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Linkage-based prosthetic fingertips: Analysis and testing

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Linkage-based Prosthetic Fingertips: Analysis and Testing

by

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ABSTRACT

This thesis consists of the research on linkage-based fingertips for prosthetic hands. These fingertips consists of small polycentric mechanisms attached to what would be the pulp in normal anatomical fingers. These mechanisms allow the prosthetic hand to conform to the shape of objects during grasp. The goal of these prosthetic fingertips is to maximize the functionality of the hand while minimizing the number of inputs that the user has to control.

The stability of the fingertip mechanisms is analyzed using the principle of virtual work. From this analysis we are able to show that the fingertip mechanism is stable for a large range of rotation of the link and for a large range of directions on which the force is applied, and that the mechanism is indifferent to the magnitude of the force applied to it (assuming that the force does not damage/deform the mechanism).

To assess if the four-bar mechanisms (fingertips) improve the grasping capabilities in robotics and prosthetics, tests were performed on prosthetic hands and robot grippers with and without the fingertips. Comparisons were made using the Southampton Hand Assessment Procedure (SHAP) protocol, which tests the differences and measures the functionality of particular types of grasp, such as power, spherical, lateral, tripod, tip and extension.

In the human testing, the overall Index of Functionality (IOF) of the Hosmer hook is 66.65 and 66.21 for the hook with the fingertips. The hook with the fingertips had a better IOF in the spherical and power prehensile pattern. When the IOF is calculated for the tasks that the fingertips were used, in 10 of 11 of the tasks, the IOF is higher than using the Hosmer hook.

In the robotic gripper testing, the Index of Functionality was not be calculated because the time to perform the tasks depended more on the robotic control system than on the physical characteristics of the gripper.

Chapter 1

Introduction

1.1 Motivation

There is a need for prosthetic hands that are simple for the amputee to use and that ease the performance of precise manipulation tasks. There has been impressive work done on robot hands, making them humanlike and able to replicate the control of each joint. On the other hand, this work has not been yet put in service to a great extent of the amputee community because the controls required are more complex than those that can be easily supplied by an amputee.

The technologies, which are called terminal devices, that are actually used by amputees are either functional or cosmetic. The most functional (and least cosmetically appealing) are the hooks. The most cosmetically appealing (and least functional) are the cosmetic passive hands (which are basically gloves).

The goal of this research is to offer improved functionality in prosthetic terminal devices by attaching mechanisms to a prosthetic hook which will improve its ability to conform to the shape of objects while not impairing its ability to achieve a stable grasp. This research seeks to improve the design of current hooks, which may continue to be the practical choice of amputees for some time. Additionally, there may be some benefit to the work in the design of simple robotic grippers.

1.2 Scope

This research describes background information on prosthetic terminal devices, and describes one mechanism, a crossed four-bar, which may improve their functionality. A stability analysis is provided to show how the crossed four-bar achieves a stable grasp. The mechanism is implemented in a hook and a robotic gripper. The functionality of hooks with and without the mechanism is compared using the Southampton Hand Assessment Procedure (SHAP).

1.3 Thesis Overview

Information about prosthetic background, including the upper-limb prosthetics user priorities, is presented in Chapter Two. Chapter Three consists of the analysis of the crossed four-bars and a comparison to a stiff-hinged mechanism using the method of virtual work. The design of a prosthetic hook and the paddles of the gripper is presented in Chapter Four. Chapter Five provides an overview of the method, the SHAP test, used to evaluate the benefits of the fingertips in the hook and in the gripper paddles. Chapter Six presents the results of the paddles with the fingertips compared to the paddles of the Wheelchair-Mounted Robotic Arm, and the hook with the fingertips compared to a commercially available hook. The conclusions and recommendations for future work for this research are presented in Chapter Seven.

Chapter 2

Background

This chapter consists of the background of prosthetic hands. It describes the causes associated with upper limb amputation and the different types of terminal devices that are currently available. To be able to improve prostheses, the user priorities and the tendencies in design criteria of recent research are also presented.

2.1 Epidemiology

Statistics of upper limb amputations in the United States from 1988 to 1996 have shown that 78.1% of the upper limb amputations are associated to trauma, 3.1% are congenital, 1.5% are related to cancer and, 17.3% are related to dysvascular disease [1]. Although 85,000-90,000 people in the United States have lost an upper limb, only about 34,000 (40%) use prosthetic arms or hands [2].

2.2 Prosthesis

A prosthesis is an artificial substitute or replacement of a part of the body such as a tooth, eye, a facial bone, the palate, a hip, a knee or another joint, the leg, an arm, etc. A prosthesis is designed for functional or cosmetic reasons or both [3].

Functional upper limb prostheses generally can be divided into two categories: body powered prostheses and myoelectric prostheses [4]. Body-powered prostheses are powered and controlled by gross limb movements. These movements, usually of the shoulder, upper arm, or chest are captured by a harness system which is attached to a cable that is connected to a terminal device. Some advantages of the body-powered prostheses are that they are highly durable, and are usually of moderate cost and weight. Some disadvantages are that the prosthetic users feel uncomfortable and must use a restrictive control harness. Although new materials aid in reducing discomfort [5], the harness must be tight in order to capture the movement of the shoulder and support the prosthesis. The tight harness can also restrict range of motion and the functional envelope (the area in space where the patient can control his or her prosthesis). Others dislike the look of the hook and control cables and request a prosthesis that is more "lifelike" [5].

Myoelectric control uses the electrical signals generated by muscle contraction as the control input for a prosthesis controller. They function by transmitting electrical activity that the surface electrodes on the residual limb muscles detect to the electric motor [5]. Myoelectric prostheses may give more proximal function and increased cosmetics, but they can be heavy and expensive. They have less sensory feedback and require more maintenance.

2.3 Terminal devices

The terminal device is the end effector or prehensor that is situated on the end of the arm prosthesis [6]. Terminal devices are divided in two categories: passive and active terminal devices. The main advantage of a passive terminal device is its cosmetic appearance. With newer advances in materials and design, a device that is virtually indistinguishable from the native hand can be manufactured. However, passive terminal devices usually are less functional and more expensive than active terminal devices [4].

Active terminal devices usually are more functional than cosmetic; however, in the near future, active devices that are equally cosmetic and functional will be available. Active devices can be broken down into two main categories: 1) myoelectric-based devices hooks and 2) prosthetic hands with cable. A prosthetic hand usually is bulkier and heavier than a hook, but it is more cosmetically pleasing. A prosthetic hand can be powered with a cable or myoelectricity. With the myoelectric device, the patient can initiate palmar tip grasp (to hold smaller objects like pencils) by contracting residual forearm flexors and can release by contracting residual extensors [4].

2.4 Commercially available terminal devices

Currently, there exist three types of terminal devices: hook, prehensors and hands [7]. Each type of terminal device can be either electric or body powered. Terminal devices have either voluntary closing or voluntary opening mechanisms. In the voluntary closing mechanism the device is open at rest and activation is required to grip an object. In the voluntary opening mechanism the device is closed at rest and activation is required to open the terminal device.

Hooks are made of stainless steel or aluminum. Examples of some prosthetic hooks are shown in Figure 2.1. Typical advantages of the hooks are functionality, efficiency of use, ability to grasp small objects, durability, lower maintenance and repair costs, light weight (compared to hands), better ability to see what the user is trying to hold, and the user does not have to be as careful around heat because they are made of metal [7]. They may be either canted or lyre shaped [8]. Canted fingers permit better visualization of the object to grasp.

Figure 2.1: Otto Bock hooks [9]

Prehensors (Figure 2.2) are not as cosmetically pleasing as prosthetic hands, but they offer many of the same advantages over hands as hooks do. They are much more functional than passive hands and, like hooks, offer better visual feedback to the user. Some advantages of the prehensors compared to the hooks is that they do not look as threatening, they are not likely to scratch objects and are not likely to accidentally get caught on things. They are not as good for picking up and working with small items, and they are usually bulkier at the end, which can make it difficult to see the objects being grasped [7].

Figure 2.2: Prehensors [10]

Prosthetic hands (Figure 2.3) are generally less functional than hooks and prehensors. There are three types of artificial hand mechanisms: passive, voluntary closing and voluntary opening. Passive hands are used for cosmetic reasons, they have the appearance of an anatomical hand; but they need to be opened and closed using the sound hand.

Figure 2.3: Female passive hand [8]

The focus of this thesis is in body-powered terminal devices. A summary of the commercially available body-powered terminal devices is shown in Table 2.1.

Table 2.1: Functionality and weight of body-powered terminal devices commercially available

Manufacturer	Name	Type	Functionality	Weight
Hosmer [8]	Hooks	Hook	cable-activated	85-397 gm
	APRL	Hook	cable-activated	243 gm
	Sierra 2-load	Hook	cable-activated	354 gm
	Soft voluntary closing hand	Hand	cable-activated, voluntary closing of the thumb and first two fingers	339 - 351 gm
	Soft voluntary opening hand	Hand	cable-activated, voluntary opening of the thumb and first two fingers	288 - 308 gm
	Dorrance 300 mechanical hand	Hand	cable-activated, voluntary opening of the thumb and first two fingers	298 gm

Table 2.1: Continued

	Dorrance 400 mechanical hand	Hand	cable-activated, voluntary opening of the thumb and first two fingers	397 gm
	Becker Lock Grip Hand	Hand	cable-activated, all five fingers operate	382 - 467 gm
	Becker Imperial Hand	Hand	cable-activated, all five fingers operate	393 gm
	APRL Voluntary Closing Hand	Hand	cable-activated, moveable thumb and two fingers	354 gm
	Sierra Voluntary Opening Hand	Hand	cable-activated, two thumb positions	354 gm
Otto Bock [9]	Body powered hooks	Hook	cable-activated	---------
	System Hands – passive	Hand	opened by the sound hand and close automatically.	185 - 290 gm
	System Hands - voluntary opening	Hand	cable-activated	215 - 340 gm
	System Hands - voluntary closing	Hand	cable-activated	340 - 380 gm
TRS [10]	Adult Grip Prehensors	Prehensor	cable-activated	278-451 gm
	Lite Touch Adult	Hand	cable-activated	284 gm

A survey of prosthetic limb users was performed at the Oxford Limb-Fitting Centre, Headington, Oxford. Many subjects were users of more than one type of prosthesis, including purely cosmetic hands, prosthetic hooks, and devices that have a cosmetic appearance but a limited functional range (such as myoelectric hands) [11]. The principal types of prosthesis that upper limb amputees use are cosmetics (21%), cosmetics-like devices (20%) and prosthetic hooks (13%) only. The cosmetic-like devices are those with some designed functional range but an anthropomorphic appearance.

2.5 Users priorities

A survey of 1,020 body-powered prosthetic users was done at The Institute for Rehabilitation and Research (TIRR), Houston in 1992. They evaluated past use of prostheses, current trends in technology and prosthetic preferences of these individuals to help define future prosthetic research. The results of the trans-radial preferences for prosthetic improvements are listed in Table 2.2 [12], one being the highest priority.

Table 2.2: Trans-radial body powered items for improvement [12]

Item name	Rank
Wrist rotated the terminal device	1
Could do coordinated motions of 2 joints at the same time	2
Wrist moved terminal device from side to side	3
Wrist moved terminal device up and down	4
Required less attention to perform certain functions	5
Could hold small objects better	6
Could hold large objects better	7
Could use it in vigorous activities	8
Weighted less	9
Looked more like a human hand	10

2.6 Design of terminal devices criteria

New requirements for the design of prosthetic hands in recent research are that they must be lightweight, compact, reversible (simplicity of manufacture of both left and right hands), quiet (in the case of myoelectric hands), cosmetic (the device must be attractive), functional, efficient, and price (the device must be produced at a cost that will allow the hand to be priced competitively) [13,14,15]. Each hand has its own design criteria and requirements. Design criteria of some terminal devices in research are shown in Table 2.3.

Table 2.3: Design criteria of some terminal devices in research

		Design Criteria		
Prosthetic hands	Type	Weight	Functionality	Cosmetics
The Southampton hand [13]	Myoelectric	Yes, n/a	Able to grasp everyday objects	5 fingers
The IOWA hand [18]	Myoelectric	Yes, n/a	Yes, n/a	5 fingers, uses a cosmetic glove
The RTR II [19]	Myoelectric	Yes, n/a	Adaptive grasp	3 fingers
The Spring hand [14]	Myoelectric	Yes, n/a	Yes, n/a	3 fingers
The VA endoskeletal hand [15]	Body-powered	203 gm	Able to grasp everyday objects	5 fingers

2.7 Assistive robot manipulators

Upper limb assistive devices are those devices that help people with limb limitations to perfom activities of daily living. A variety of devices are commercially available. Most of the devices that currently exist are for a specific task (button hooks for dressing, utensils with adjustable rings, etc.).

There currently exists a number of assistive robot manipulators. The ARM or MANUS, the Handy I, the RAID project, Raptor, DeVAR, Robotic Assistive Appliance and the Helping hand are some of these manipulators [16].

Some of the end effectors of these manipulators have revealed that some aspects of the gripper have room for improvement. The difficulties experienced by the Assistive Robotic Manipulator (ARM), also known as MANUS are typical. It had presented difficulty handling large objects that weight more than 2 kg. When the center of mass could not be enclosed by the gripper or an external load was applied to it, the objects tend to rotate or tilt. When a large object is positioned near the base of the gripper, the two proximal phalanges drive the object out of the gripper, when the gripper closes [17]. It is possible that the four-bar mechanism developed for the prosthetic hand may aid robotic grasp.

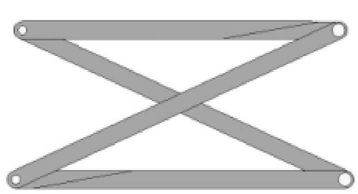
2.8 Underactuation

A mechanism is said to be underactuated when it has fewer actuators than degrees of freedom. When applied to mechanical hands, underactuated mechanisms can be used to obtain an adaptive grasp that resembles human grasping more easily than a hand with completely independent degrees of freedom could achieve [14]. Some underactuated mechanism based prosthetic hand prototypes are the SPRING hand [14] and the Iowa hand [18] which is based on a cable transmission, the RTR II [19], the Lin ATG prosthetic hand [20] and the Whole Arm Manipulator (WAM) [21] which connects to the finger segments via a solid mechanical linkages. A survey of the most well known underactuated robotic hands is shown in [22]. The crossed four-bar mechanism explained in the next chapter is underactuated and part of its simplicity comes from the fact that it performs it stabilizing function without the need for external actuation.

Chapter 3

Kinematic Analysis

A brief description of equations that can be used to calculate the orientation of the links in the four-bar is presented in this chapter. Then the analysis of the crossed four-bar and the stiff hinged (Figure 3.1) mechanism were developed to find the stable region of each mechanism, which is accomplished by the principle of virtual work.



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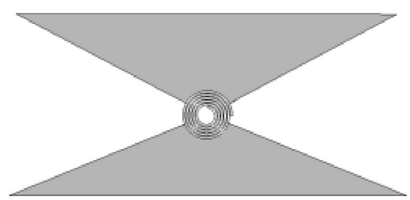

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Figure 3.1: CAD models of the (a) Four-bar and (b) stiff-hinged mechanism

3.1 Analysis of four bar mechanism

The lengths of the links are L_1, L_2, L_3, and L_4 (Figure 3.2), and the angles that links 2, 3 and 4 make with respect to link 1 are respectively θ_2, θ_3 and θ_4. For a particular mechanism with fixed geometry, given any of the angles, the other two can be found by solving the equations:

$$L_2 \cos\theta_2 + L_3 \cos\theta_3 = L_1 + L_4 \cos\theta_4 \qquad (3.1)$$

$$L_2 \sin\theta_2 + L_3 \sin\theta_3 = L_4 \sin\theta_4 \qquad (3.2)$$

For any given position of the four-bar, the method of virtual work can be used to determine the conditions in which the four-bar will be in equilibrium.

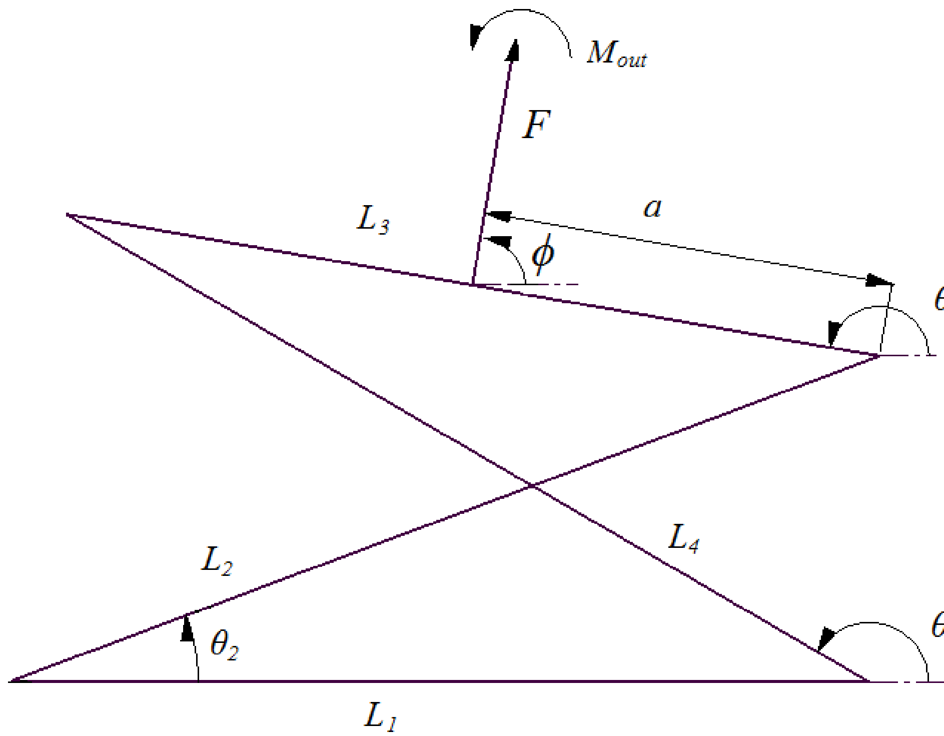


Figure 3.2: Model of the crossed four-bar

3.2 Principle of virtual work

The principle of virtual work states that the net virtual work of all active forces is zero if and only if an ideal mechanical system is in equilibrium [2]. The total virtual work of the system can be written as

$$\delta W = \sum_i \vec{F}_i . \delta \vec{z}_i + \sum_j \vec{M}_j . \delta \vec{\theta}_j - \sum_k \frac{dV_k}{dq_k} \delta q_k \qquad (3.3)$$

Where:

δW is the virtual work

F is the applied force vector

M is the applied moment vector

V is the potential energy

δz is the virtual displacement

$\delta\theta$ is the virtual angular displacement and

q is the generalized coordinate.

