DESIGN OF A GONIOMETRIC INPUT DEVICE FOR MASTER/SLAVE CONTROL OF A TRANSHUMERAL PROSTHESIS

By

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To my loving wife, Amber, whose caring must know no bounds.

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CHAPTER I

INTRODUCTION

The Center for Intelligent Mechatronics is developing an upper limb prosthesis powered by chemofluidic actuation. The device uses the catalytic decomposition of hydrogen peroxide into steam and oxygen to supply high pressure gas to nine pneumatic cylinders which function as the device's mechanical actuation.

The goal of the prosthesis is to enable amputees to regain the ability to perform so-called "activities of daily living." These sorts of activities are not well defined but can be thought of as any task which is regularly performed by an average person on an average day. Some examples include mundane tasks such as drinking from a glass, dressing one's self, etc. Since the term is fundamentally ambiguous, a means for evaluating the performance of the prosthesis relative to a natural upper limb must be developed in order to ascertain the device's usefulness to a disabled individual.

While it is certainly possible to develop software that can emulate the sequence of motions a person follows to achieve a given task, it is a time-consuming and laborious process. Further, pre-programmed motions would not employ the visual feedback and cognition for many such tasks. The tactic employed by the author is to instead use real-time measurements of a normal human subject to serve as a reference trajectory for the prosthesis. This method provides signals which are guaranteed to be in the range of normal human performance and by definition serve as a metric of comparison for the performance of the prosthesis.

To this end, an electrogoniometer has been developed that measures the relevant joint rotations of an operator's upper limb and provides signals in proportion to these measurements to the prosthesis. The prosthesis, in turn, is made to follow these signals to form a master-slave relationship between the human operator outfitted with the electrogoniometer and the prosthetic arm as shown in Figure 1. Use of the described goniometer also allows testing to take place without the necessity of having an amputee operator and commensurate neural signal capture techniques and subsequent training with the device.

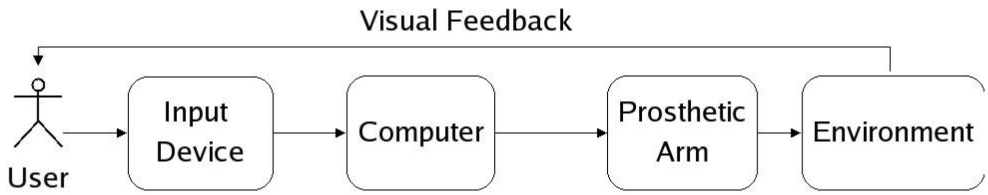

Figure 1. Block diagram of master/slave system

CHAPTER II

SLAVE SYSTEM DESCRIPTION

Overview

Because the electrogoniometer is designed specifically to provide input signals for the particular prosthetic arm in question, it is useful to give an overview of how the prosthesis is designed and constructed. The prosthetic arm has nine degrees of actuation as follows:

1. Elbow flexion/extension
2. Wrist flexion/extension
3. Wrist pronation/supination
4. Wrist radial/ulnar deviation
5. Differentially coupled thumb opposition and palm "cup ping" motion
6. Thumb flexion/extension
7. First digit flexion/extension
8. Second digit flexion/extension
9. Differentially coupled flexion/extension of third and fourth digits

Elbow and Wrist

The prosthetic arm features a traditional elbow as well as a three axis-of-rotation wrist. Each of these four arm rotational axes is actuated by a bidirectionally powered pneumatic cylinder and powered by the catalytic decomposition of hydrogen peroxide as described above. Use of the bidirectional cylinders allows the replacement of a pair of antagonistic muscles in a normal joint with a single actuator in the synthetic joint.

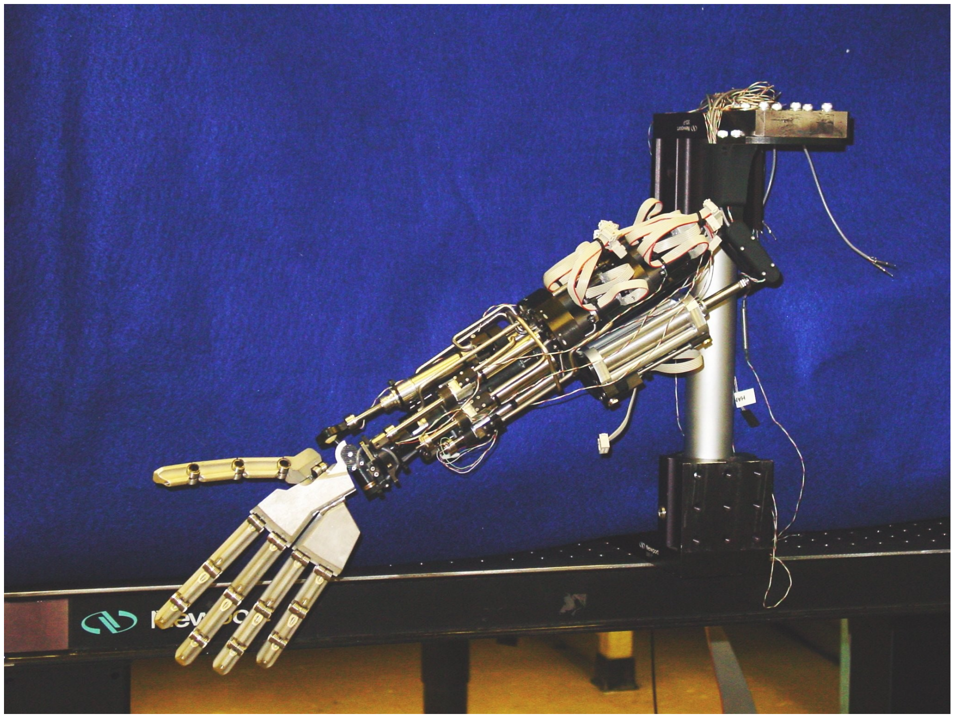

Figure 2. Prosthetic arm as a slave for input device commands

Hand

The hand portion of the prosthesis is anthropomorphically designed and features four fingers and a thumb. Each of the phalanges is composed of three links which are connected in series by a pair of counter-wound torsional springs at each joint as shown in Figure 3. A cable is affixed to the distal most link and is threaded through the interior of each link as well as through the interior of the palm. The cable is then terminated at its finger's actuator. Application of a pulling force on the cable causes equal angular retraction at each of the three finger joints.

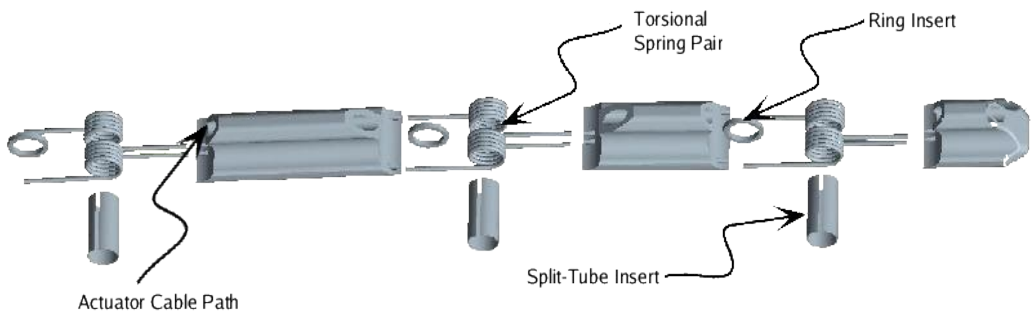

Figure 3. Exploded view of stereotypical prosthetic finger

The fingers are actuated by a unidirectionally powered pneumatic cylinder for the first digit, second digit, the thumb, the coupled third and fourth digits, and the thumb opposition. This actuation scheme allows each finger's "curl" to be controlled by a single actuator and reduces the total number of actuators needed for the arm. Although there is an intrinsic loss of independent degrees of freedom, it is argued that the loss is of redundant functionality and that the loss does not have an excessively negative effect on the aggregate performance of the synthetic arm. Feedback control is made possible using only load cells in the path of each actuation cable as sensors.

