flex sensor. The smaller peaks are caused by the buckling.

similar problem with the thumb sensor may have caused the open thumb calibration value to be higher than the relaxed thumb calibration value on three subjects, in this case, those with the largest hands.

6 Conclusions and Future Work

This prototype glove device has several advantages for use as a dextrous master for telesurgery. First, it is quite inexpensive compared to commercially available dextrous masters. It incorporates a wrist rotation sensor, which would be useful in orienting a surgical tool inside the body cavity. The device is lightweight and has very little friction and thus is not fatiguing to the operator. The system is currently sampling the glove sensors at 50Hz, which is sufficient for sampling human hand outputs, as discussed in section 4.3 above. The motions of the thumb and index finger correspond in a natural way to the motion of the gripper of the slave robot. For a simple test suturing task, input from the thumb, finger, and wrist should be sufficient to convey the motions of an operator using the thumb-two finger grasp for a hand-held straight needle. Since the signals from the joint sensors and the rotation sensor can be mapped directly to desired positions of the robot joints, very little computation is needed for position control of the slave.

This glove is an initial prototype, however, and much work remains to be done. The robotic slave will eventually have more degrees of freedom, so more sensors will be required on the glove to control them. To better control articulated robotic fingers, the glove should have separate flex sensors for each joint. The calibration procedure should also be further developed to more precisely define a map between sensor readings and control outputs. For better telepresence and more accurate control, the glove should also incorporate force feedback. Tactile feedback would also help the surgeon to navigate inside the abdomen and to distinguish cancerous from normal tissue. The current glove prototype is also somewhat tedious to put on and remove; future prototypes should have an improved physical design for easy assembly and disassembly. The glove prototype and the miniature robotic hand prototype will be incorporated into a testbed surgical workstation on Robotworld, on which we can test the prototypes on such tasks as suturing and knot tying. My preliminary data suggests that the glove device will function well as a master for executing these test tasks.

Minimally invasive techniques have changed the traditional approach to many common types of operations as well as opened up possiblities for new operations. Telesurgery has the potential to further revolutionize surgery, allowing surgeons to perform endoscopic and laparoscopic operations with increased confidence, versatility, and dexterity. The prototype glove device described here is the first step in developing a dextrous master to provide a natural means of controlling a miniature robotic hand in the context of a teleoperative surgical workstation.

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