The analysis of the mechanism is developed using the method of virtual work [10]. The position vector of the force applied to the crossed four bar linkage (Figure 3.2) is given by:

$$\vec{Z} = [L_2 \cos\theta_2 + L_3 \cos\theta_3]\hat{i} + [L_2 \sin\theta_2 + L_3 \sin\theta_3]\hat{j} \tag{3.4}$$

A fictitious moment, M_{out}, is applied as a measure of how far the four-bar is away from equilibrium given a force, $\vec{F}$ acting in the direction, ϕ, applied at a fraction, a, of the length of link 3, L_3.

3.3 Crossed four-bar mechanism

The virtual work due to the force is found by applying the dot product of the force vector and the virtual displacement. Given the force, F, the virtual work due to the applied force is found to be

$$\delta W_F = -F\cos\phi(L_2 \sin\theta_2 + aL_3 \sin\theta_3 \frac{d\theta_3}{d\theta_2})\delta\theta_2 + F\sin\phi(L_2 \cos\theta_2 + aL_3 \cos\theta_3 \frac{d\theta_3}{d\theta_2})\delta\theta_2 \tag{3.5}$$

Where:

$$\frac{d\theta_3}{d\theta_2} = h_{23} = \frac{L_3 \sin(\theta_3 - \theta_4)}{L_2 \sin(\theta_4 - \theta_2)} \tag{3.6}$$

h_{23} is the four-bar kinematic coefficient [10],

ϕ is the angle of the force

a is the distance at which the force is applied, as shown in Figure 3.2.

The virtual work due to the moment is found by applying the dot product of the moment and the virtual angle displacement.

$$\delta W_M = -M_{out} \frac{d\theta_3}{d\theta_2} \delta\theta_2 \tag{3.7}$$

The net virtual work is the sum of the virtual work due to the force and due to the moment is found to be

$$\delta W = -F\cos\phi(L_2 \sin\theta_2 + aL_3 \sin\theta_3 \frac{d\theta_3}{d\theta_2})\delta\theta_2 + F\sin\phi(L_2\cos\theta_2 + aL_3\cos\theta_3 \frac{d\theta_3}{d\theta_2})\delta\theta_2 - M_{out}\frac{d\theta_3}{d\theta_2}\delta\theta_2 \tag{3.8}$$

From the principle of virtual work (if equilibrium, the virtual work is equal to zero), the moment on link 3 of the crossed four-bar mechanism required for equilibrium is found to be

$$M_{out} = F\sin\phi(L_2 h_{23}\cos\theta_2 + aL_3\cos\theta_3) - F\cos\phi(L_2 h_{23}\sin\theta_2 + aL_3\sin\theta_3) \tag{3.9}$$

When M_{out} =0, the crossed four bar is at equilibrium which occurs when the force angle, ϕ, satisfies

$$\tan\phi = \frac{L_2 h_{23}\sin\theta_2 + aL_3\sin\theta_3}{L_2 h_{23}\cos\theta_2 + aL_3\cos\theta_3} \tag{3.10}$$

which does not depend on the magnitude of the force, *F*.

3.4 Stiff-hinged mechanism

Using the principle of virtual work, the work due to the torsional spring is

$$\delta W_M = -k(\theta_2 - \theta_{20})\delta\theta_2 \tag{3.11}$$

Using the principle of virtual work for the stiff-hinged mechanism, as in the crossed four-bar mechanism, the moment is found to be

$$M_{out} = k(\theta_2 - \theta_{20}) + F\sin\phi(L_2\cos\theta_2 + aL_3\cos\theta_3) - F\cos\phi(L_2\sin\theta_2 + aL_3\sin\theta_3) \tag{3.12}$$

where k is the spring stiffness.

When M_{out}=0 in the stiff-hinged mechanism

$$\tan\phi = \frac{k(\theta_2 - \theta_{20})}{F\cos\phi(L_2\cos\theta_2 + aL_3\cos\theta_3)} + \frac{L_2\sin\theta_2 + aL_3\sin\theta_3}{L_2\cos\theta_2 + aL_3\cos\theta_3} \tag{3.13}$$

This is a definite contrast to the four-bar mechanism in that equilibrium in the stiff-hinged mechanism depends on the ratios of the spring stiffness and the applied force.

3.5 Stability analysis

Using the moment equation, equation (3.9), M_{out} as a function of the angle of link 3, θ_3, and the angle force, ϕ, can be found. The equilibrium moment of the crossed bar is found for different locations of the applied force by changing the value of distance a. Appendix A shows different plots of the angle of link 3 and the angle force for different values of the magnitude a and for the geometric parameters stated in Table 3.1.

Table 3.4: Geometric parameters

Set	L_1	L_2	L_3	L_4
1	1.04	1.125	1	1.125

The curves represent the moment that would be required to balance the applied force. Equilibrium curves for the different mechanisms were developed using the angle of the link, the force angle and a moment created by the force. Each equilibrium curve represents a different position on the coupler link of the four-bar (distance *a*).

Figure 3.3 shows the plot of the equilibrium curve when *a* =0.5, i.e. the center of link 3, in a range from 0^o -360^o. Equilibrium without an applied moment is achieved when the moment out of the mechanism is equal to zero. When the mechanism is loaded at 90^o (pulling on the mechanism) in a way that changes the orientation of link 3 from a value of 180^o (horizontal) to 200^o (slightly tipped), this corresponds to moving from point *A* to point *B* in Figure 3.3. At this position a moment, M_{out}, of 5 Nmm, assuming an applied force of 1 N, would be required to hold it in equilibrium. Because there is nothing in the mechanism to provide that moment the linkage will tend to continue to rotate in the positive direction and the perturbation will grow i.e. θ_3 will continue to get bigger. We say that this situation is unstable because even a very small perturbation will grow until reaches the physical limits of the mechanism's rotation.

In the other hand, when the applied force is pushing in the vertical direction, $\phi=270^o$, on the center of link 3 and link 3 is perturbed from 180^o to 200^o (from *C* to *D* in Figure 3.3), the resulting force is -5 Nmm, indicating that this unbalanced moment will cause link 3 to rotate in the negative direction, back to its original position. Because small perturbation tends to be resisted, we say that this equilibrium position is stable when negative values of moment are above an equilibrium contour line (where M_{out}=0) and positive values of moment are below the line. An examination of the plots in Appendix A shows that when the slope of equilibrium contours line at a point is negative (up to the left, down to the right), the equilibrium point is stable. On the other hand, when the slope of an equilibrium contour line is positive (up to the right, down to the left) the equilibrium point is unstable.

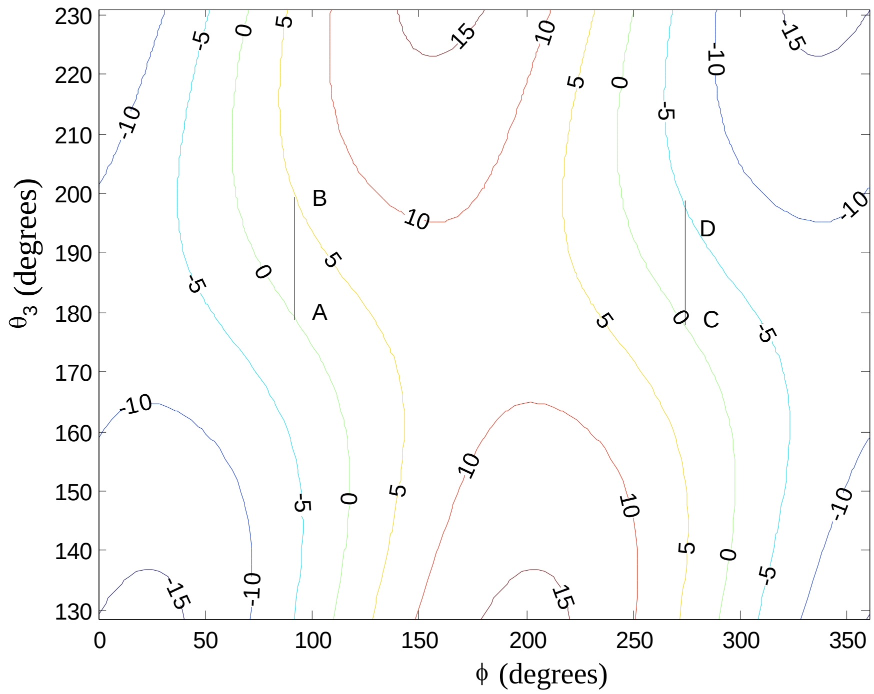


Figure 3.3: Stability of four bars when a=0.5

The stable region for the crossed four-bar mechanism is the shaded region in Figure 3.4. The advantage of this mechanism is that the magnitude of the force does not change the stability of the mechanism and it is stable over a wide range of motion and for a wide range of applied force directions and locations.

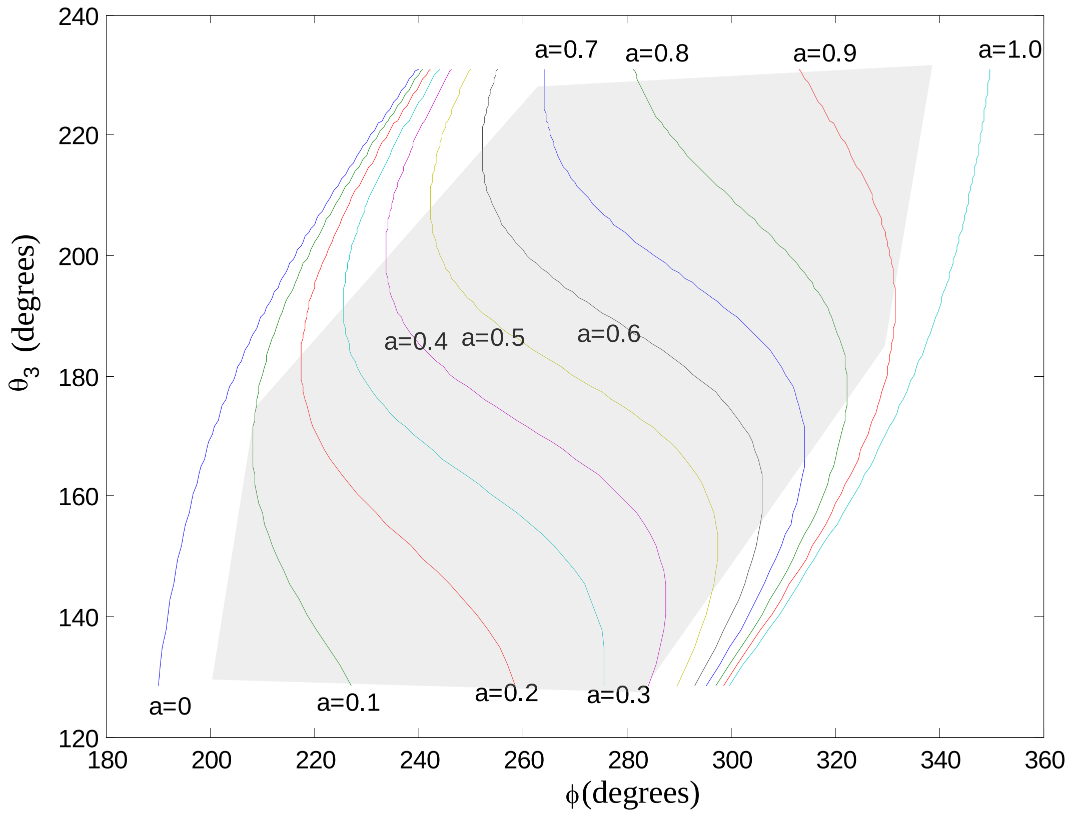


Figure 3.4: Stability region of four-bar mechanism

In the stiff-hinged model, the magnitude of the force plays a major role in the stability of the mechanism, the mechanism presents 3 different types of stability depending on the ratio of the force to the spring stiffness. Figure 3.5 shows the stability when the ratio of the force to the spring stiffness is equal to one.

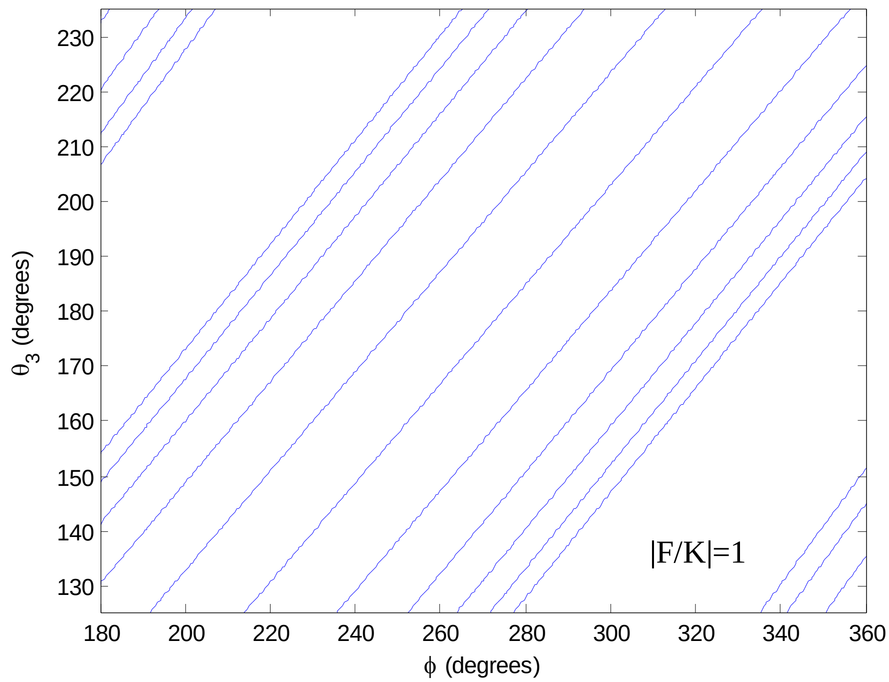


Figure 3.5: Stability region of the stiff-hinged mechanism when |F/K|=1

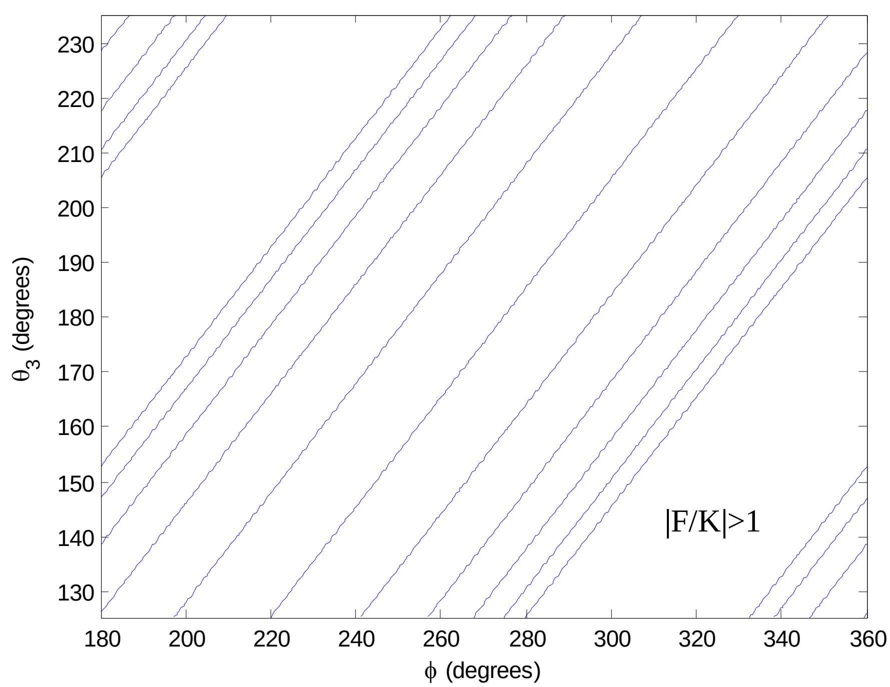


Figure 3.6: Stability region of the stiff-hinged mechanism when |F/K|>1

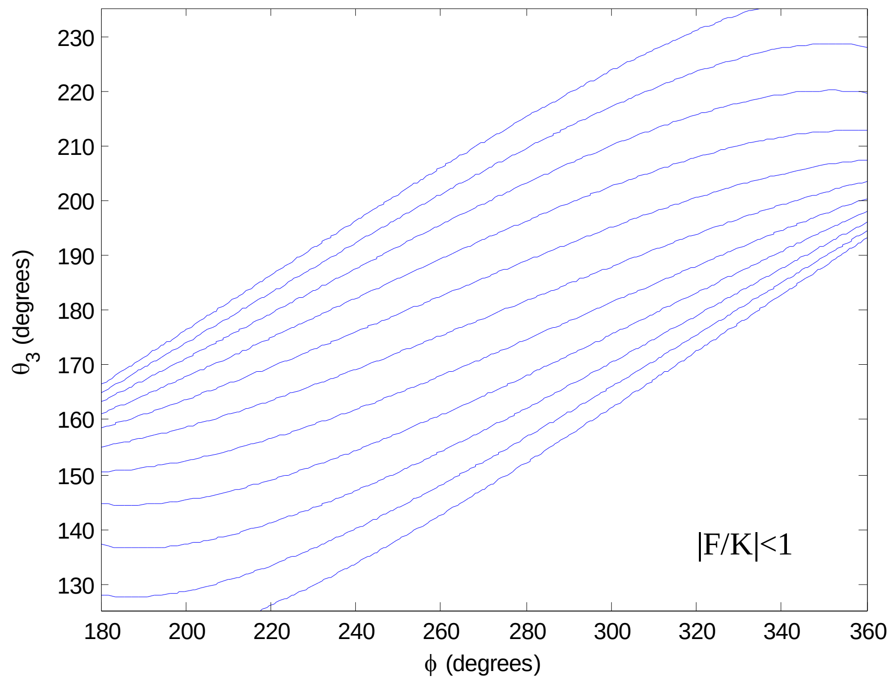


Figure 3.7: Stability region of the stiff-hinged mechanism when |F/K |<1

Figure 3.6 shows the stability when the magnitude of force is bigger than the spring stiffness (F/K>1). When the magnitude of the force is less than the spring stiffness magnitude (F/K<1), Figure 3.7, the stable region decreases and tends to be dominated by the torsional spring. The disadvantage of the stiff-hinged mechanism is that the degree to which it conforms to the shape of an object depends on the grasping force.