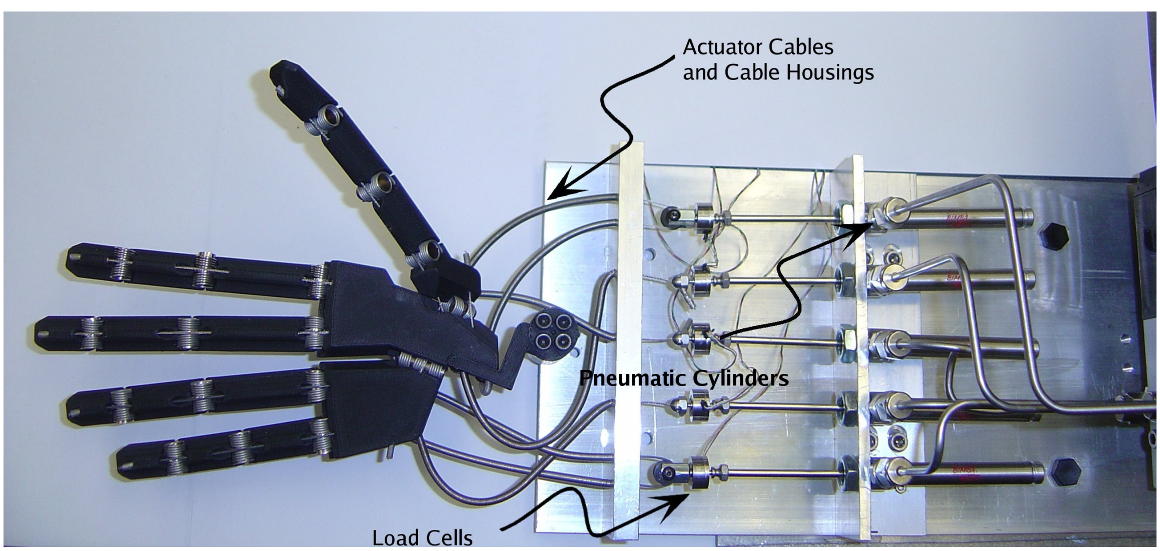

Figure 4. Servopneumatic hand testing apparatus.

In essence, the synthetic hand is designed with force control in mind as most, if not all, important activities undertaken with a natural hand involve interaction with foreign objects through pressing, grasping, and other methods. That is, there is no need to transition between force control and position control, as the sets of torsional springs in the finger joints allow force control to be used at all times. When the fingers are in contact with an object, the pre-contact motion of the fingers is replaced by the application of some force on the object. In other words, the fingers will naturally conform to the shape of an object as a product of the joint springs and the cable actuation system.

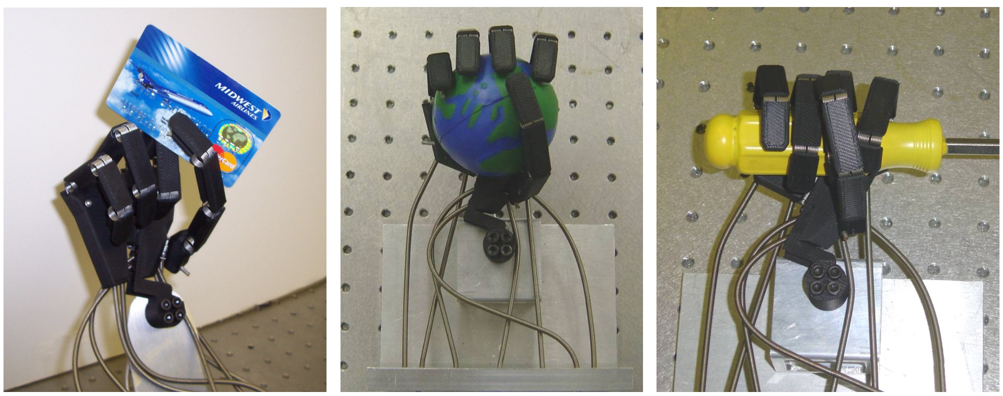

Figure 5. Prototype hand demonstrating lateral pinch, spherical, and cylindrical type grasps.

CHAPTER III

HUMAN FACTOR CONSIDERATIONS

Elbow and Wrist

The joint motion of the human elbow and wrist can be idealized as simple pin joints. However, because of the complex geometries of human bones, the actual motion of the elbow and wrist is complex and difficult to characterize. Therefore, any device which attempts to capture or measure this motion must necessarily make allowances for these non-ideal features. For the prosthetic arm in question, the elbow and wrist joints are designed as actual pin joints in which rotation occurs about a fixed axis. Because of this disparity, the input device must reduce the complex rotary motion of the human operator's joints into a comparable motion about a fixed axis.

Hand

As noted in the description of the slave system earlier, the prosthetic hand is designed to negate the need for a control system that switches between force control and position control. While this is convenient for control of the hand and provides natural motion of the individual phalanges, providing a reference command to the control system is made somewhat more difficult since a signal which is indicative of the internal torque in the user's finger needs to be identified. Alternatively, a more easily measured signal that the user can easily exert and that requires no more than trivial mental effort to distinguish as being mapped to a force applied by the prosthesis actuators could be used.

Traditional user interfaces that involve hands are focused on displacement-type interaction. These include gloves that measure the user's hand and arm configuration, joysticks, and mice, which can be thought of as measuring the relative excursion of the user's hand. As the prosthesis is using force control in the hand, it is important for the input device to provide force reference commands. Few devices exist that measure force input and these are mostly limited to expensive haptic devices that in general do not provide measurements that map well to the actuated degrees of freedom in the prosthesis and some video game controllers that have only crude force resolution.

A preliminary input device prototype for hand input was similar to the Immersion CyberGlove and would have allowed the user to directly command finger positions of the prosthesis. Note that this prototype was constructed before the design and the control scheme of the prosthetic hand had been finalized. The glove device was custom manufactured and featured integrated flexible resistive sensors (Spectra Symbol) that provide a resistance change proportional to the average radius of the sensor's deformed shape. However, while the prototype functioned as expected and the user was able to intuitively control hand position of a graphical computer simulation, the resultant signals were not particularly well suited for control of the physical prosthesis.

As the prosthesis is not outfitted with position sensors on the hand and fingers, no possibility exists for position signals to be used in a servo control scheme. Since the fingers are constrained with springs, however, it would be possible to transform the load cell measurements on the prosthesis into assumed finger position signals for feedback comparison with the position signals from the glove input device. Unfortunately, this notion does not allow for the interaction of the device with external objects that will constrain the prosthetic fingers' motion. Alternatively, the position signals from the human operator could have been used as proportional to desired forces. This proved impractical as the small forces needed to realize gestures when the prosthetic hand is not in contact with other objects required greater spatial resolution than a human operator could realistically achieve using the prototype.