Chapter 4

Design

In order to measure the benefits of the fingertips, the fingertips are compared to existing terminal devices. For this, a prosthetic hook and the paddles of a gripper were designed. This chapter consists of the design procedure for the hook and the paddles of a robotic gripper.

4.1 Fingertips

The bars of the crossed four-bar are pinned connected, as shown in Figure 4.1. The bar lengths of the fingertips are L_1=L_3 20.01mm and, L_2=L_4= 21.6 mm. The fingertips have a rubber gripping surface that is 2 mm wide. This makes an overall height of 12.50 mm.

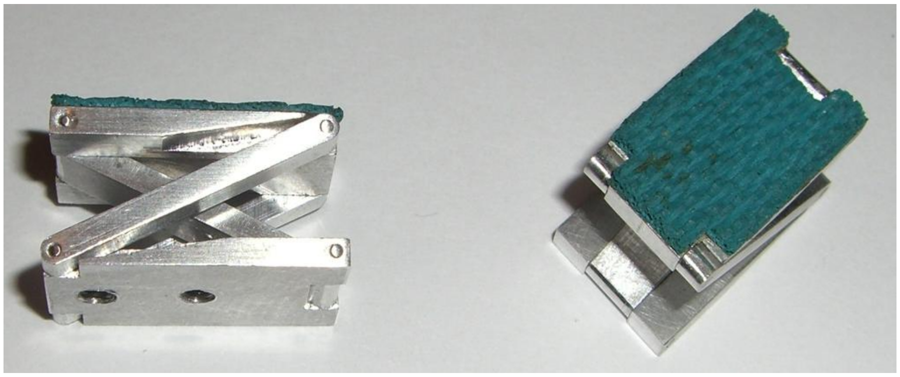


Figure 4.1: Fingertips

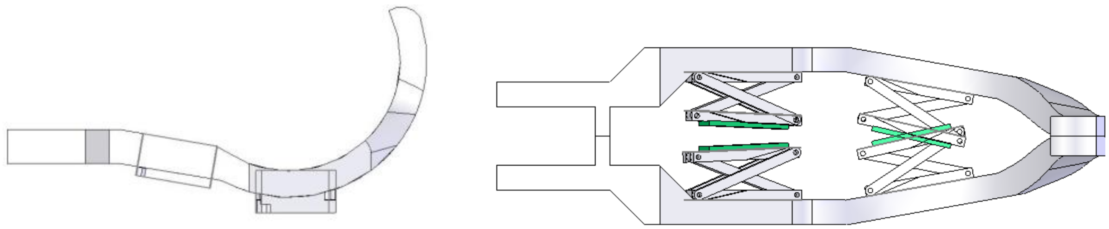
4.2 Hooks

One of the commercially available hooks is the Hosmer-Dorrance 555 hook. Some characteristics of this hook are [8]:

1. It is made of aluminum
2. It has lyre-shaped fingers, which allows the user to grasp small objects with the tip of the tine and ease in picking up cylindrical objects.
3. The fingers are nitrile rubber line
4. It is 13.3cm (5-1/4") long
5. It weights 4.5oz (121gm)
6. It is generally a light duty device

To be able to measure if the fingertips possess some kind of benefit, the fingertips will be attached to a hook. Before the fingertips are placed on the hook, a CAD model was developed to determine the best location for the fingertips.

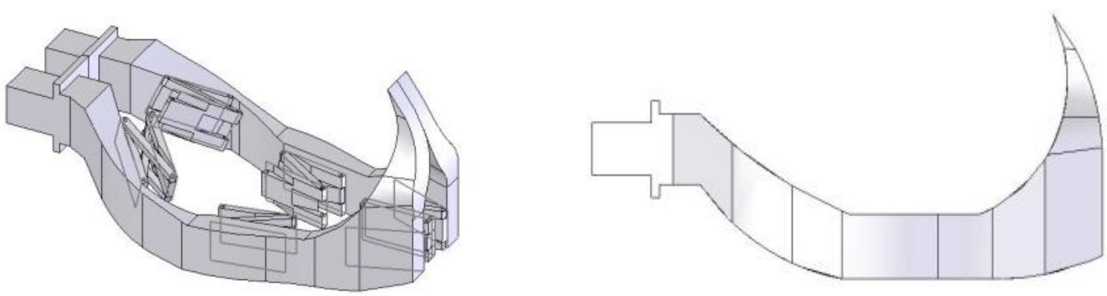
A CAD model of the 555 Hosmer hook is shown in Figure 4.2. One of the problems of attaching the fingertips to the existing hook is that there is not enough space to place them. An example of this is shown in Figure 4.2, the fingertips are intersecting each other and there is no space to place them because the hook is mostly curved.



a b

Figure 4.2: (a) Lateral and (b) top view CAD model of 555 Hosmer hook with the fingertips

Because of lack of space in the normal hooks, another prosthetic hook was designed to meet with the specifications of the fingertip. Figure 4.3 shows a cad model of the hook with the fingertips attached. Some changes in this design is that the designed hook is 154.7 mm of length and is 47.46 mm wide. The inside of the hook is wider (47.46 mm vs. 18 mm) than the Hosmer hook, therefore, there is more space when the fingertips are attached. By implementing this change, the distal part of the hook is able to have the fingertips together when the hook is closed and other fingertips are 10 mm apart.



a b

Figure 4.3: (a) Isometric and (b) side view of hook with fingertips attached

4.2.1 Manufacture

There were difficulties in the manufacture of the prosthetic hook, for this reason another prosthetic hook was developed. This design is 16.3 cm long, and has a maximum inside width of 34 mm to attach the fingertips. With that inside width, there is only room to attached 2 fingertips in each side of the hook.

4.3 Robot gripper paddles

A robotic gripper, shown in Figure 4.3, was designed for Wheelchair-Mounted Robotic Arm developed at USF. It has shown to be able to grasp different door handles (knob and lever handles), sheets of paper, a ball, a cup and a rectangular object [31].

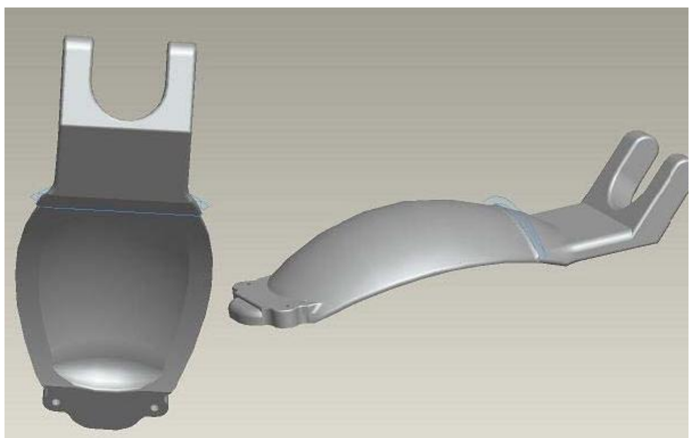


Figure 4.4: Gripper paddles used in Wheelchair-Mounted Robotic Arm

The Wheelchair-Mounted Robotic Arm does not have sufficient space to incorporate the fingertips to it. For this reason, an alternative robotic paddle for the gripper incorporating the fingertips was designed.

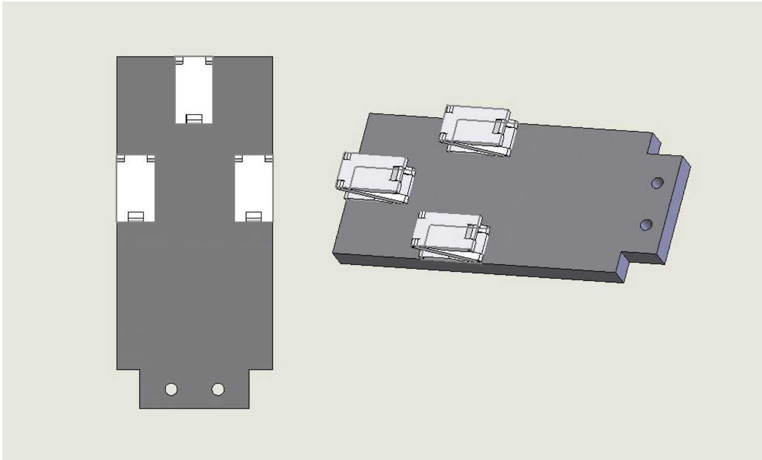


Figure 4.5: Isometric CAD model of the gripper paddles with the fingertips attached

The paddles are made of aluminum and are 114.30 mm (4 in) height and 50.8 mm (2 in) wide. This gripper consists of six fingertips (3 on one side and 3 on the other side of the gripper) in parallel, as shown in Figure 4.4, and has a similar size of the paddles used for the Wheelchair-Mounted Robotic Arm. The top of each fingertip is adjacent to another fingertip on the other paddle. This configuration should make the gripper be able to pick up small objects better.

Chapter 5

The SHAP Test

This chapter consists of a description of the methodology of the fingertip's assessment. For this, the SHAP test, a standardized hand assessment, will assist in the evaluation of the hooks. First, the different types of human prehensile patterns used in the hand assessment procedure are explained. Each type of prehensile pattern will be used to provide the index of functionality of the different hooks, comparing them with the anatomical hand.

5.1 Prehensile patterns

The major function of the hand that a prosthesis tries to replicate is grip [4]. Two different functional types of grasps are differentiated: power grasp and precision grasp [25]. Power grasp includes cylindrical (or power), spherical (or flexion), hook (or extension grip) and lateral prehension when the thumb is adducted. Precision grip includes palmar prehension (or tripod grip), tip and lateral prehension when the thumb is abducted [26]. The hand forms of each one of these types of grasp is shown in Figure 5.1. The general characteristics of each prehensile pattern are as follows:

1) Spherical grip: all fingers and the thumb are flexed, rotated and abducted to surround and support the object. Also categorized as the five fingered grip [28].

2) Tripod pinch: the pulp of the thumb is opposed to the pulp of the index and middle fingers.
3) Power grip: all fingers are flexed around the object. The palm of the hand is used for object opposition rather than active force generation by the thumb. Also categorized as diagonal and transvolar, first, cylindrical or hook grips [25,28].
4) Lateral pinch: A small, flat object is held between the lateral (radial) aspect of the middle or distal phalanx of the index finger and the pulp of the thumb [27].
5) Tip pinch: The pulps or the volar aspects of the fingers including the pulps and the pulp of the thumb surround the object and support it against its center. Only one or two of the radial fingers and the thumb participate and the contact areas are limited to the tips [27].
6) Extension grip: all fingers are extended and adducted with the thumb in extension and opposition [28].

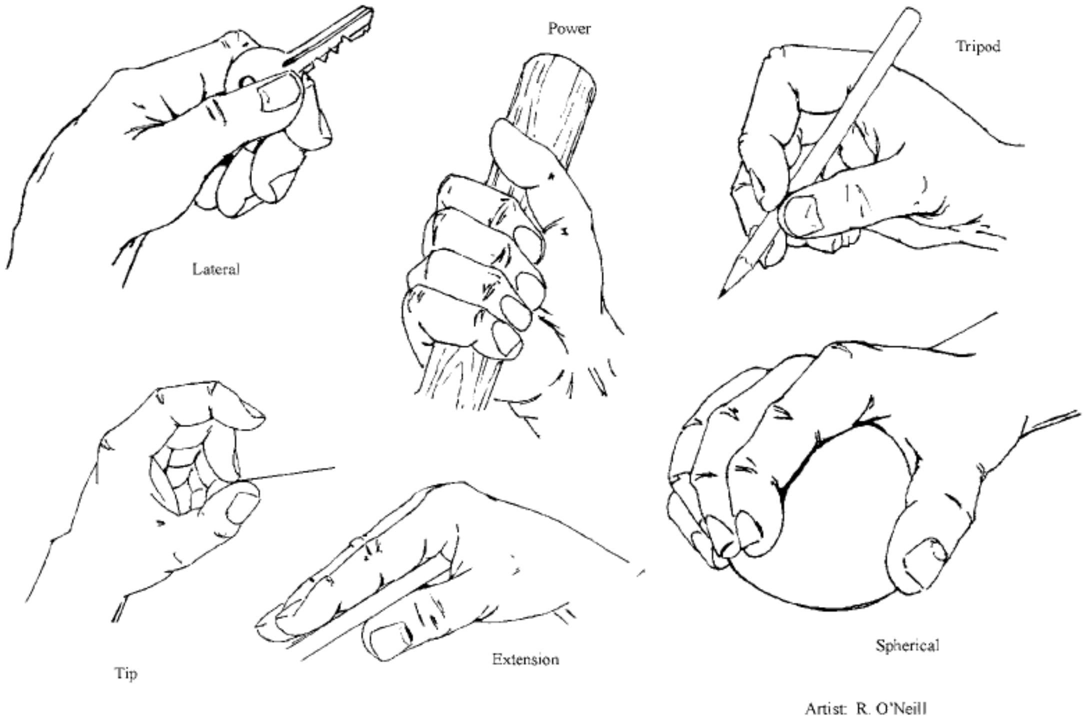


Figure 5.1: Different types of human grasps [29]

The difference between the two broader categories of grasp is that the hand position for the power grasp is static (fixed position) and for precision grip the hand position is dynamic (for object manipulation). In Figure 5.1, the power (*b*), extension (*e*), lateral (*a*) and spherical (*f*) prehensile patterns correspond to a power grasp because the hand position is fixed. The tip and tripod grasps, Figure 5.1 *d* and *c* respectively, are used for manipulation, for this reason they are part of the precision grasp.

5.2 Southampton hand assessment procedure

The purpose of the Southampton Hand Assessment Procedure (SHAP) is to determine the effectiveness of a terminal device and controller by focusing the evaluation in the unilateral performance of the user. The SHAP consists of twenty six (26) timed tasks;

twelve (12) are abstract tasks and fourteen (14) consist of activity of daily living (ADL) (Figure 5.2). This assessment tool is designed to be a standardized and objective method of evaluating pathologic or prosthetic hand function. The SHAP test has undergone validation and reliability studies [29] which support its use as an objective assessment tool.

The abstract-objects tasks evaluate prehension without the complication of the tools or equipment used during the ADL's that often cause intermediate grip patterns or adverse evaluation effects. Because the shape and form of an ADL task is likely to be known to the subject, a psychologic prejudice may exist as to the ability to perform the task. The abstract objects remove such an effect to a limited extent. The abstract objects are produced in two sets for use in the SHAP procedure. The first is made of noncompliant dense materials (heavyweight abstracts) and the second is from marginally compliant, low density materials (lightweight abstracts), to produce a difference in both weight and yield [29].

Colin Light [28] divided the fourteen (14) activities of daily living in the six prehensile patterns as shown in Table 5.1. A spherical grip is required for 10% of the tasks, a tripod grip for 10%, a power grip for 25%, a lateral grip for 20%, a tip grip for 20%, and an extension grip for 10%. This configuration ensures that a full range of natural grips will been evaluated.

Figure 5.2: SHAP objects

For these tasks, the opposite hand acts only as a stabilizer, thereby ensuring the functional assessment for the impaired hand. The self timed nature of the SHAP eliminates the need for subjective opinion by the assessor.

Table 5.1: SHAP activities of daily living and 'natural' grip classification [A4]

	Task	'Natural' grip classification
1	Pick up coins	Tip
2	Undo buttons	Tip/Tripod
3	Simulate food cutting	Tripod/Power
4	Simulate page turning	Extension
5	Remove jar lid	Spherical
6	Pour water from jug	Lateral
7	Pour water from carton	Spherical
8	Move a jar full of water	Power
9	Move an empty tin	Power
10	Move a tray	Lateral/Extension
11	Turn a key	Tip/Lateral
12	Open/close a zipper	Tip/Lateral
13	Rotate a screw	Power
14	Turn a door handle	Power

5.3 SHAP Test

Personal and prosthetic history was collected from each person. The information included: age at time of the assessment, ethnic category and gender.