Figure 6. Preliminary position-based finger sensor package

CHAPTER IV

INPUT DEVICE DESIGN

Elbow and Wrist

As previously noted, the input device (shown in Figure 7) must be able to provide signals proportional to a rotation about a fixed axis for the motion of the elbow and wrist while also accommodating the complexities of the human user's movements. In order to accomplish this, the device uses simple rotary potentiometers and incorporates compliance into its structure where needed. Note that structural compliance need only be minimally integrated into the input device design since a human arm has substantial compliance to conform to a device that is reasonably designed for the task.

Measurement of human joint rotation requires some portion of the measuring device to be fixed to the proximal and distal links of the rotating joint. In this particular case, the only practical medium for affixing a device to is the subject's skin. Unfortunately, skin is a notoriously poor surface for affixing to because its movement is not coupled in a straightforward way to the movement of the underlying bone structure, which is conceptually the best analog for comparison with the prosthesis. It is thus desirable to minimize the number of contact points between the device and the subject's skin while still providing sufficient references for angle measurement.

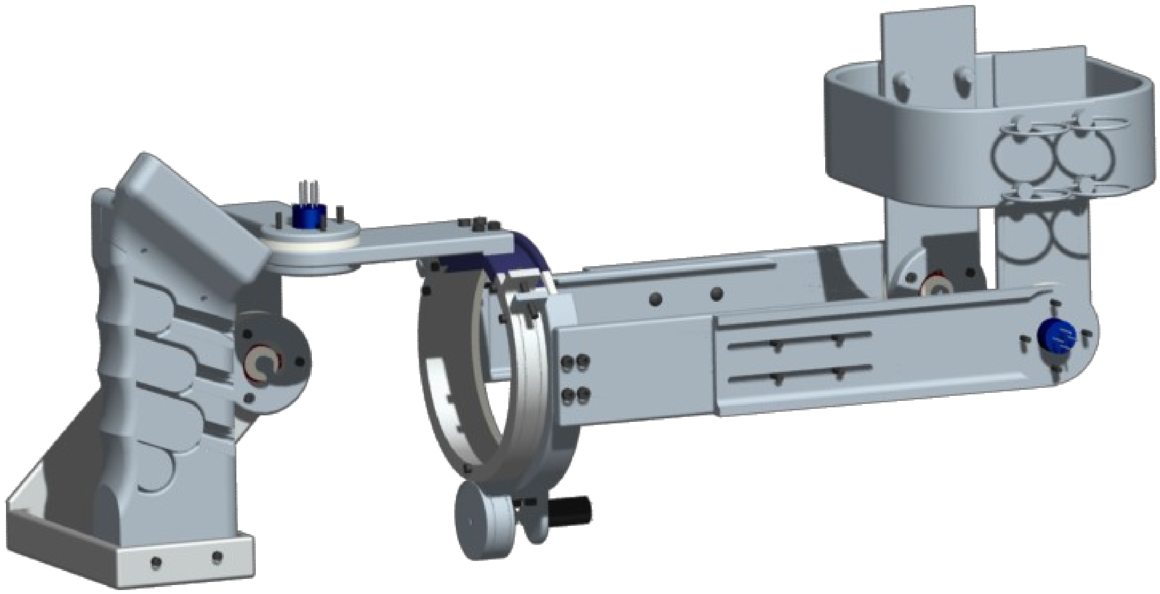

Figure 7. Fully integrated input device model

The input device achieves this by having only three points of contact with the user, one of which is the hand portion that is actively held by the user in the process of sending finger reference signals. The other two contact points are foam-lined cuffs at the upper arm and above the wrist.

Measurement of the elbow and wrist flexion and extension and writst radial/ulnar deviation is accomplished by potentiometers (ETI SP12S-10K) placed coaxially with the respective joint axes as shown in Figure 8.

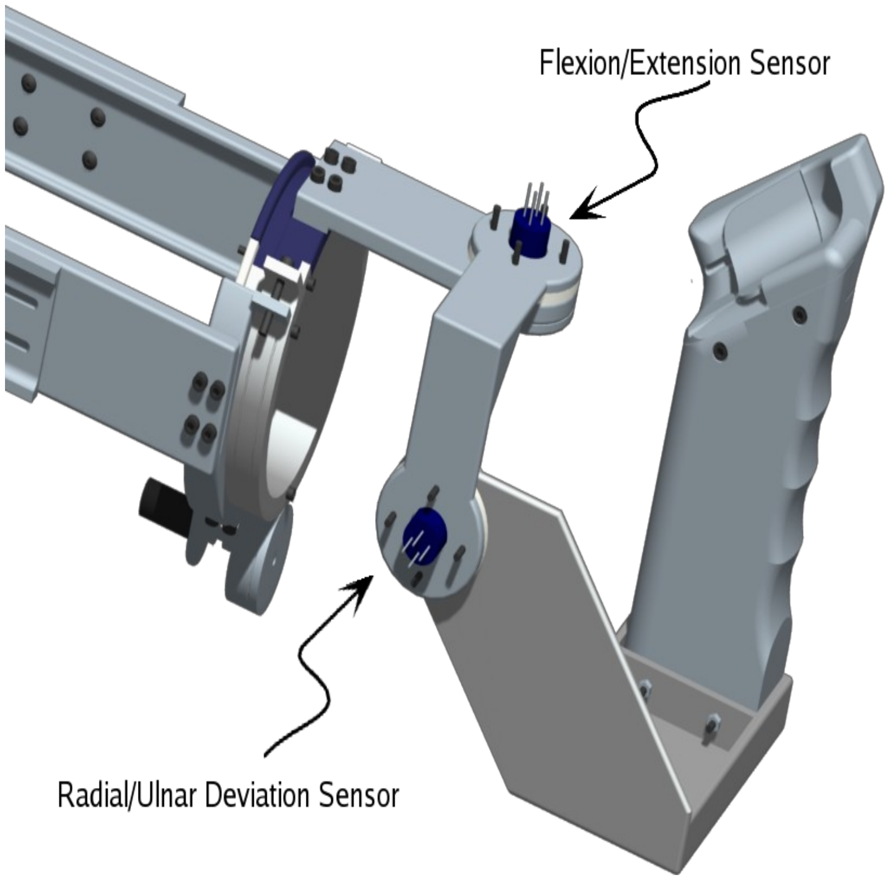

Figure 8. Wrist flexion/extension and radial/ulnar deviation motion sensors

It is worth noting that encapsulation of the coaxial potentiometers is not entirely trivial. Potentiometers are precision instruments and their integrated bearings are not designed to support any appreciable load. Therefore, the potentiometers have been housed in order to isolate them from most stresses. The bearing scheme that is used on the elbow, wrist flexion/extension, and wrist radial/ulnar deviation is shown in Figure 9. Here, the preponderance of the stress is taken by the bearing sleeve. In the initial planning of the input device, the bearing sleeve was to be fabricated from Teflon and its mating pieces were to be aluminum. Since in the version of the device that was actually produced, all non-standard pieces are fabricated from ABS, the bearing sleeve and its next-proximal component could be amalgamated into a single unit. However, to avoid repeating design work as well as to retain the design history of the device, the bearing scheme is left as-is.

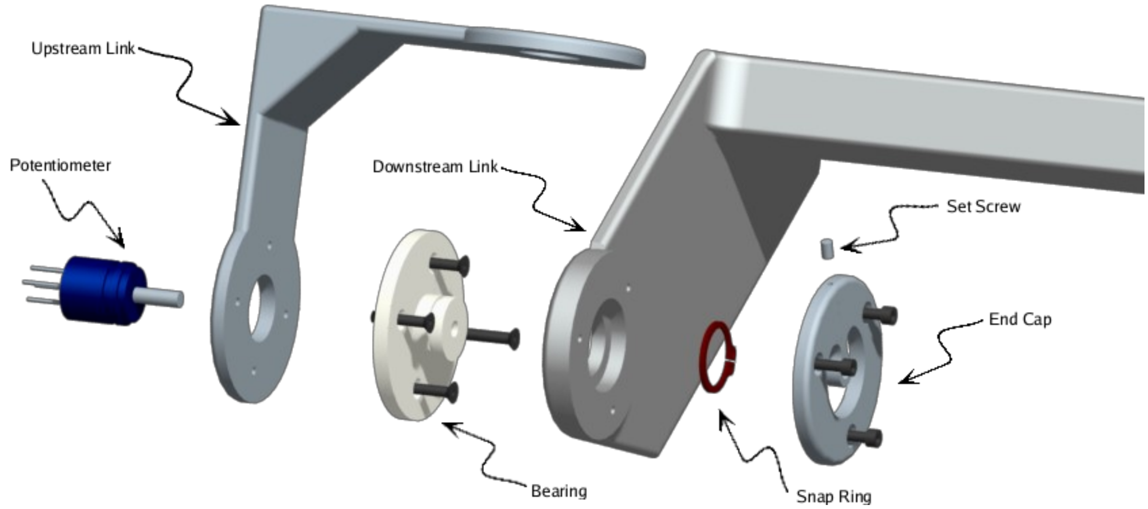

Figure 9. Exploded view of typical potentiometer stress relief bearing design

Pronation/supination of the wrist is measured by segmenting the frame surrounding the user's forearm into proximal and distal components. These two segments are connected via a rotary bearing that circumscribes the user's forearm as shown in Figure 10. The distal segment is allowed to rotate along with the user's pronation/supination movement and features a removable segment to allow the device to be donned and doffed by the user. Both pieces of the bearing cuff feature foam padding adhered to their interior surfaces so that the cuff can be reasonably secured to the user's wrist.

Also attached to the cuff that comprises the rotary bearing is a capstan mechanism. A cable is attached to the rotating portion of the bearing cuff wound around the capstan and terminated at a second attachment to the bearing cuff as demonstrated in the following figure. Using a multi-turn potentiometer (ETI MW10B-5-10K) to measure the rotation of the capstan, the pronation/supination rotation, subject to some transmission ratio, is measured. While it is conceivable that pronation/supination could be measured via a coaxial potentiometer, such a strategy would involve considerably more structure and complexity than the strategy employed.

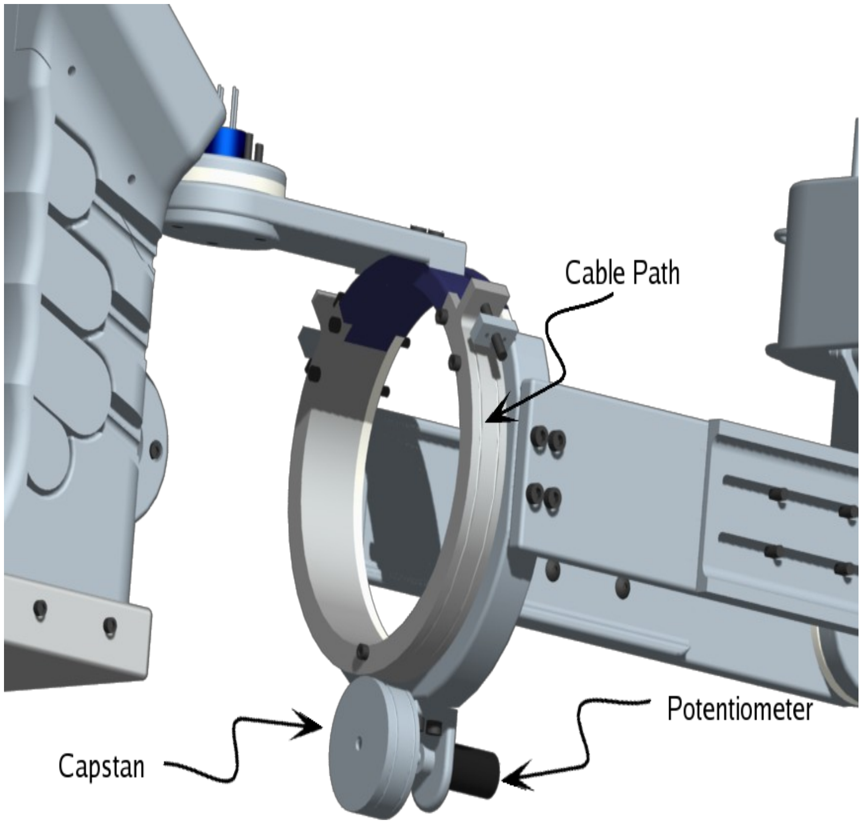

Figure 10. Wrist pronation/supination motion sensor and assembly

Hand

In order to provide force command inputs to the hand tendons on the prosthetic arm, a joystick-shaped input device was designed and fabricated as shown in Figure 11. The device is shaped to be grasped identically to a traditional joystick or flight stick and is distally attached to the radial/ulnar deviation measurement structure.