The subjects were asked to perform the SHAP using their hand, a standard hook and the hook with the fingertips attached. The detailed protocol is stated on Appendix B. The hand results will be used to obtain the normative data for the test. A boundary condition of 8 times that of the norm is imposed in each task of the SHAP test to prevent a subject from taking too long [29]. This definite, if arbitrary, limit on the time allowed to perform a task, provides a numerical value that can be used when subjects are unable to perform a task.

5.3.1 Abstract objects

Subjects picked up each abstract object from the SHAP board (Figure 5.3), moved it through an obstacle and placed it on the SHAP board. For these tasks, the opposing hand acts only as a stabilizer. Time for each task ends when the object is placed on the SHAP board. The time was taken by the participant and recorded by the assessor. Each task was performed three times. The abstract objects are:

1. lightweight spherical
2. lightweight tripod
3. lightweight power
4. lightweight lateral
5. lightweight tip
6. lightweight extension
7. heavyweight spherical

8. heavyweight tripod
9. heavyweight power
10. heavyweight lateral
11. heavyweight tip
12. heavyweight extension

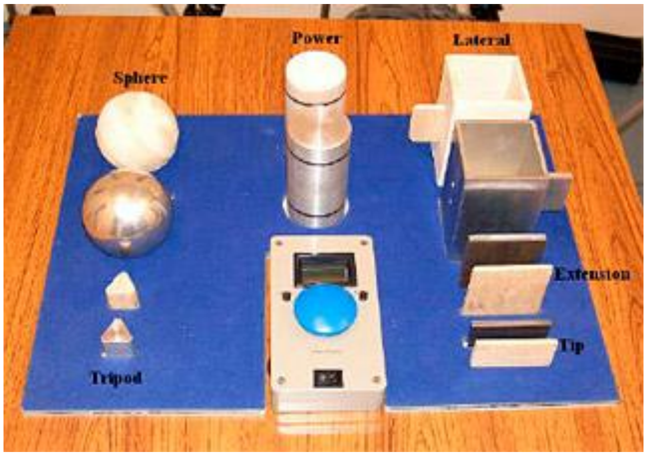


Figure 5.3: Abstract SHAP objects

5.3.2 Activities of daily living

Subjects performed different activities of daily living (Figure 5.4). The time was be taken by the participant and recorded by the assessor. Each task was be performed three times. The tasks considered were to:

1. pick up coins
2. undo buttons
3. simulate food cutting
4. simulate page turning
5. remove a jar lid
6. pour water from jug

7. pour water from carton
8. move a jar full of water
9. move an empty tin
10. rotate a screw
11. turn a door handle
12. open and close a zipper
13. turn a key
14. move a tray

Figure 5.4: Activities of daily living objects

5.4 Index of functionality

The score given by the SHAP test is a functional score; 100% indicating normal hand function, made up of six sub-scores for each of the different hand grips: lateral, power, tripod, tip, extension and spherical. The Index of Functionality (IOF), which provides an original metric capable of distinguishing between levels of function, may be obtained for each prehensile pattern, which themselves are comprised of multiple tasks.

Colin Light [28] creates the Index of Functionality using the Euclidean squared distance, a measure between samples in an i-dimensional problem, where i=1,2… 6 (prehensile patterns) in this case. This distance d (equation 15) is determined using the z value (equation 14) for each prehensile pattern.

$$z_i = \frac{x_i - \bar{x}_i}{s_i} \tag{5.1}$$

Where:

x_i is the subject's time for prehensile pattern

$\bar{x}_i$ is the mean time for pattern i in the normative sample data taken from healthy subjects

s_i is the standard deviation of times for the pattern i in the normative sample.

$$d = \sqrt{\sum_{i=1}^{6} (z_i)^2} \tag{5.2}$$

The index of functionality (distance d) is rescaled to a value of 100 when x_i is equal to the corresponding $\bar{x}_i$, and diminishes to 0 for a subject that reaches the boundary condition for each task (and hence is deemed to have a minimal function) [28]. The rescaled index of functionality (equation 16) is found using the slope-point equation.

$$IOF = -\frac{100}{7} * \frac{s_i}{\bar{x}_i} * z_i + 100 \tag{5.3}$$

Where the 7 in the equation 5.3 comes from the boundary condition where x_i is 8 times the mean time of the normative sample.

The index of functionality of the standard hook and the hook with the fingertips will be generated to provide an overall assessment of their relative function.

5.5 Human subjects

For this research, subjects between the ages of 18 to 25 years were selected. Some reasons for this age interval is the convenience at university setting, a normative database has been established as the benchmark of normal hand function in that age range, and that it reduces a potentially significant variation within the group. A previous study has shown a slight increase in the time to complete the task with age [30]. The participants are going to do the different tasks of the procedure with their anatomical hand, the standard hook (Figure 5.5), and with the hook with the fingertips (Figure 5.6), for three times each. With these times, the index of functionality of both hooks and the anatomical hand will be generated.

Figure 5.5: 555 Hosmer hook.

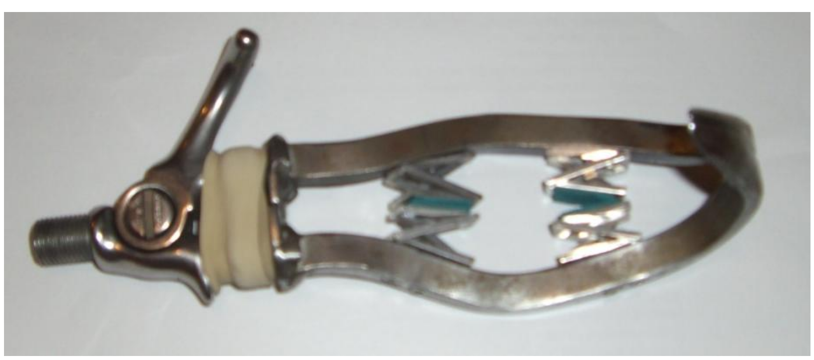


Figure 5.6: New design of the hook with the fingertips attached.

5.6 Robot gripper

A robotic gripper, shown in Figure 5.7, was designed for Wheelchair-Mounted Robotic Arm developed at USF. It has shown to be able to grasp different door handles (knop and lever handles), sheets of paper, a ball, a cup and a rectangular object [31].

Figure 5.7: Cad model of the gripper paddles used in the Wheelchair-Mounted Robotic Arm

An alternative robotic gripper incorporating the fingertips has been designed (Chapter 4). This gripper consists of six fingertips (3 on one side and 3 on the other side of the gripper) as shown in Figure 5.8, and has a similar size of the paddles used for the Wheelchair-Mounted Robotic Arm.

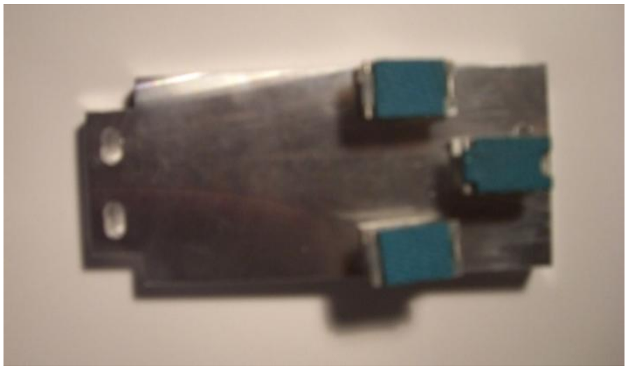


Figure 5.8: Design of the gripper paddle with the fingertips attached

Both grippers were compared using the SHAP test, they attempted to do the same tasks as the human subjects. A boundary condition of 8 times that of the norm was imposed in each task of the SHAP test. Because the time to complete the tests depends on the ability of the person to manipulate the robot gripper, the benefits of the fingertips will be distinguished by comparing which objects each one of the grippers can grasp.

Chapter 6

Results

This chapter presents the results of the human and robotic testing. The SHAP test was used to compare both hooks. A group of 10 persons (8 males and 2 females) were asked to performed the SHAP test. All the persons were right handed and nine of them are between the ages of 18 to 25. They used a pseudo-prosthesis to simulate a prosthetic user. Using this, they were able to use the conventional hook (555 Hosmer hook) and the hook with the fingertips.

6.1 Normative data

Each subject performed the procedure specified in Appendix B with their left hand to developed the normative data. The normative data for the hand, Figure 6.1, was used to calculate a range of the index of functionality for the hooks. The error bars in the normative data represents the twice the standard deviation in each task.

6.2 Hook testing

The SHAP test is a standardized test for the human hand. Some modifications were done in the SHAP protocol to be able to perform these tasks using the hooks.

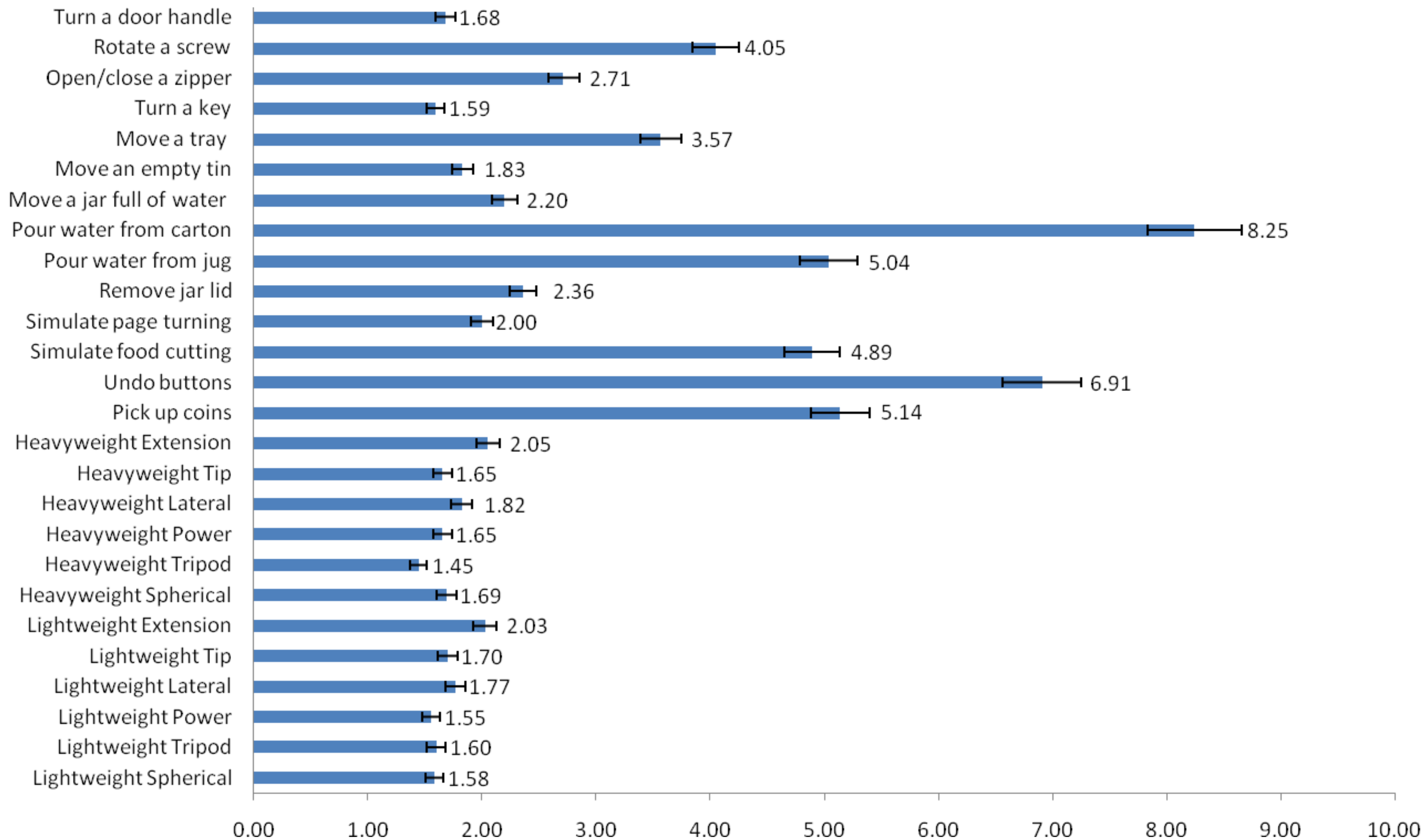


Figure 6.1: Mean normative task times for the non-dominant hand

Table 6.1: Modifications done to the SHAP test protocol in order to be used by the hooks

Tasks	Modifications
Tip and Extension Objects	The form board is not going to be directly in front of the person. The person can move it to the left or right, in such a distance that he or she is able to perform the task.
Lateral Objects	When trying to pick up this object parallel to the handle, as done with the hands, the object tends to rotate and falls. Because of this problem, the object could be lifted perpendicular to the handle.
Simulate page turning	To be able to pick up the index card, the person needs to drag it, using the hook, below the mark. In this way, the hook is able to pick it up.
Pour water from jug, pour water from carton, move a jar full of water and move an empty tin	In these tasks, the form board is not going to be directly in front of the person. The person can move it to the left or right, in such a distance that he or she is able to perform the task.

6.3 Observations

There is a time difference in subjects 9 and 10, which are females. This is because men generally tend to move more rapidly because of the greater amount of contractile force as noted in [32]. Another parameter is that subject 10 is over the age specified and with an increase in age, there is an increase in timing.

The data, Appendix C, was divided in their correspondent prehensile patterns. Appendix D, shows a plot of the mean values of each person compared to themselves using their hand, the Hosmer hook and the hook with the fingertips.

6.4 Data analysis

There were difficulties completing some of the tasks. In the test, the participants are using their non-dominant hand. Table 6.2 lists tasks that were not able to be completed by all the subjects.

Table 6.2: Tasks that were unable to be completed by all the test subjects

Task	Hook (tasks completed/ total tasks)	Hook with fingertips (tasks completed/ total tasks)
Lightweight Lateral	10/10	9/10
Heavyweight Spherical	8/10	10/10
Heavyweight Power	9/10	10/10
Heavyweight Lateral	10/10	9/10
Undo buttons	9/10	6/10
Simulate food cutting	5/10	2/10
Remove jar lid	7/10	10/10
Open/close a zipper	10/10	7/10

There is more than one way to grasp an object with the hooks. Not everyone had the same approach grasping the objects. Table 6.3 shows the tasks for which the four-bars were used by every subject, the tasks in which some used the four-bars and by not anyone. The tasks where the four-bars where not used by anyone, the objects are small. The tasks where the four-bars where used by everyone, the objects are large. We are going to be focus on the tasks that the fingertips were used by everyone.

Table 6.3: Tasks where the fingertips were used by all of the subjects, by some of them and by no one

Four-bars used by everyone	Four-bars used by some subjects	Four-bars not used by anyone
Lightweight Spherical	Lightweight Tripod	Lightweight Tip
Lightweight Power	Lightweight Lateral	Lightweight Extension
Heavyweight Spherical	Heavyweight Tripod	Simulate page turning
Heavyweight Power	Heavyweight Lateral	Turn a key
Remove jar lid	Heavyweight Tip	Open/close a zipper
Pour water from jug	Heavyweight Extension	Turn a door handle
Pour water from carton	Pick up coins	
Move a jar full of water	Undo buttons	
Move an empty tin	Simulate food cutting	
Rotate a screw		
Move a tray		

In the heavyweight spherical object task, Figure 6.2, two subjects were not able to performed the task. The plot shows that six subjects were able to complete the task in less time taken using the hook with the fingertips. Just one subject had a better timing using the Hosmer hook.

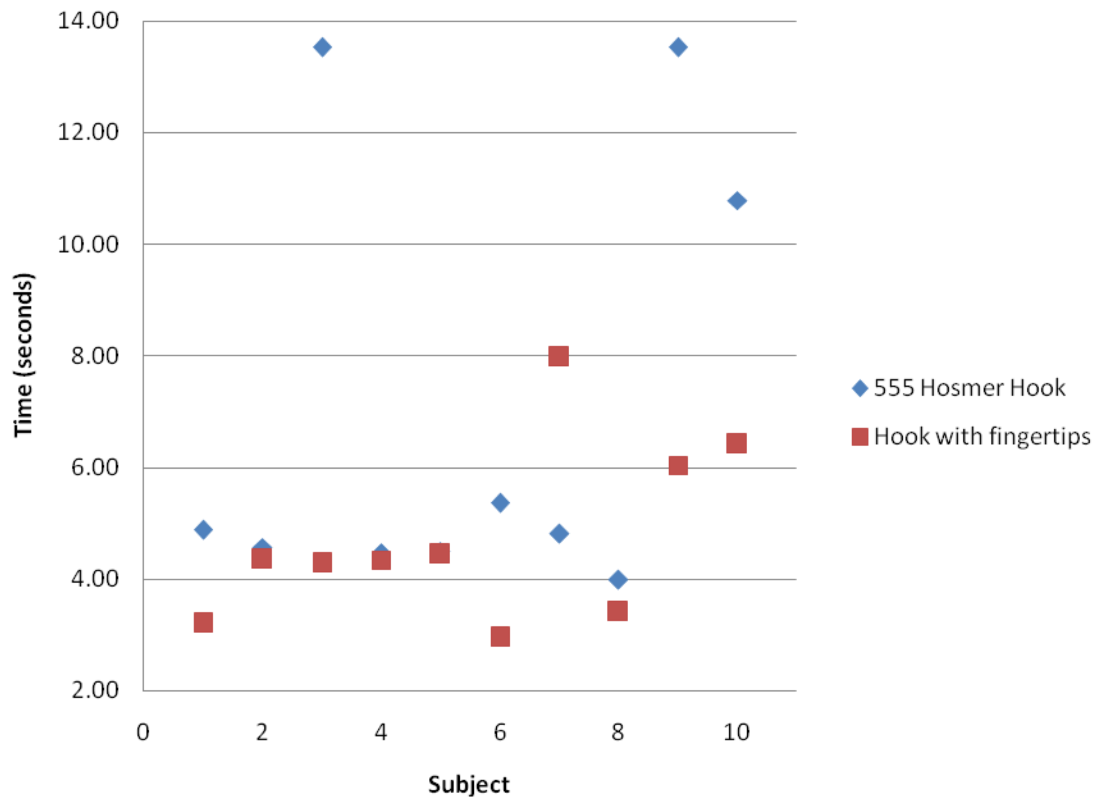


Figure 6.2: Mean times of hooks performing the heavyweight spherical object task for each subject

Everyone was able to perform the lightweight spherical task, Figure 6.3. Five of the subjects had a significant difference in the time to perform the tasks using the hook with the fingertips. Two subjects had better timing using the Hosmer hook.