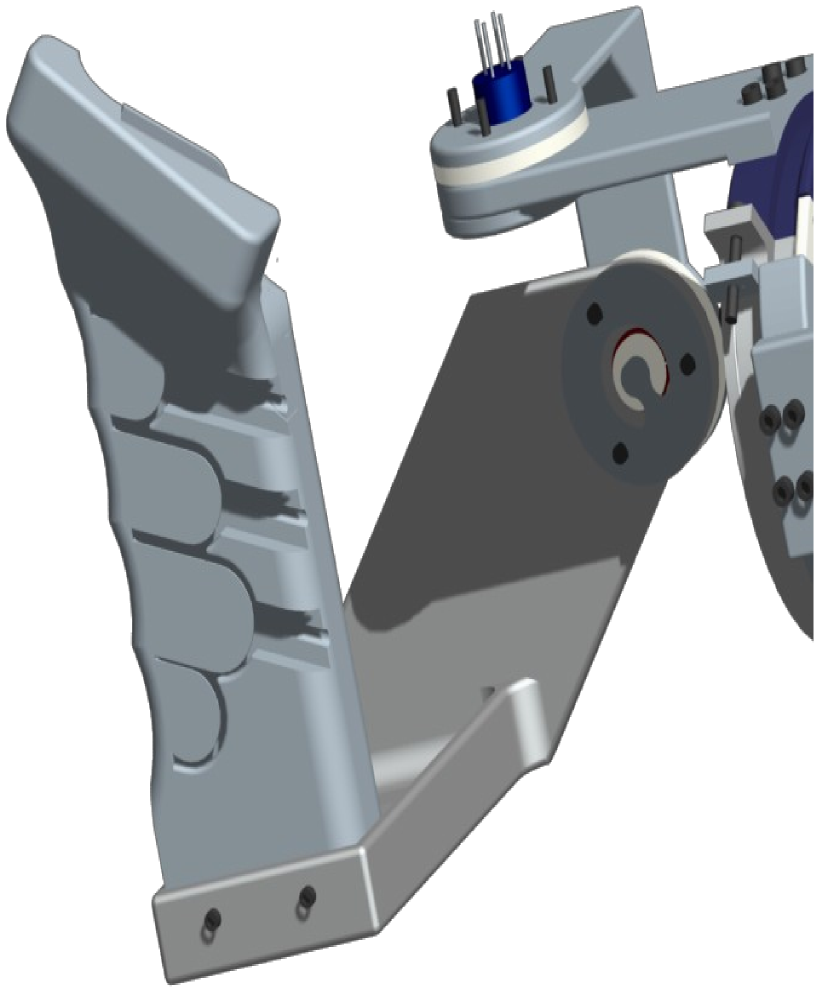

Figure 11. Joystick enclosure for finger force sensors

Below the first through fourth digits, ergonomically shaped indentations are made. In each of these indentations, a recessed hole is located directly beneath the pad of the distal phalanx and is sized to accommodate a compression load cell (Omegadyne LCKD-10). The recessed hole is formed to be slightly less deep than the height of the load cell so that the load cell is secured to the joystick but also so that a usable loading surface is still available. The joystick then incorporates thin cantilevered beam segments that cover the indentations as shown in Figure 12. These beam segments have protrusions on their undersides that are designed such that they are in contact with the protruding faces of the compression load cells and are made thin so that the great majority of the applied force is transmitted to the load cell and not resisted by the beam structure. The described interface for the first through fourth digits consists basically of a series of carefully shaped piano-key-like structures that provide a sizable surface for application of forces on the load cell by the user.

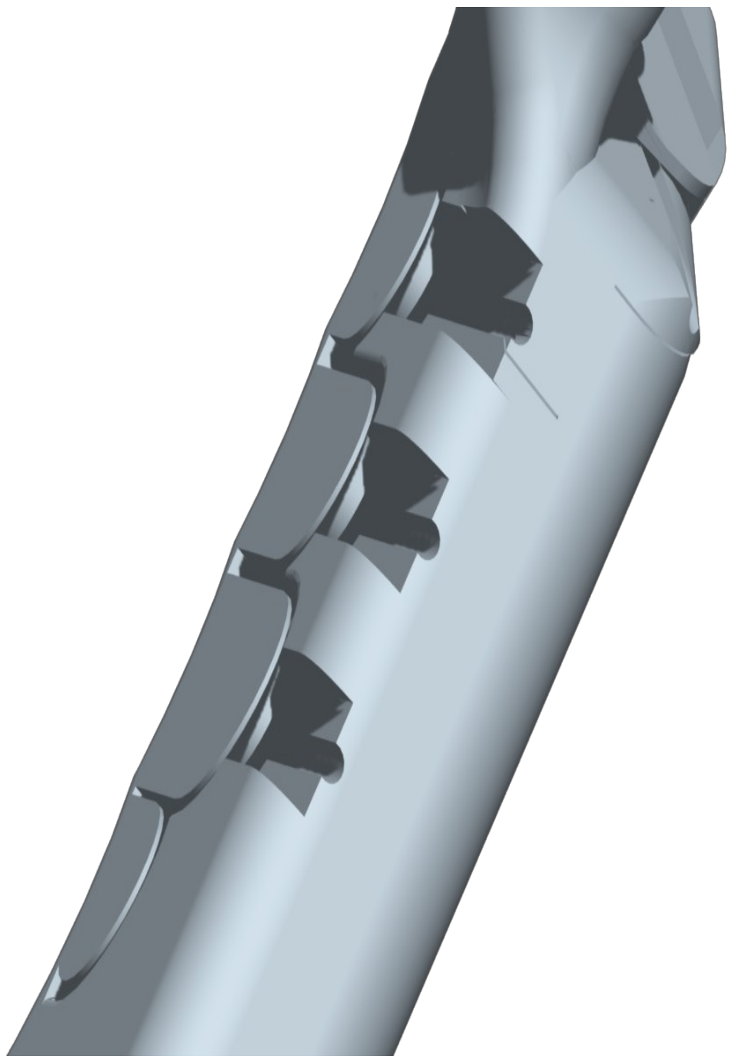

Figure 12. Joystick finger load cell enclosure

Signals resulting from this scheme are proportional to the force applied by the user's individual fingers and are used as force commands for the closed-loop force control of the corresponding tendons on the prosthesis. The control scheme for the hand actuators is then a simple comparison between the desired actuation force as supplied by the joystick input device and the measured actuation force from the feedback sensors on the prosthesis.

For the thumb, the same tactic is employed as for the fingers, but must be modified since two degrees of actuation (I.E., two tendons) are used in the thumb. A load cell is again located beneath the distal most phalanx of the thumb but is joined by a second load cell oriented perpendicular to the first and placed so that it is aligned with the distal most knuckle of the thumb to sense lateral forces, as shown in Figure 13. This second load cell is restrained by being press fit into a recessed hole bored into a wall which protrudes from the top of the joystick and follows the general contour of the thumb on its left side. A quarter-pipe shaped element is suspended over these two load cells by a small point connection at the quarter-pipe's corner. Insertion of the thumb into this structure permits the user to exert a two-dimensional force vector which is resolved into components by the two perpendicularly oriented load cells. The two input force components are then used by the prosthesis controller as the desired thumb flexion force and the desired thumb abduction force respectively.

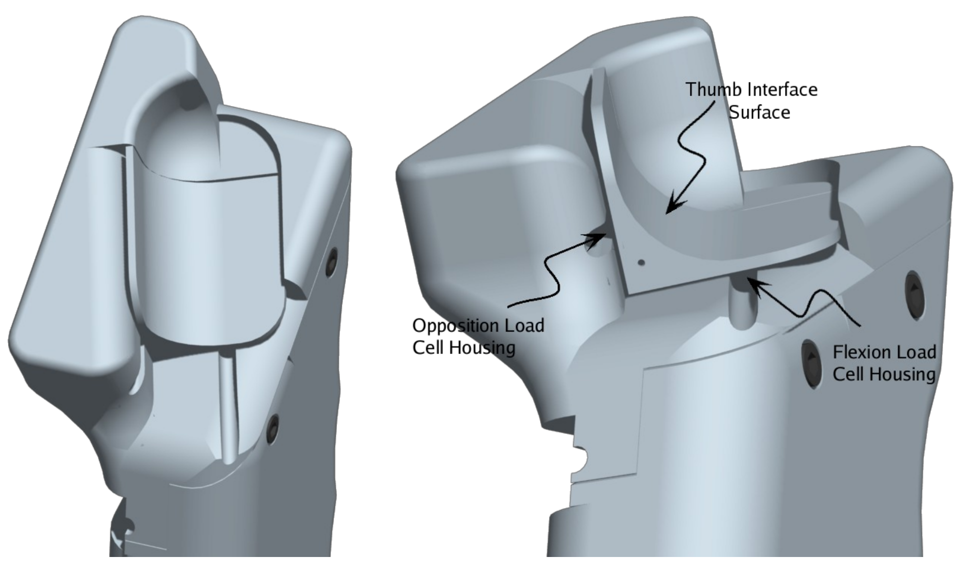

Figure 13. Detail of thumb load cell packaging; Top View (left) and Back View (right)

In order to best fit the human form factor, unusual and difficult to machine part shapes are necessary and so the device was constructed of rapidly prototyped parts built by a Dimension SST

3D printer. This permitted quick iterations of design to best fit the complex human form without the long inherent waiting interval when machining is involved. An additional advantage is gained by this construction method in that the laminated ABS plastic allows the device to more easily conform to the user because of its slight intrinsic flexibility. The fully assembled goniometric input device is shown in Figure 14.

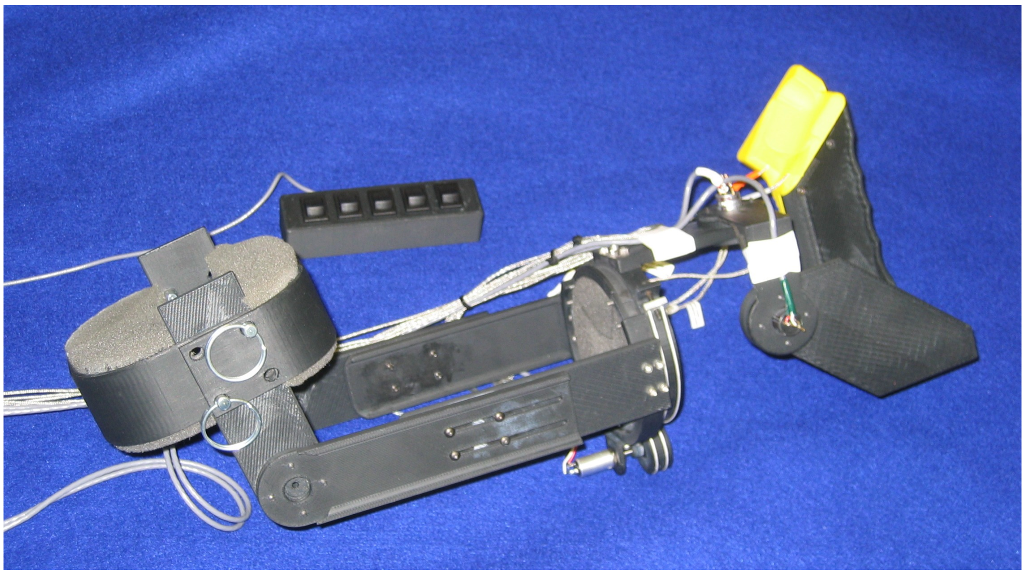

Figure 14. Assembled goniometric input device

Donning the Device

When not worn, the device breaks down into three components. Thus, when donning the device for use, only two connections need to be made. The first is to secure the upper arm cuff to the user's upper arm. Mechanically, this connection is made using four quick-release pins (McMaster-Carr 98320A124) to facilitate the user assembling the device one-handed.

The second connection is to completely encircle the user's forearm by the rotary bearing cuff. This is done by inserting the distal measurement assembly into the rotary bearing cuff and securing the connection with two small cap screws. The three components as well as the procedure for donning the device are shown in Figure 15.

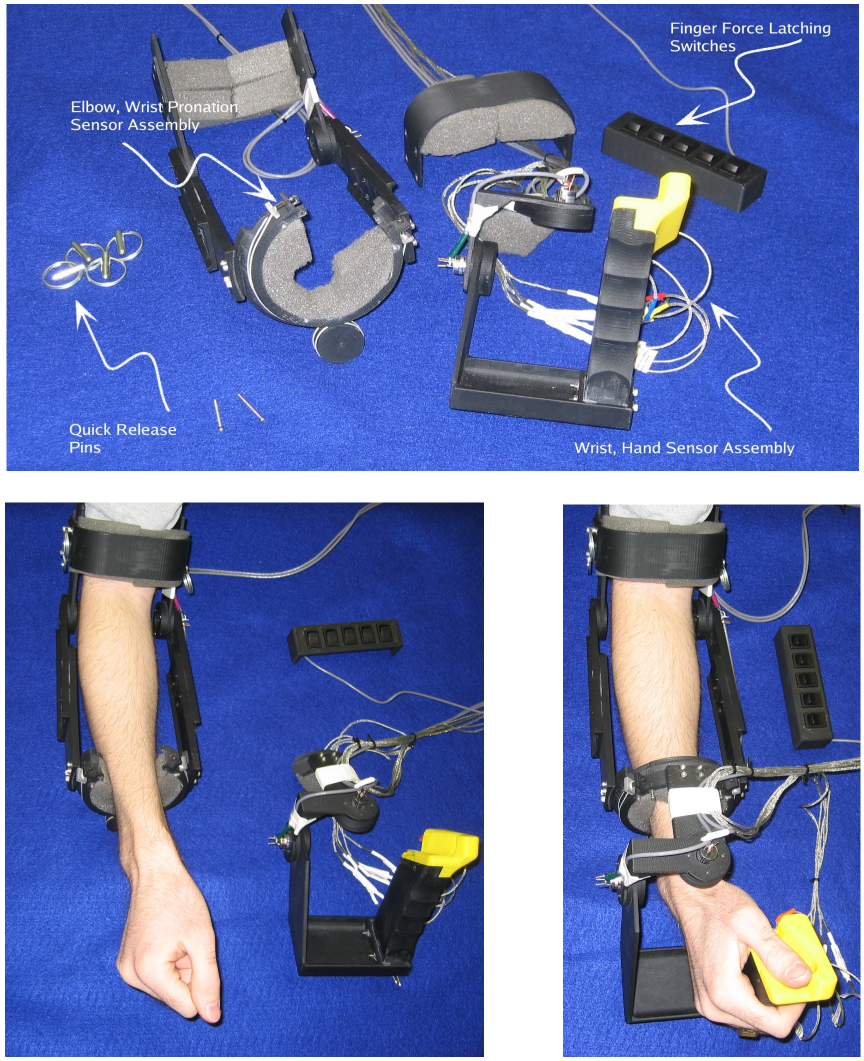

Figure 15. Donning the device, counterclockwise from top

CHAPTER V

INPUT DEVICE TESTING WITHOUT PROSTHESIS HARDWARE

Relative to the synthetic arm, the input device is a simple machine as it does not contain any custom metallic parts or actuation. As such, the input device was completed far ahead of the time that the prosthesis was ready to receive signals from it.

To test both the capability of the input device to accurately capture joint angle data from the human user as well as to test the human user's ability to effect meaningful behavior in the highly underactuated prosthesis before hardware was available, a software environment was created in which the angles measured by the input device were mapped onto a graphical representation of the eventual prosthetic arm. The software did not make any attempt to simulate the dynamics of the arm through use of mass properties estimates and other design specifications because it was assumed at the time that the control scheme implemented alongside the physical prosthetic arm would accurately interpret the input signals and act accordingly to place the arm in the desired configuration.

Use of the software simulation environment was especially helpful with regard to the hand portion of the input device as it permitted testing and evaluation of the two principal approaches that were conceived. Additionally, the simulation was an integral part of the design process for the prosthetic hand. It was used both to validate the notion that the differential coupling of different degrees of freedom would behave as expected and be useful to the user and to ensure that the orientation of the thumb was set so that the hand would move naturally and provide the correct functionality.

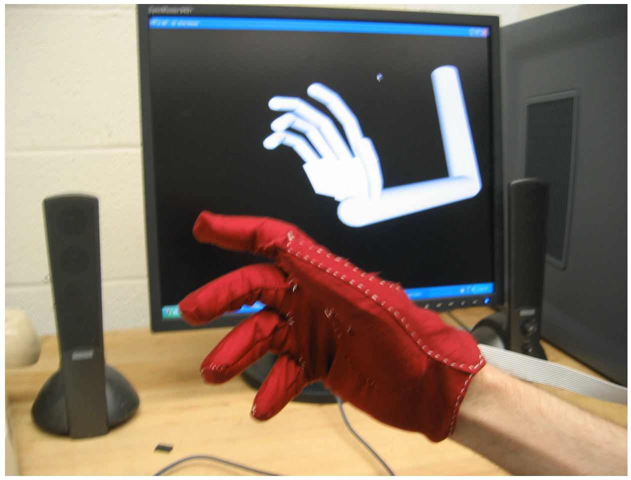

Figure 16. Use of hand input prototype with simulation software

CHAPTER VI

FINGER CONTROL

A final portion of the author's work on the prosthetic arm was development of a control structure for the finger actuators. Control of the fingers is mostly trivial as it is simply the control of a first order system and requires only a proportional controller to be both stable and have quick response. Integral control effort is added to compensate for the difficult-to-characterize deadband in the valves used.