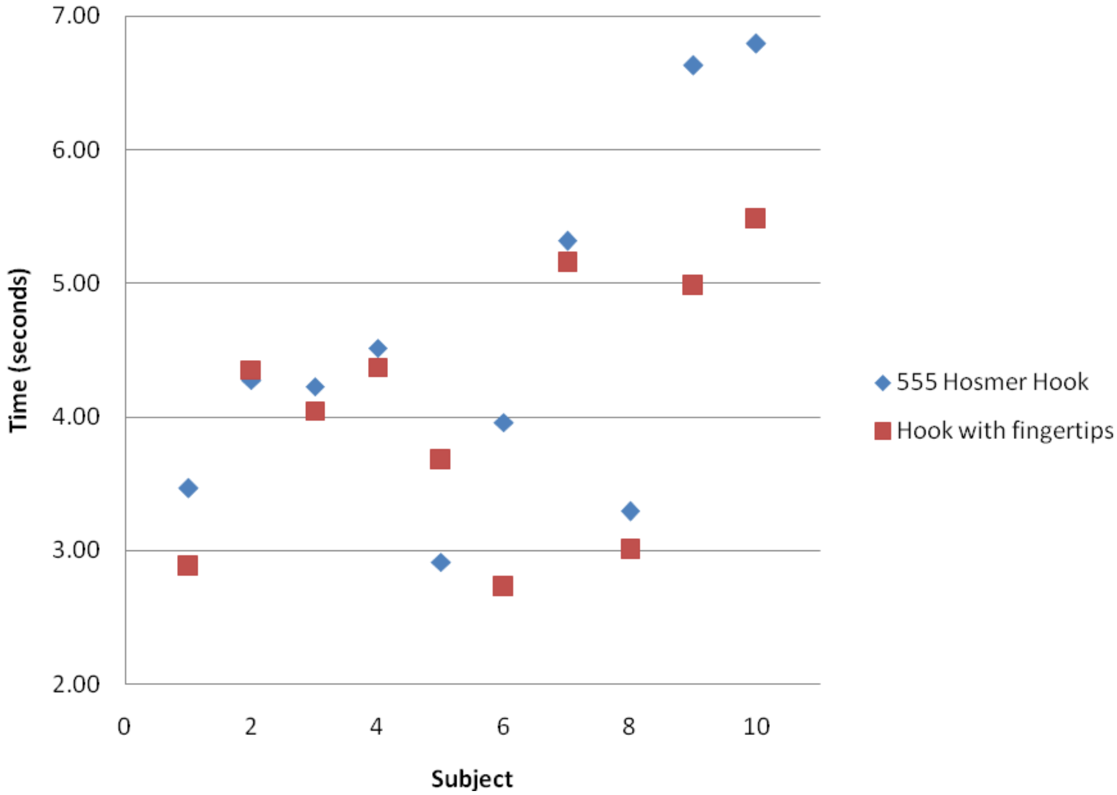


Figure 6.3: Mean times of hooks performing the lightweight spherical object task for each subject

In the lightweight power task, Figure 6.4, six subjects had a better timing using the hook with the fingertips, two subjects did better with the Hosmer hook and two subjects do not show a significant difference in the time.

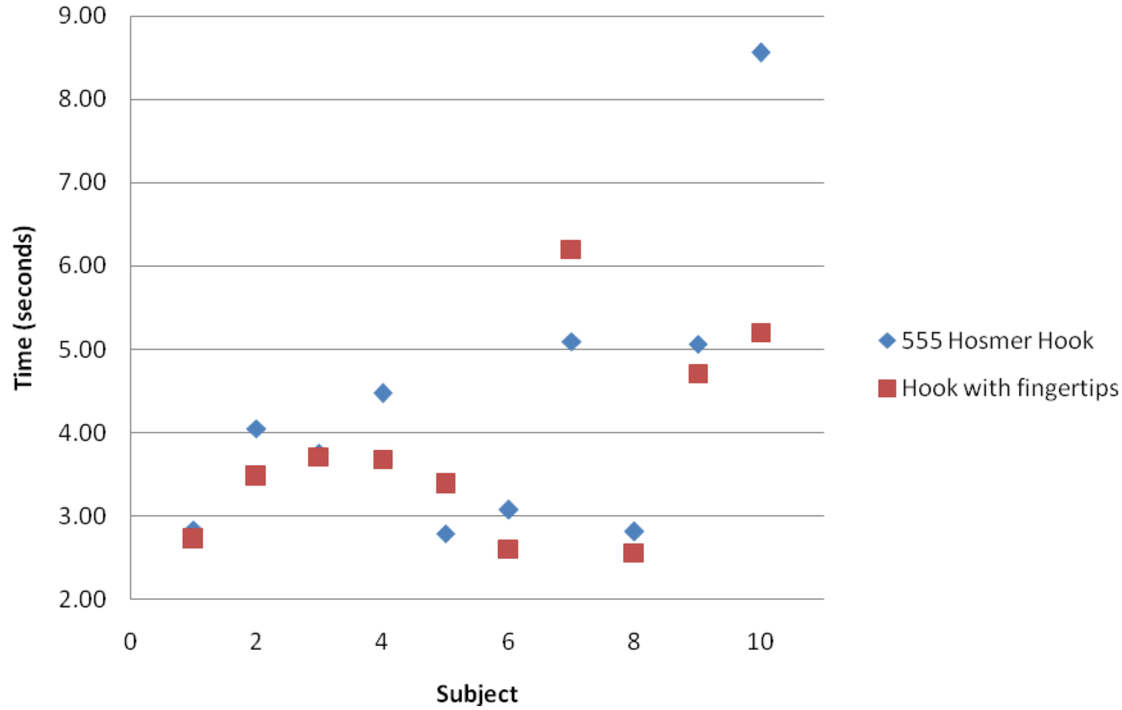


Figure 6.4: Mean times of hooks performing the lightweight power object task for each subject

In the heavyweight power task, Figure 6.5, one subject was not able to perform the task using the Hosmer hook, it was too heavy and could not pick it up. All the subjects had a better time using the hook with the fingertips.

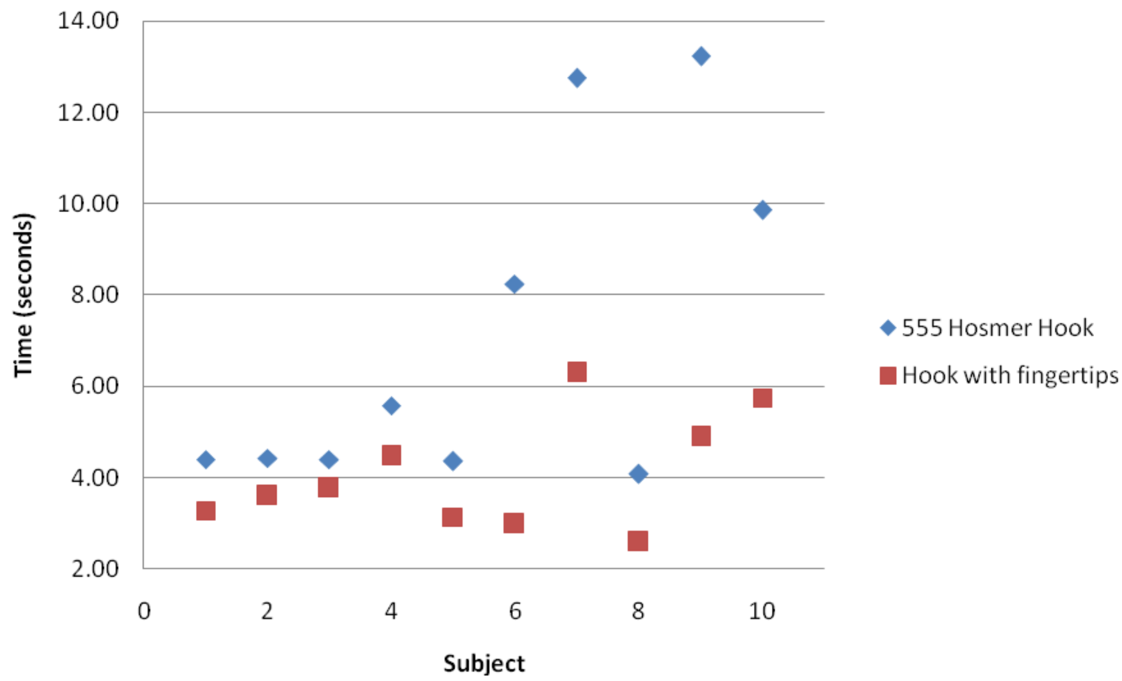


Figure 6.5: Mean times of hooks performing the heavyweight power object task for each subject

Seven persons were able to remove the jar lid with the Hosmer hook, as shown in Figure 6.6. Of the seven subjects that completed the task with both hooks, five subjects had a better time using the hook with the fingertips, one subject had a better timing using the hook and one person do not show any significant difference.

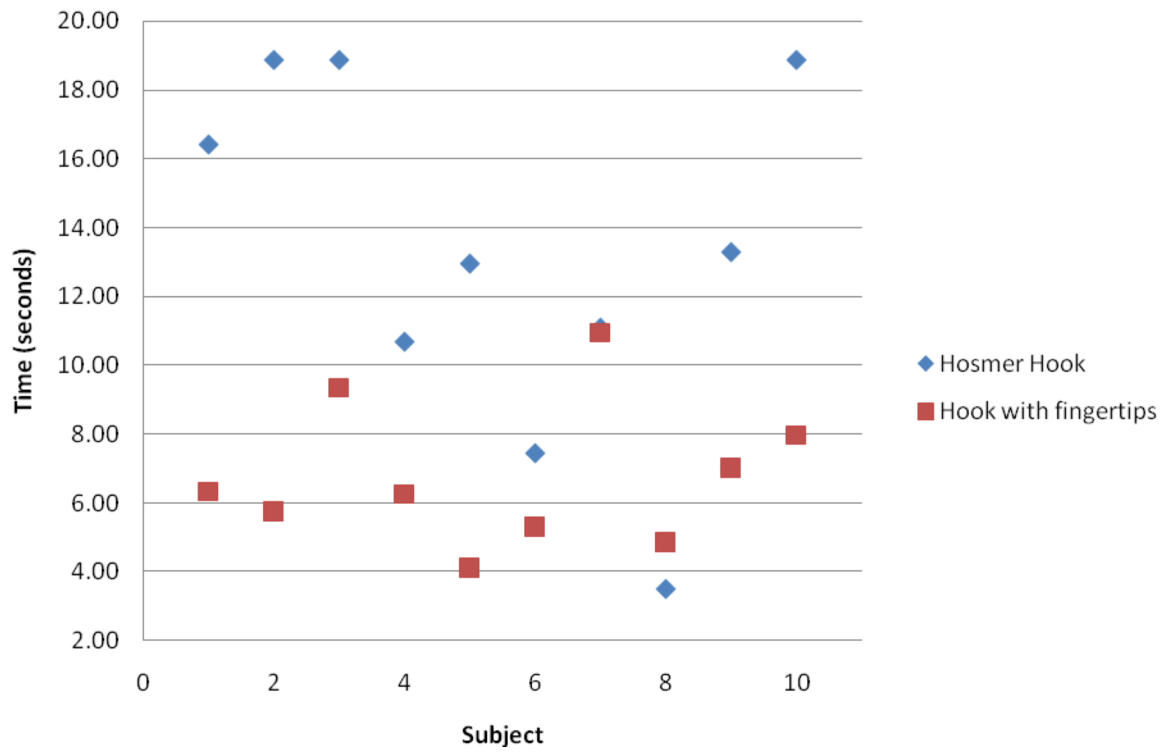


Figure 6.6: Mean times of hooks removing the jar lid for each subject

When the subjects were pouring water from the jug, six subjects had better time using the hook with the fingertips, one had better time using the Hosmer hook, and three subjects do not show any significant difference as shown in Figure 6.7. The Hosmer hook had a standard deviation of 5.27 and the hook with the fingertips of 3.55.

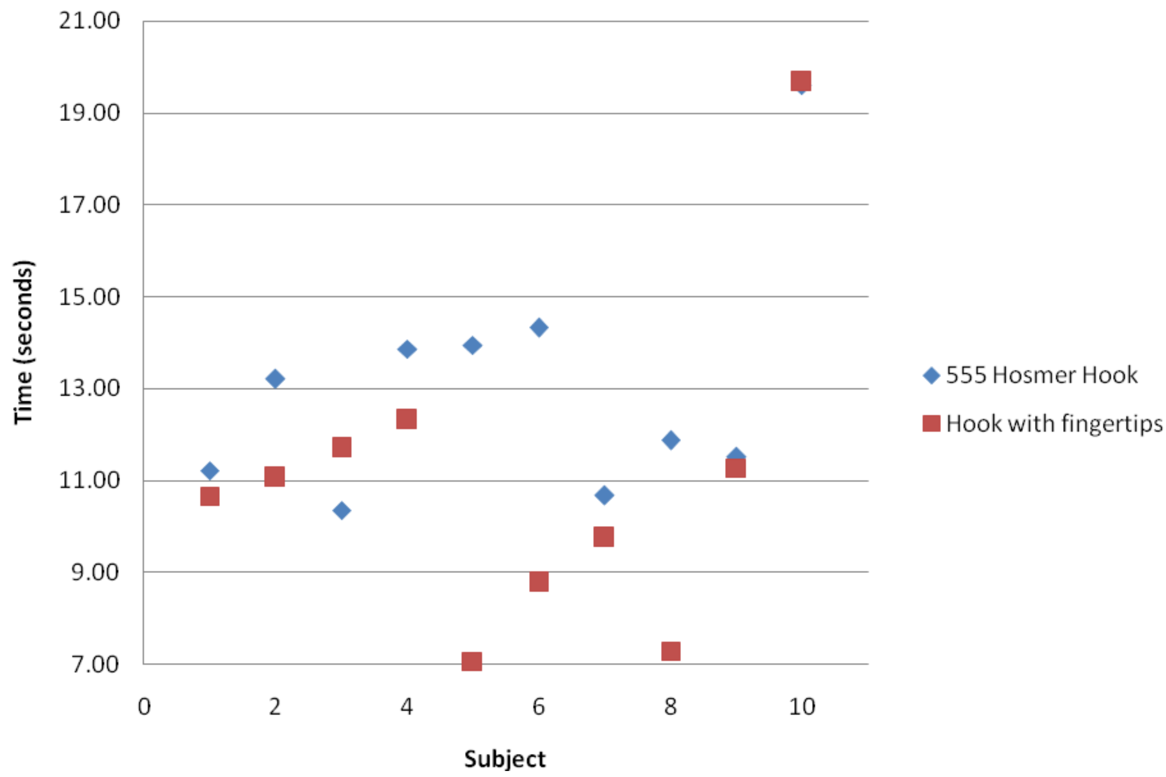


Figure 6.7: Mean times of the hooks pouring water from a jug for each subject

In the task of pouring 200 ml of water from a carton, five subjects had a better timing using the hook with the fingertips, three subjects using the Hosmer hook, and two subjects do not show any significant difference, as shown in Figure 6.8. For this tasks, subjects 2,3,5,6,7,9, and 10 rotated the carton 90 degrees and then picked it up. In this way, they did not need to use much force in opening the hooks.