The lone point of interest with regard to control of the fingers is the revelation that one's fingers are not well suited to applying more than a small force over any appreciable length of time. Few people are accustomed to applying such types of force and onset of fatigue appears to occur rapidly. To aid the human operator in using the device for an extended period, two improvements were made.

The first is computational. As a first effort at relieving the user of the finger force burden, the signal was simply amplified so that a small user force was needed to apply the actuator's maximum force. However, this proved to make the task of gesturing (I.E. control of hand configuration without application of force to an external object) extremely difficult. To remedy this situation, a nonlinearity was associated with the signal from the input device. The specific nonlinearity used was squaring the signal, although many other shapes could have been used with equal success. This allows for the user to have good resolution in the low range of forces while simultaneously providing ease of use in the high end of forces.

Although this method was mostly successful, the task of applying required finger forces while simultaneously moving the wrist and elbow proved to be rather difficult as this kind of activity is not commonly practiced by most people. Additionally, because the human wrist does not rotate on a fixed axis, most notably in the radial/ulnar deviation sense, the hand input device appeared to drift away from the user and become out of his reach when certain wrist motions were performed, causing him to lose applied pressure to the finger transducers.

This problem was solved by the association of a memory latch with each of the user's commanded finger forces that can be controlled individually by the user with a series of five electrical switches that are shown in Figure 15. Flipping of the switch causes the controller to hold the last commanded force until the switch is disengaged. Using this feature makes it much easier for a user to grasp an object and then manipulate it throughout the prosthetic arm's workspace.

CHAPTER VII

RESULTS

As stated earlier, it is not easy or even useful to quantify the performance of the prosthesis because success is defined relative to human performance. The ability to perform tasks is the end goal of the prosthesis and the ability to demonstrate this performance easily and intuitively is the end goal of the input device.

As part of testing the hand mechanical design and actuation system without the wrist and elbow, as well as the joystick-like apparatus for finger command input, several grasps were successfully shown. It was also shown that the hand is able to grasp a bottle cap in such a way that it can be unscrewed with the other hand, as shown in Figure 17.

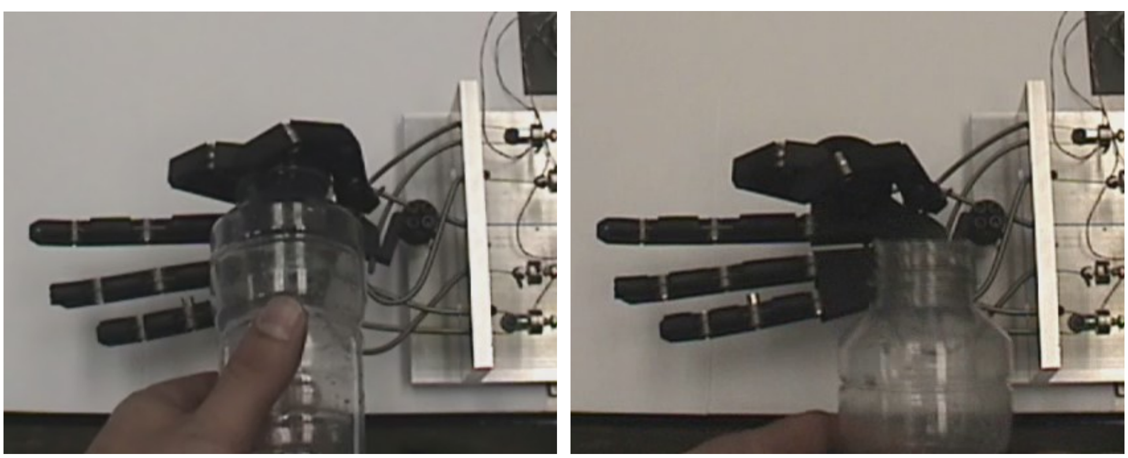

Figure 17. Unscrewing a bottle cap

While this round of testing validated the design of both the hand and the corresponding portion of the input device, there is little functionality that can be demonstrated using only a stationary hand beyond showing grasps and some simple tasks such as bottle cap unscrewing.

When the full arm prosthesis was assembled, other demonstrations that use the wrist and the elbow were able to be executed. Most, if not all, of these demonstrations require simultaneous coordinated use of the elbow, wrist, and hand. The first, shaking hands with the robotic device, is meant to exemplify that the prosthesis is safe to be deployed around humans and that the arm has the force resolution necessary to produce a reasonably delicate touch.

Figure 18. Shaking hands

Figure 19 through 22 show that it is possible with practice to produce cylindrical, lateral pinch, and spherical type grasps. The astute reader may note that these were shown to be possible with the hand design earlier in this paper. However, the previous tests were executed using a series of knobs that a user could pull and lock in place in succession and not with computer control and pneumatic actuation. The previous demonstration was meant to show the potential of the synthetic hand and not to demonstrate its speed of actuation and human-like dynamic performance.

Using the goniometric input device, the same grasps were replicated in a dynamic sense with the prosthesis actuated and controlled and with only visual feedback available to the operator of the input device. This lends credence to the belief that it will eventually be possible for amputees to train themselves to achieve similar success with the device, since the development plan calls for tactile and other sensory data not available while using the input device to be transmitted to the user.