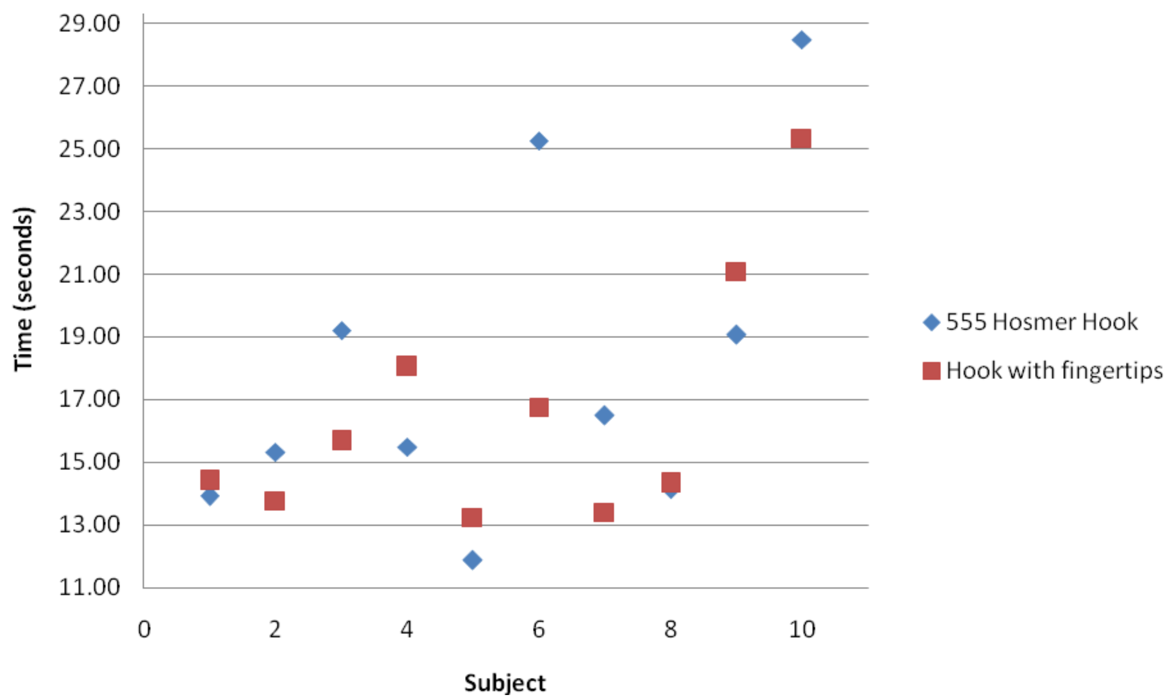


Figure 6.8: Mean times of the hooks pouring water from a carton for each subject

Some problems were encountered lifting the jar full of water with the conventional hook. When the subjects tried to lift the jar by the base, the objects tended to descend (caused by the weight and friction on the fingers). Most of the subjects grasped the jar in between the lid and the base. This helped them to secure the object before lifting it. As shown in Figure 6.9, seven subjects had better timing using the hook with the fingertips, two subjects had better time using the Hosmer hook and one did not show any time difference.

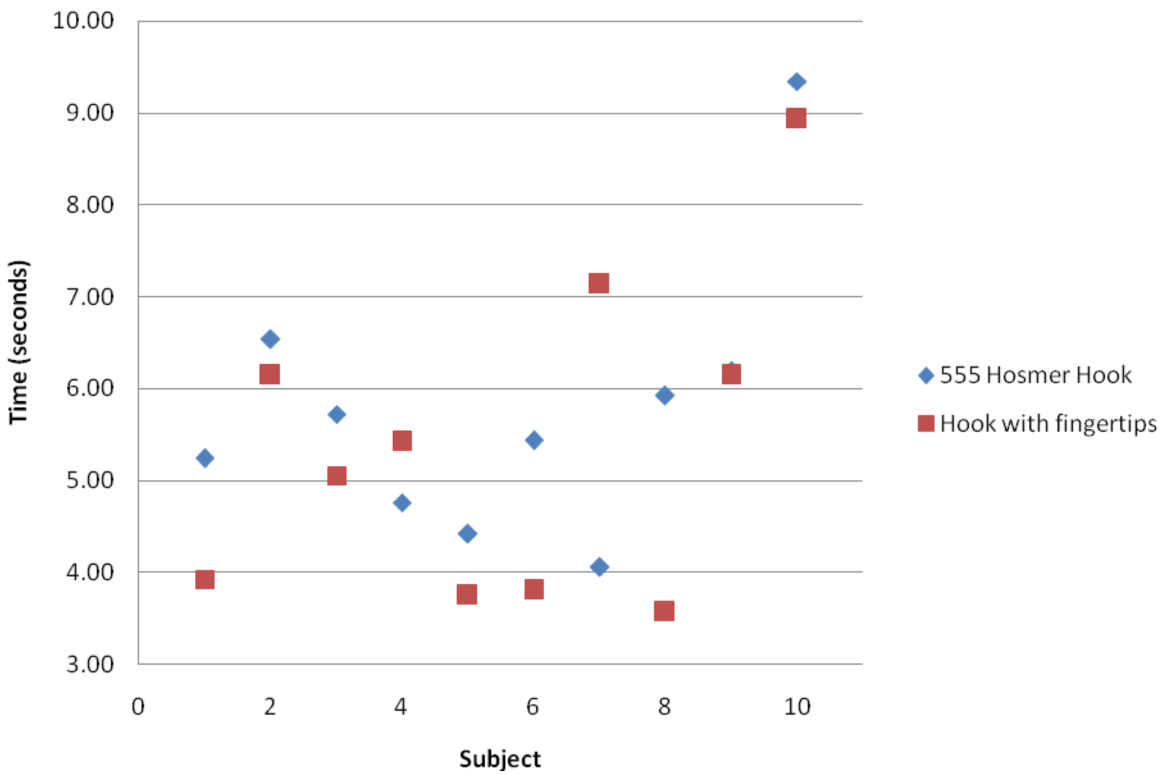


Figure 6.9: Mean times of the hooks moving a jar full of water for each subject

In moving the empty tin, Figure 6.10, five subjects had better time using the hook with the fingertips, two subjects had better time using the Hosmer hook, and three did not show any significant difference.

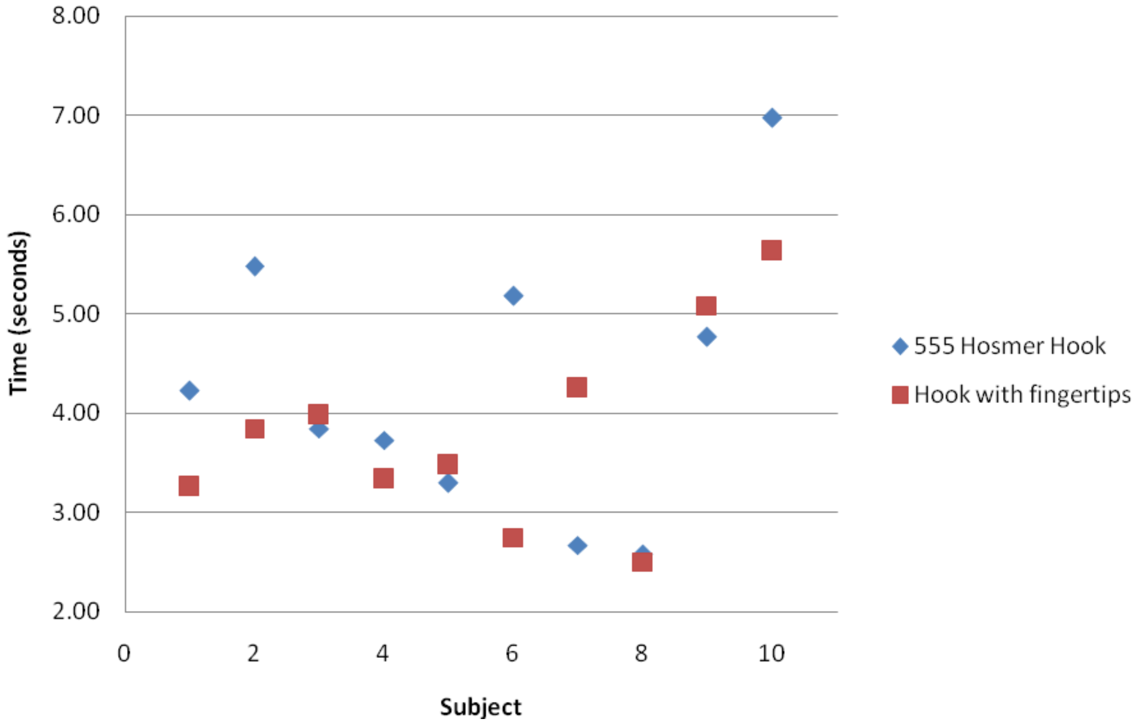


Figure 6.10: Mean times of the hooks moving an empty tin for each subject

To rotate the screw, with the hook with the fingertips, the subjects dragged down the screwdriver, and picked it up using the last 2 fingertips. Figure 6.11 shows that seven subjects had better time using the hook with the fingertips, and three had better time using the Hosmer hook.

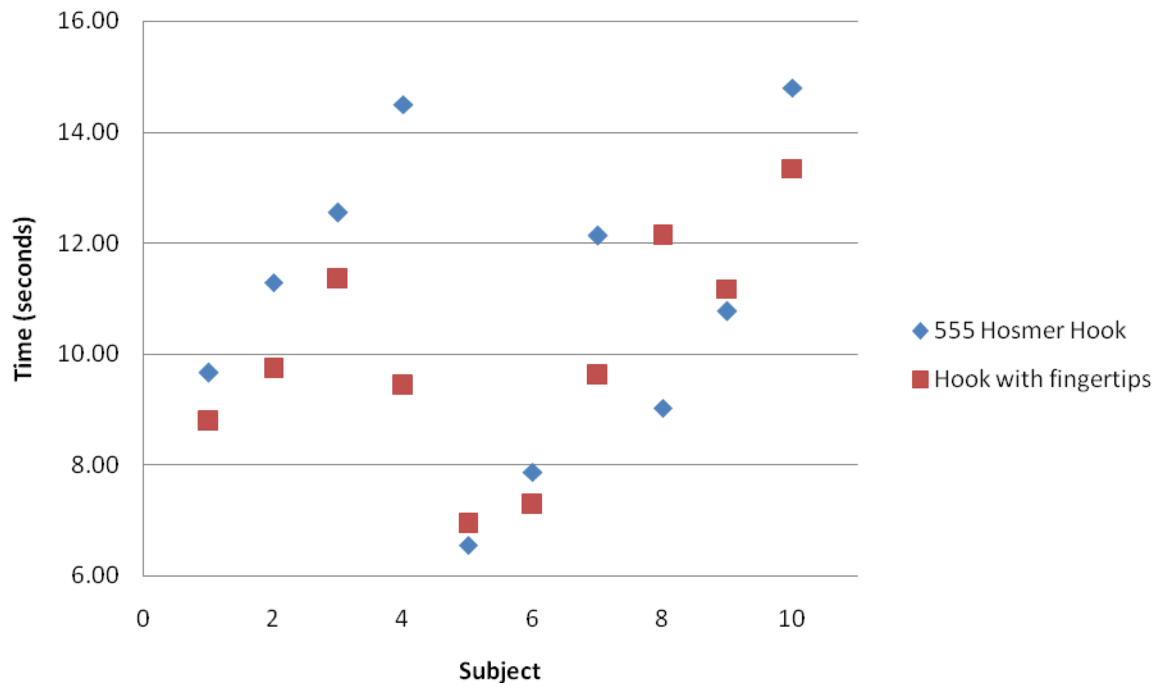


Figure 6.11: Mean times of the hooks rotating a screw for each subject

6.4 Index of functionality

The overall Index of Functionality (IOF) of the Hosmer hook is 66.65 (ranged from 46.25 to 80.03) and 66.21 (ranged from 47.15 to 77.42) for the hook with the fingertips. One caveat in interpreting the IOF is that some of the tasks could not be completed by some subjects. This increases the timing, (because the boundary condition of 8 times the mean normative value is used), and decreases the IOF.

Table 6.4 shows the Index of Functionality for each prehensile pattern. In the spherical and power grasps, the hook with the fingertips had a better average IOF. This is also because in at least in one of the tasks of the other prehensile patterns, one or more subjects could not perform it.

Table 6.4: Average, minimum and maximum index of functionality for the Hosmer hook and for the hook with the fingertips for each prehensile pattern

	Hosmer			Hook with fingertips		
Prehensile pattern	average	min	max	average	min	max
Spherical	61.43	35.28	87.04	77.64	63.41	86.79
Tripod	54.58	34.70	63.60	46.85	31.18	56.51
Power	65.81	44.69	74.75	70.98	56.76	77.68
Lateral	73.94	52.53	86.92	69.63	40.44	85.15
Tip	67.26	48.08	79.98	56.58	31.66	76.18
Extension	73.42	57.59	88.70	69.66	47.28	86.03

The mean Index of Functionality of the tasks for which the subjects always used the fingertips, Table 6.5, shows that the hook with the fingertips was able to perform 10 of 11 of the tasks in less time than using the fingertips. An exception of this was moving the tray. The most significant improvements are in the heavyweight spherical task, heavyweight power task, removing the jar lid and pouring water from a jug.

Table 6.5: Average index of functionality of the tasks where the fingertips were used by everyone

Task	Hosmer	Hook with fingertips
Lightweight Spherical	73.35	77.60
Lightweight Power	75.18	79.11
Heavyweight Spherical	54.81	74.25
Heavyweight Power	52.63	79.07
Remove jar lid	34.34	73.18
Pour water from jug	77.26	83.22
Pour water from carton	83.23	85.52
Move a jar full of water	76.81	79.24
Move an empty tin	80.92	84.52
Move a tray	72.43	71.32
Rotate a screw	75.79	79.10

The mean Index of Functionality of the tasks where any subject used the fingertips, Table 6.6, the importance is the shape and material of the hook. For the page turning, turn a key and to open and close a zipper tasks, the subjects used the inner side and the tips of the hooks. The significant difference in the task of opening and closing the zipper, the problem in the hook with the fingertips is that it does not have any friction material in the inner side of the finger, and the Hosmer hook has a rubber coating at the tips.

Table 6.6: Average index of functionality of the tasks where the fingertips were not used by anyone

Task	Hosmer	Hook with fingertips
Lightweight Tip	73.02	76.94
Lightweight Extension	81.07	82.00
Simulate page turning	70.80	70.91
Turn a key	77.81	79.22
Open/close a zipper	61.22	36.17
Turn a door handle	87.18	86.42

The mean Index of Functionality of the tasks that not all the subjects used the fingertips, Table 6.7, shows that the hook with the fingertips was able to performed 3 of 9 of the tasks in less time than using the fingertips.

Table 6.7: Average index of functionality of the tasks where some of the subjects used the fingertips

Task	Hosmer	Hook with fingertips
Lightweight Tripod	73.65	77.61
Lightweight Lateral	77.06	76.31
Heavyweight Tripod	72.48	77.15
Heavyweight Lateral	77.84	71.58
Heavyweight Tip	70.51	69.51
Heavyweight Extension	77.19	78.35
Pick up coins	61.00	54.43
Undo buttons	60.00	23.20
Simulate food cutting	12.17	9.44

Some uncontrolled variables in the testing are:

1) Strength and agility of the person: some of them are quick learners and are able to perform the tasks easily. Upper body strength helps them to open the hook faster.
2) Frustration: there is a level of frustration that the person has when is not able to complete a task. Some of the activities of daily living are difficult to performed using the hooks. These tasks are picking up coins, to undo buttons, simulate food cutting, pouring water and opening and closing the zipper.
3) Rubber bands: the rubber bands were changed after every two subject to reduce their tendency to degradate over time.

6.5 Robotic gripper testing

The robotic gripper was test using the Manus robotic arm. The movement of the arm was controlled using the Phantom, and the closing and opening of the gripper was controlled using the user interface of the wheel chair mounted arm. This change was done because there were problems controlling the movement of the arm with the Wheelchair-Mounted Robotic Arm (WMRA) system.

The paddles of the WMRA gripper have a smooth finish. The gripper could grasped all the items in the set of lightweight objects. The heavyweight objects are made of steel, and the paddles do not have sufficient friction to be able to grasp the heavyweight object.

When using the fingertips, the paddles could perform all the abstract objects tasks with the exception of the heavyweight lateral object. In this task, the object rotates when the gripper was ascending and it was dragged to the end position for the task.

Chapter 7

Conclusions and Recommendations

7.1 Conclusion

In the human testing, the mean Index of Functionality (IOF) of the Hosmer hook is 66.65 and 66.21 for the hook with the fingertips. The hook with the fingertips had a better IOF in the spherical and power prehensile pattern. This was because in the other prehensile patterns one or more subjects could not perform one or more tasks and the subjects did not use the fingertips in all the tasks. When the IOF is calculated for the tasks that the fingertips were used, in 10 of 11 of the tasks, the IOF is higher than using the Hosmer hook.

In the robotic gripper testing, the Index of Functionality was not be calculated because the time to perform the tasks depended more on the robotic control system than on the physical characteristics of the gripper.

7.2 Recommendations for future work

1. Analysis of the four-bar mechanism with other dimensions to increase the stability region.

2. The fingertips had shown that they can conform to different shapes. The functionality of the hook with the fingertips will increase if it had a friction surface at the tips or having small fingertips all over the inner side of the finger. This will help in picking up small objects.
3. For the robotic gripper, another testing may be using the theory of contact points. But one observation is that it will be good to incorporate a friction surface in the WMRA paddles to increase the materials that the gripper can grasp.
4. Detailed statistical analysis of the results.

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Appendices

Appendix A: Instantaneous stability of the crossed four-bar mechanism

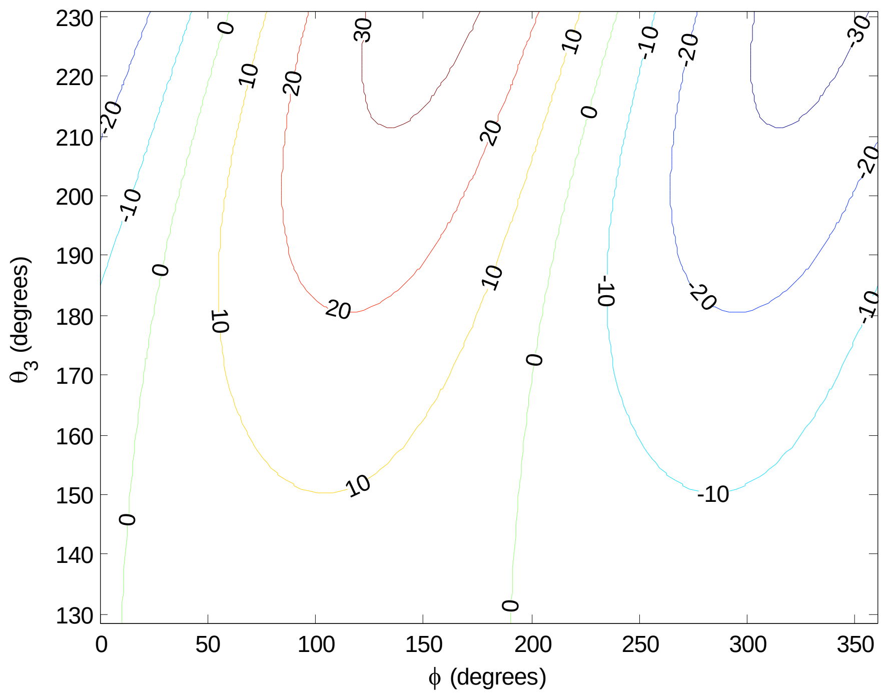

Figure A.1: Instantaneous stability of crossed four-bar mechanism for a=0

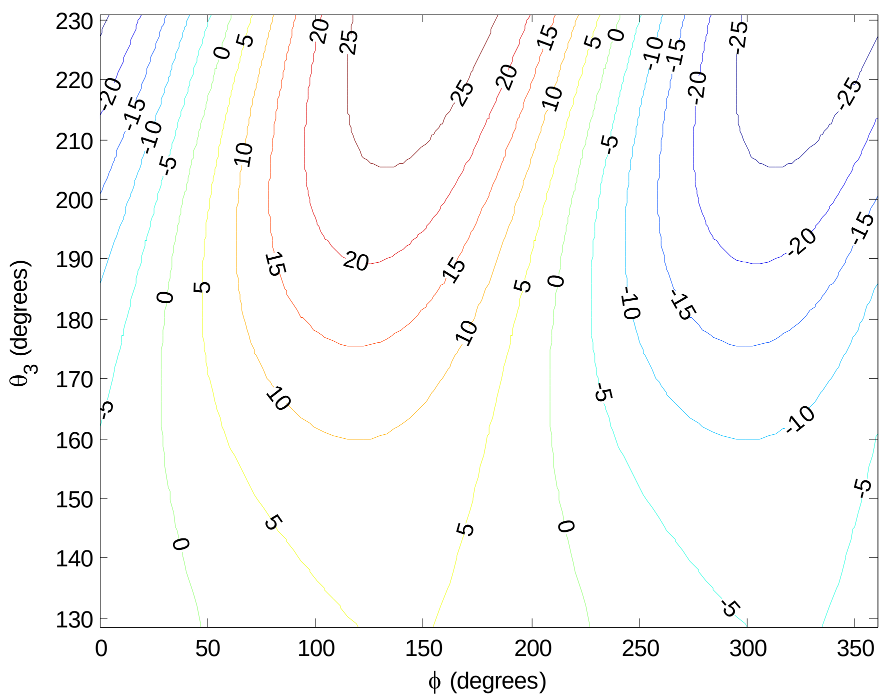

Figure A.2: Instantaneous stability of crossed four-bar mechanism for a=0.1

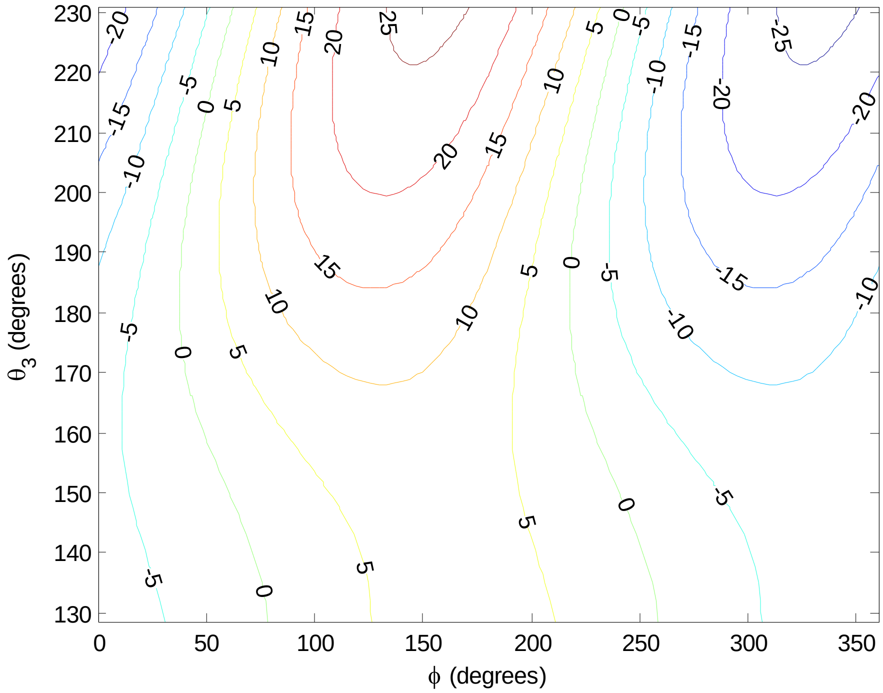

Figure A.3: Instantaneous stability of crossed four-bar mechanism for a=0.2

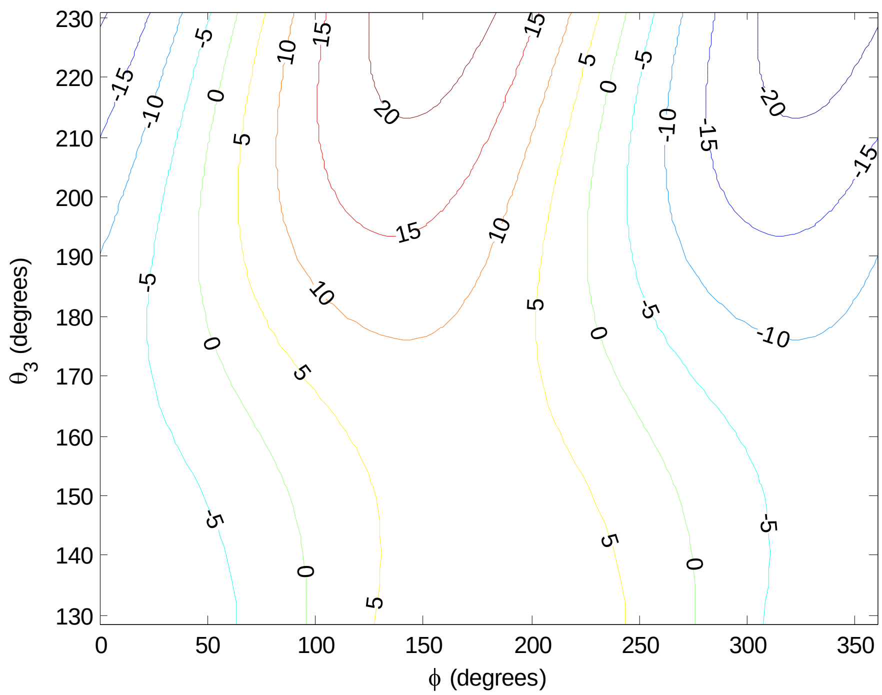

Figure A.4: Instantaneous stability of crossed four-bar mechanism for a=0.3

Appendix A: (Continued)

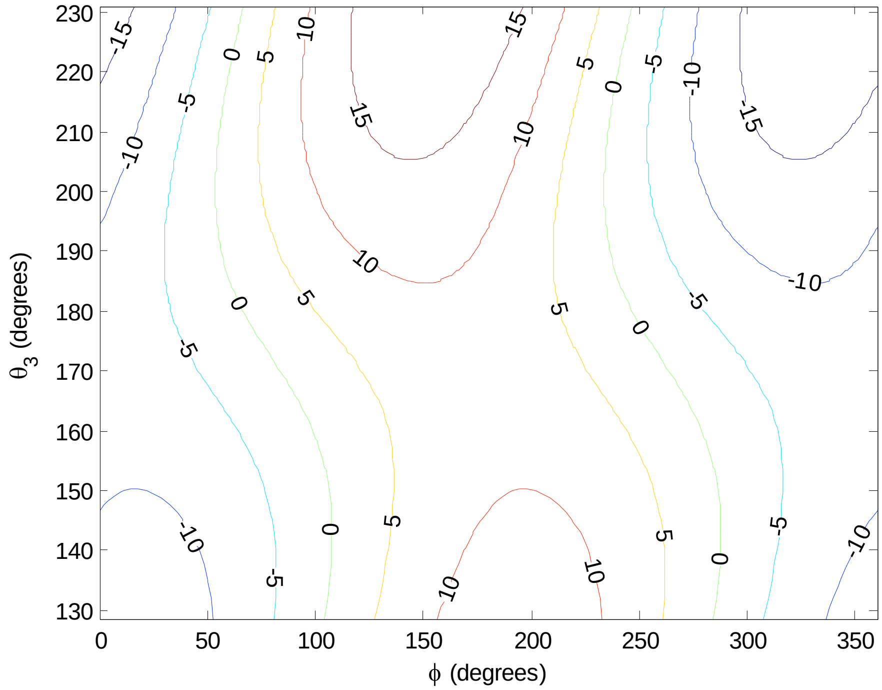

Figure A.5: Instantaneous stability of crossed four-bar mechanism for a=0.4

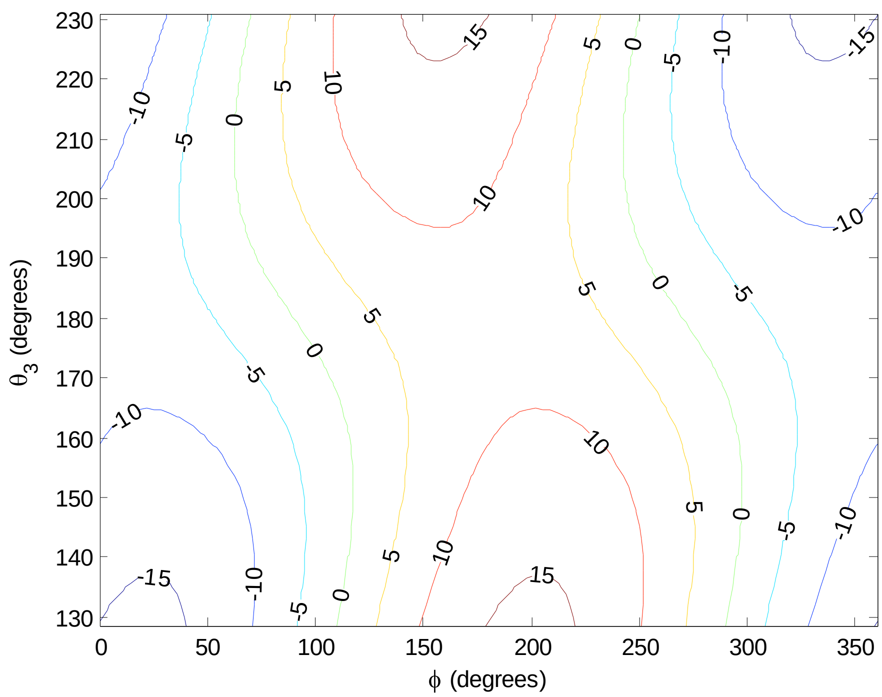

Figure A.6: Instantaneous stability of crossed four-bar mechanism for a=0.5

Appendix A: (Continued)