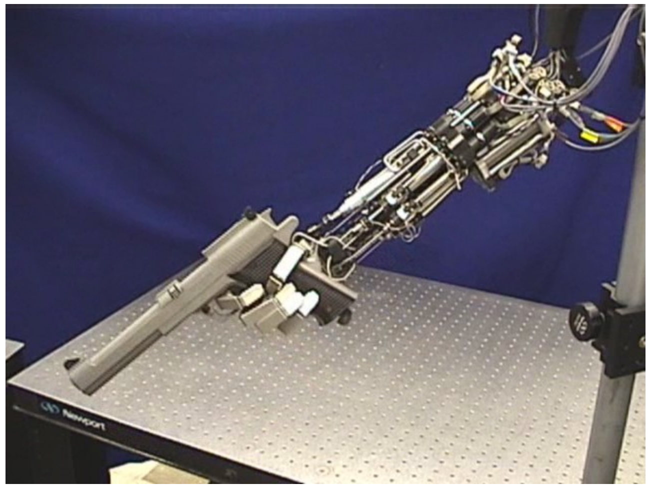

Figure 19. Holding a pistol with grasp suitable for firing

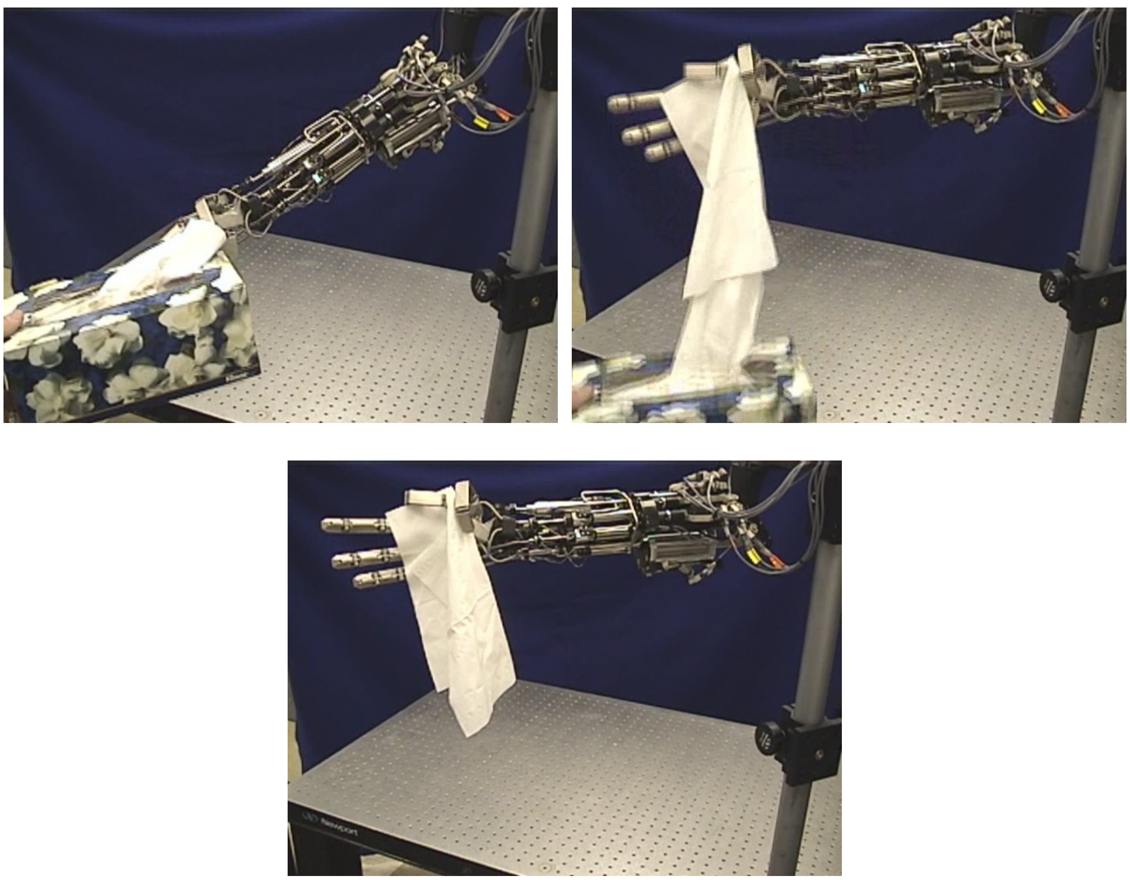

Figure 20. Removing a tissue from box

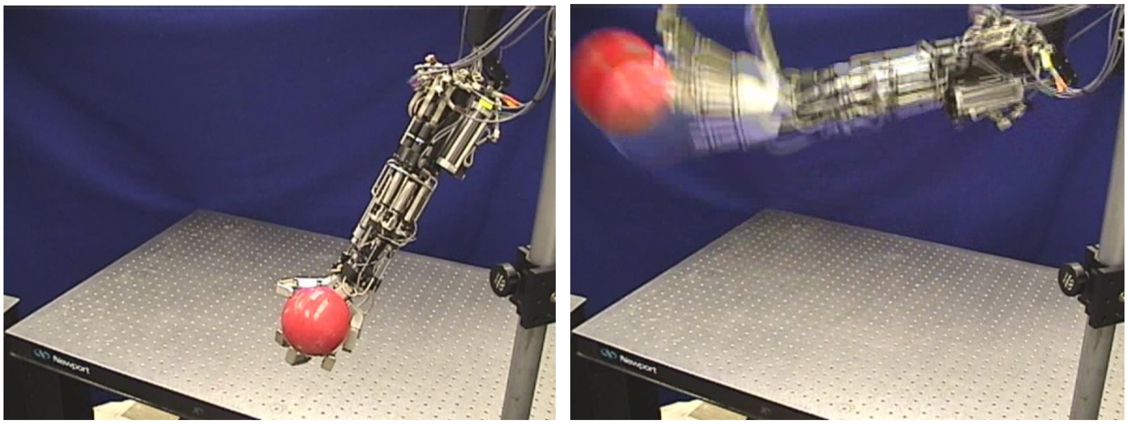

Figure 21. Tossing a ball

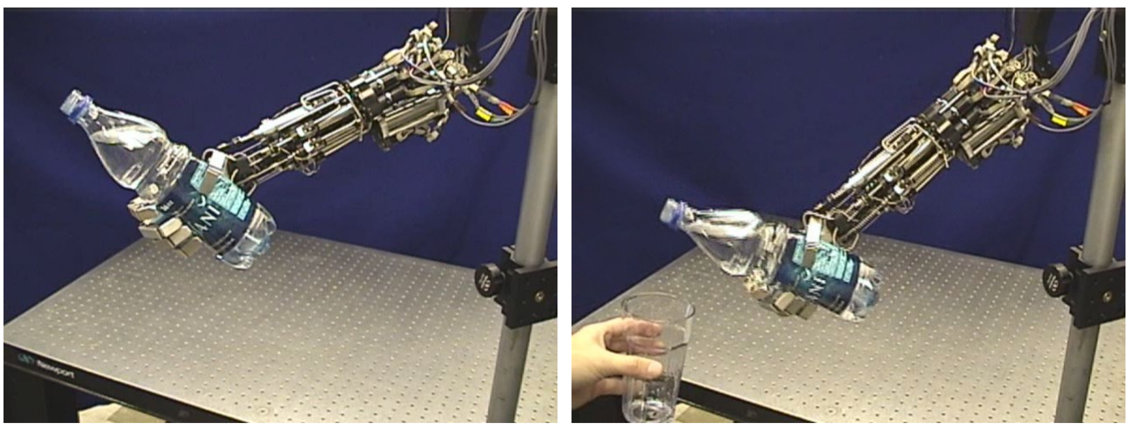

Figure 22. Pouring water from a bottle.

CHAPTER VIII

CONCLUSIONS

The goal of the goniometric input device was to demonstrate the potential capabilities of the transhumeral prosthesis as well as to provide indications of what a future amputated user can hope to achieve with the device. Testing of the device continues, but to date, it has been shown that it is possible to toss a ball, pour water from a bottle, pull a tissue from a box, appropriately wield a gun, and shake hands with another person.

Transmission of signals to the prosthesis via the input device is intuitive since the degrees of actuation can be mapped in a straightforward manner to their organic analogues on the human user. The main difficulty in controlling the arm arises from the fact that the prosthesis has attenuated range of motion relative to a normal arm, most noticeably in the pronation/ supination motion. When attempting to request a motion beyond the hardware limitations of the synthetic arm, it will appear not to respond, requiring some adjustment on the part of the operator.

Additionally, the only mode of feedback to the user is visual. In a demonstration involving the grasping of some external object, the object will often block the user's view of the prosthesis and make his task much more difficult. This becomes more of a problem as the number of digits used in the grasp becomes less and redundant points of contact are not available. These tasks are usually possible but require more attempts because of the lack of other sensory feedback. Haptic feedback would presumably solve the problem, but the sensors needed to relay this information to the operator are absent from the design of the prosthesis. Further, inclusion of this type of functionality in the input device would vastly increase its complexity, cost, and time of development. Thus, while the demonstrations herein indicate that considerable functionality can be achieved without haptic feedback, the addition of such feedback would presumably further improve performance.

It is hoped that the development of the goniometric input device and its subsequent use in demonstrating the capabilities of the arm have accelerated its development and furthered the goal of a more capable prosthesis for those individuals whose quality of life would be most improved by its availability.

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