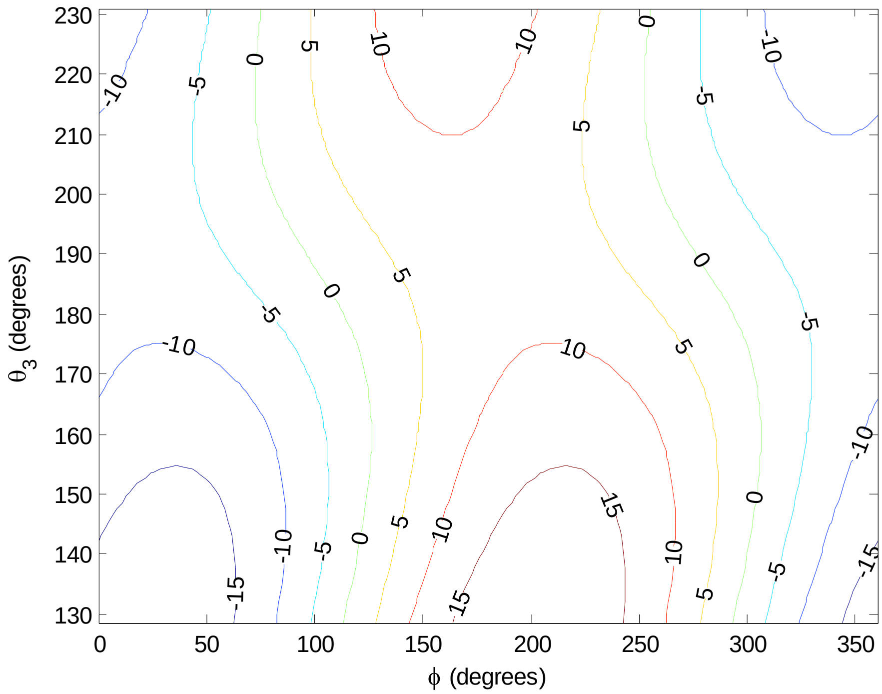

Figure A.7: Instantaneous stability of crossed four-bar mechanism for a=0.6

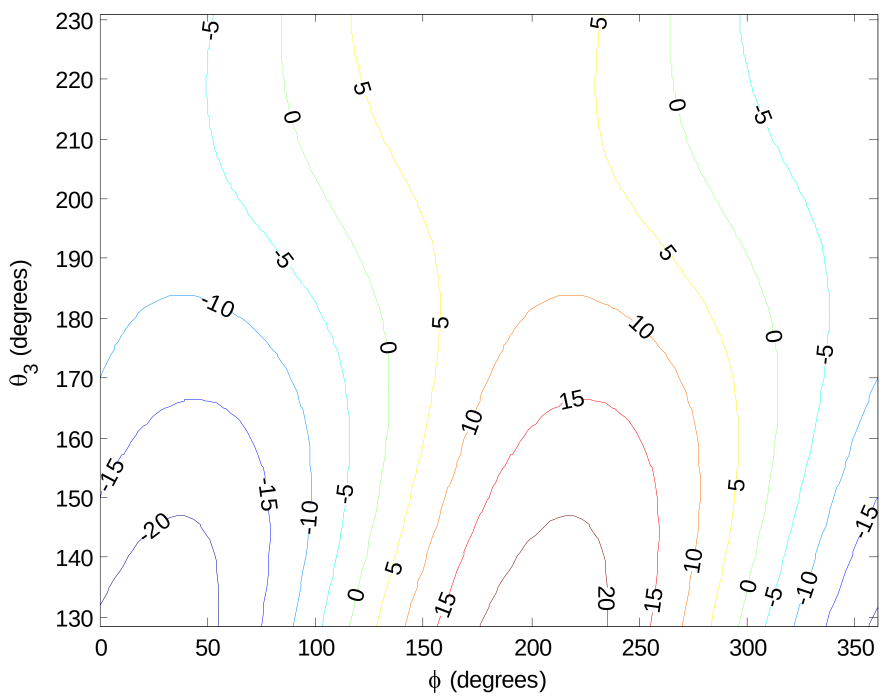

Figure A.8: Instantaneous stability of crossed four-bar mechanism for a=0.7

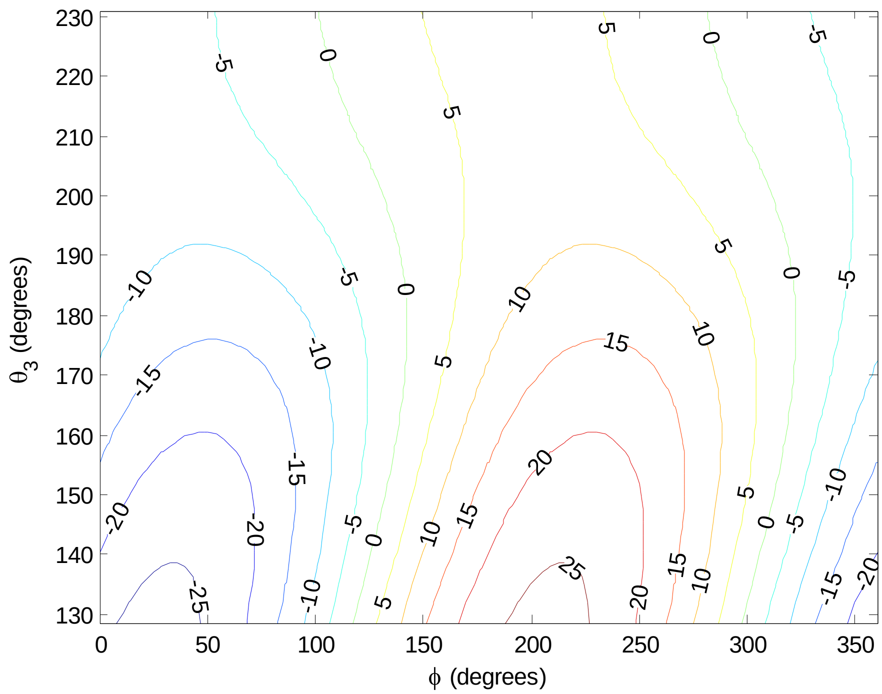

Figure A.9: Instantaneous stability of crossed four-bar mechanism for a=0.8

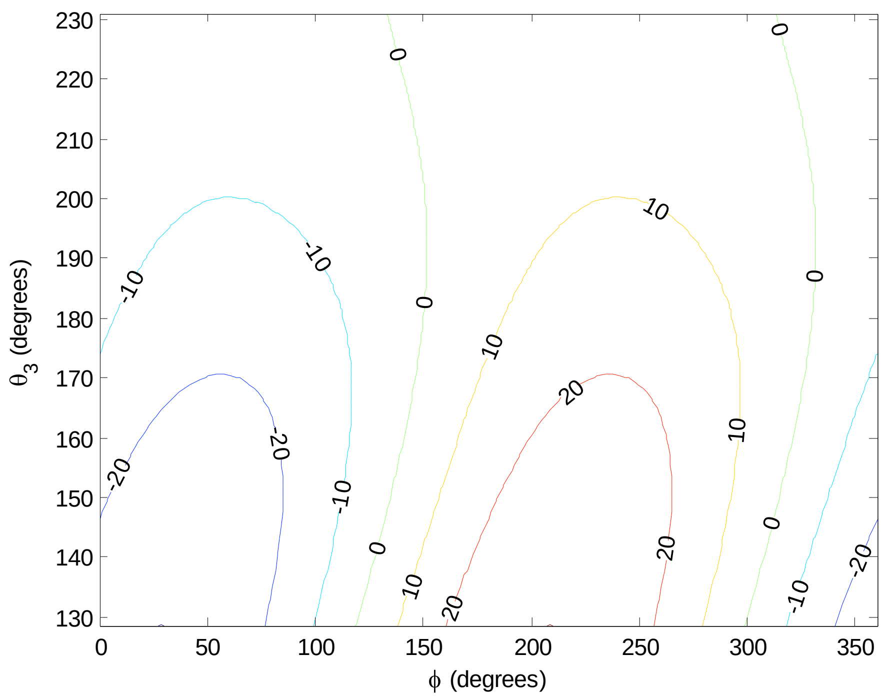

Figure A.10: Instantaneous stability of crossed four-bar mechanism for a=0.9

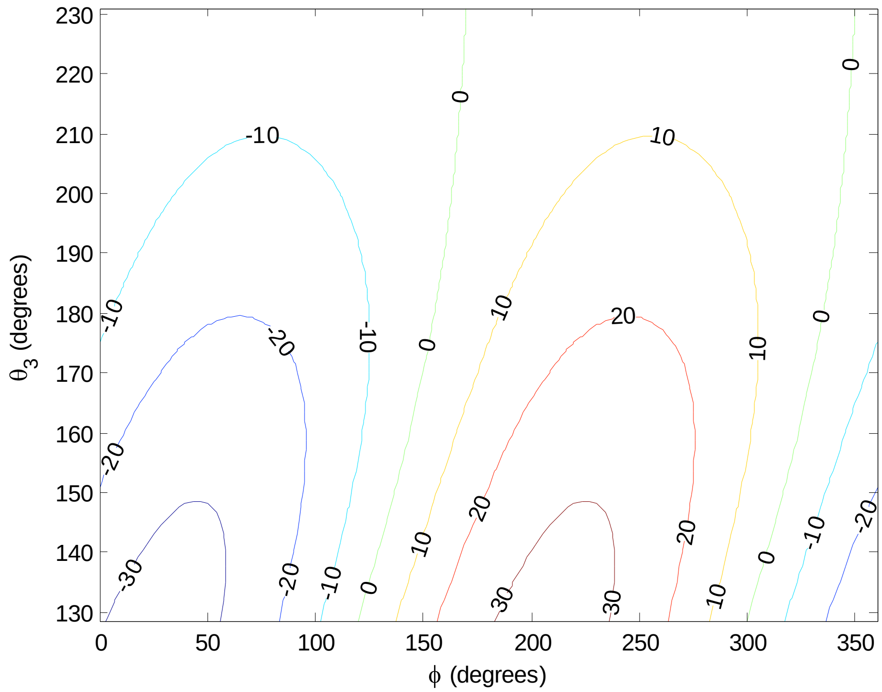

Figure A.11: Instantaneous stability of crossed four-bar mechanism for a=1.0

Appendix B: SHAP Test

Protocol by Colin Light [28].

B.1 Setting up the assessment

The subject should be seated at a table. With relaxed shoulders and arms resting on the table, the subject's elbows should be at a 90^0 angle.

Place the test platform (red/blue sided) directly in front of the subject (blue side facing upwards), approximately 3 inches from the front edge of the table. Fit the timer unit into the pace provided in the front of the platform. For each of the following abstract tasks, the board should be moved from left to right so that each task is directly in front of the subject, thereby ensuring no bias towards one hand. The case and all ADL objects may be removed from the table.

B.2 Procedural notes

Each task should be demonstrated to the subject using slow, clear movements, ensuring that the subject is aware of the appropriate grip. The subject should be given the opportunity to ask questions prior to the commencement of each task.

It is important to note that the demonstration should be carried out using the corresponding hand under assessment, to avoid any confusion for the subject.

Prosthesis users should be encouraged to practice each task, prior to timing the event, in order to determine the most appropriate technique (as many users often carry out tasks with the natural hand alone). Due to the difficulties associated with myoelectric prostheses, if it is apparent that the device has failed to respond to user demand, than a note should be made, and a retest allowed. If the prosthesis is similarly unresponsive, the second task time should be recorded and a note made of the difficulties encountered.

Only one chance to carry out the timed task should be given, unless a serious handling error causes an unrealistic result. The time to complete the task (and the appropriate grip if readily identifiable) should be recorded, as well as any relevant notes.

When establishing any form of normative data it is imperative that the task is carried out fully. Due to the need to complete in the minimum time, there is frequently a temptation to 'rush' the task without actually fulfilling the exact requirements. Under these circumstances the task should be repeated.

B.3 Abstract objects

The lightweight objects are to be used first. If a subject cannot complete the task, this should be recorded as C/C (cannot complete).

"A series of abstract objects will be placed on the board. The task involves moving the object from the rear slot to the front slot. Only the hand under assessment should be used for any of these tasks, including the starting and stopping of the timer."

1. Spherical: place the 'spherical object' in the appropriate slot. Place the 'tip object' in the slot between the rear and front 'spherical object slots' to create a small barrier. Move the board so that these slots are directly in front of the subject (maintaining the distance from the slot to the table). Using a spherical grip, move the ball over the barrier to the front slot.

Appendix B: (Continued)

"*Start the timer, pick up and move the object as demonstrated with as few mistakes as possible, and as quickly as possible, to the front slot. Complete the task by depressing the blue button again.*"

2. Tripod: place the 'tripod object' in the appropriate rear slot. Using a tripod grip, move the object to the front slot.

   "Start the timer, move the object as demonstrated and as quickly as possible to the front slot, and then stop the timer."

3. Power: place the 'power object' in the appropriate rear slot. Move the board so that these slots are directly in front of the subject (maintaining the distance from the front of the table). Using the power grip, pick up the object by the cylinder (between the two markers), and move to the front slot.

   "*Start the timer, pick up the object between the two markers as demonstrated, and move it as quickly as possible, to the front slot, and then stop the timer.*"

4. Lateral: place the 'lateral object' in the appropriate slot with the handle facing towards the subject. Move the board so that these slots are directly in front of the subject (maintaining the distance from the front of the table). Using a lateral grip, pick up the object by the handle, and move to the front slot.

   "Start the timer, move the object as demonstrated and as quickly as possible to the front slot, and then stop the timer."

5. Tip: place the 'tip object' in the appropriate slot. Using a tip (either 2 or 3 point) grip, move the object to the front slot.

Appendix B: (Continued)

"Start the timer, move the object as demonstrated and as quickly as possible to the front slot, and then stop the timer."

6. Extension; place the 'extension object' in the appropriate rear slot. Using an extension grip (with the thumb in front of the object, and fingers extended flat on the rear side), move the object to the front slot.

"Start the timer, move the object as demonstrated and as quickly as possible to the front slot, and then stop the timer."

The procedure should now be repeated, in the same order using the metal objects. If a subject has failed to complete tasks lightweight objects, then the appropriate heavier object tasks may be ignored (to avoid undue strain on the subject). In this instance, a 'cannot complete (C/C)' should be recorded on the form.

Once completed, place the form board objects in the foam. Turn the test platform over (the red side facing upwards), and position as before, with the timer on the place provided. The platform should remain centred in front of the subject for all ADL tasks.

B.4 Activities of daily living

Each task should be demonstrated to the subject using slow, clear movements, ensuring that the subject is aware of the appropriate grip.

During instructions to the assessor, references to 'handed' infers the hand under assessment (not necessary the subject's dominant hand).

"The second stage of this assessment consists of 14 everyday activities, which should be timed in the same manner by depressing the blue button to start and stop the

timer. Again tasks should be completed as quickly as possible, with as few mistakes as possible, using only the appropriate hand unless otherwise instructed."

1. Pick up coins: arrange the two 2p and two 1p coins in the designated areas on the red platform. Place the jar in the designated spot for this test with the lid removed. Pick up each coin in turn (by sliding to the edge of the platform), using a tip or tripod grip, and drop into the jar. Move from right to left. Reset the task.

   "Start the timer, lift each coin in turn as quickly as possible, drop in the jar, as demonstrated, and then stop the timer."

2. Button board: Place the button board to the right of the timer unit if assessing the right hand, and to the left if assessing the left hand. The buttons should be farthest from the timer units. Undo each button in turn, using only the assessed hand (as a test of dexterity) in a tripod grip. The other hand may be used to steady the board, but may not assist in the task. The board should remain on the platform. Reset the task.

   "Start the timer, and using only the appropriate hand, undo all four buttons in any order as demonstrated and as quickly as possible. You may steady the board with your other hand so that it remains on the platform throughout the task. Then stop the timer using only the appropriate hand. You may now practice this task."

3. Cutting: place the knife to the side of the timer unit (approximately arranged for the assessed hand). Place the plasticine "food item" in the designated area on the red platform. Pick up the knife and using the other hand to steady the object, cut it

clearly into two sections. Then replace the knife on the platform, remould the plasticine, and reset the task.

"Start the timer, use the knife provided to cut the plasticine object clearly into two sections, as demonstrated and as quickly as possible. You may use the other hand to steady the object. Return the knife to the platform, and then stop the timer."

4. Simulated page turning: place the 4 inch by 6 inch card in the designated area on the opposing side of the platform to the hand under assessment. Using an extension or tripod grip, pick up the card, turn over and place in the opposite designated area (as if turning the page of a book). Reset the task.

"Start the timer, lift, turn over (as if turning the page of a book), and replace the card on the platform, as demonstrated and as quickly as possible. Then stop the timer."

5. Jar lid: the lid should be placed on the empty jar, and tightened only with sufficient force as would be expected for everyday use/shelf storage. The jar should be placed in the designated area on the red platform. Both hands should be used for this task. Pick up the jar with the non-assessed hand, undo the lid, (using a flexion grip with the lid firmly in the palm to form a combined power/precision grip) using the assessed hand, and return both the jar and the lid to the platform. Reset the task.

"Start the timer, pick up the jar, and undo the lid with the hand under assessment as demonstrated and as quickly as possible. Return the jar and the lid to the platform and stop the timer."

Appendix B: (Continued)

To avoid repetitive filling/emptying of objects with water during the following four tasks, it is advisable to fill a separate container with approximately one pint of water. It may also be advisable to have a towel nearby.

6. Pouring from jug: fill the jug with 100 ml of water (100 ml is marked on the jug). Place the jug on the designated area on the red test platform, with the handle pointing to the right for right handed subjects, and to the left for left handed subjects. Place the jar (without lid) on the designated left area for right handed people, and on the designated right area for the left handed people. Lift the jug by the handle (in a lateral grip), and pour the water into the jar. Reset the task.

"Start the timer, and whilst ensuring as little spillage as possible, pour the water from the jug to the jar, as demonstrated and as quickly as possible. Then stop the timer. You should avoid trying to empty the jug to every last drop, and merely ensure the vast majority of the water has been transferred."

7. Pouring from carton: fill the carton with 200 ml of water. Place in the designated area on the red platform with the spout pointing towards the jar (according to the handedness criteria described for the previous test). Pick up the carton using a flexion grip (similar to a 'flat' spherical grip), and pour the water into the jar. Reset the task.

"Start the timer, and whilst ensuring as little spillage as possible, pour the water from the carton to the jar, as demonstrated and as quickly as possible. Then stop the timer. Again you should avoid trying to empty the jug to every last drop, and merely ensure the vast majority of the water has been transferred."

Appendix B: (Continued)

8. Large heavy object: fill the jar with water (to the full mark), and tighten the lid. Place in the designated area on the left side of the red platform (for right handed), or on the right side (for left handed people). Place the empty carton lengthways along the middle of the platform (without obscuring the timer) to create a barrier. Lift the jar over the carton, using a power grip, and place in the opposing marked area.

   "Start the timer, move the jar over the carton to the opposing marked area, as demonstrated and as quickly as possible. Then stop the timer."

   The water may now be disposed of and any will form no further part of the assessment procedures.

9. Large light object: place the empty tin in the appropriate area on the left hand side of the red platform (if right handed), or on the right hand side (if left handed). Place the carton to create a barrier as before. Lift the tin over the carton, using a power grip, and place on the opposing marked area.

   "Start the timer, move the tin over the carton to the opposing marked area, as demonstrated and as quickly as possible. Then stop the timer."

Place the test unit (with foam inside) on the table, directly in front of the subject, 3 inches from the front. Place the platform on the foam base and the timer unit on the appropriate slot. The final 5 tasks will involve the use of the unit.

10. Lift tray: place the platform (red side upwards), on the table to the left of the test unit (for right handers), or to the right (for left handers), with the board slightly overhanging the front of the table by approximately one inch, with the long edge facing forwards. The timer should remain in the unit. Both hands should be used to pick up the platform, using a lateral (or extension grip). Assuming a right hander: lift the 'tray' over the test unit base (whilst remaining seated) and place on the table to the right of the unit. Return the platform to the left hand side of the unit.

    "Start the timer, move the tray from left to right hand side of the test unit, as demonstrated, and as quickly as possible. Then stop the timer."

11. Rotate key: return the platform to the test unit base (red side upwards). Place the key on the lock so it appears vertical. Turn the key to the white mark using a lateral grip.

"Start the timer, rotate the key as demonstrated and as quickly as possible, at least one quarter turn clockwise, to the white mark, and release (at which time the key will spring back), and then stop the timer."

12. Open/close zip: ensure the zip is closed and lies flat against the back board. Open and close the zip using a lateral, or two point tip grip.

    "Start the time, open and then close the zipper in as short as time as possible, as demonstrated, and then stop the timer."

13. Rotate screw: place the screwdriver in the designated area on the red platform (on the right hand side for a right handed subject, or on the left for a left handed

subject). The screw is mounted on a clip, which should be attached to the front of the case. Use the area directly in front of the screwdriver (between the handle and clasp on the case). Ensure the arrow is vertical. Use two hands to guide the screwdriver to the screw, and rotate it 90 clockwise to the mark using one hand only (in a combined power/precision grip, also known as a diagonal volar grip). Reset the task.

"Start the timer, use the screwdriver to rotate the screw a quarter turn clockwise to, or beyond, the white mark, as demonstrated and as quickly as possible. Once completed, the screwdriver should be replaced on the platform and the timer stopped. Two hands may be used to guide the screwdriver to the screw, but only the appropriate hand should be used in turning the screwdriver."

14. Door handle: rotate the door handle (using a hook or power grip) until it is fully open, and then release.

    "Start the timer, rotate the door handle until it is fully open, and then release, as demonstrated and as quickly as possible. Then stop the timer."

Table C.1: Lightweight abstract objects time for subject #1

	Anatomical hand (sec)				Hook (sec)				Hook with fingertips (sec)			
Task	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
Spherical	1.28	0.90	0.89	1.02	3.55	3.46	3.39	3.47	2.93	2.83	2.88	2.88
Tripod	1.19	1.13	1.37	1.23	3.38	3.77	3.84	3.66	2.67	2.93	3.58	3.06
Power	1.15	1.14	1.28	1.19	3.61	2.49	2.40	2.83	2.69	2.94	2.53	2.72
Lateral	1.35	1.39	1.41	1.38	3.04	3.07	2.86	2.99	3.22	3.03	2.60	2.95
Tip	1.39	1.32	1.41	1.37	3.70	3.23	3.76	3.56	2.70	3.23	2.93	2.95
Extension	1.45	1.71	1.63	1.60	3.05	3.53	2.73	3.10	2.99	3.83	3.94	3.59

Table C.2: Heavyweight abstract objects time for subject #1

	Anatomical hand (sec)				Hook (sec)				Hook with fingertips (sec)			
Task	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
Spherical	0.97	1.05	0.93	0.98	4.49	4.82	5.31	4.87	4.11	2.83	2.68	3.21
Tripod	1.27	1.14	1.25	1.22	3.55	3.20	2.97	3.24	2.76	2.86	2.94	2.85
Power	1.13	0.99	0.95	1.02	3.59	5.34	4.28	4.40	2.74	4.30	2.77	3.27
Lateral	1.30	1.34	1.23	1.29	3.72	3.78	2.63	3.38	3.04	2.89	2.73	2.89
Tip	1.10	1.17	1.39	1.22	3.51	5.46	4.36	4.44	3.43	1.87	3.05	2.78
Extension	2.16	1.99	1.83	1.99	3.67	4.60	4.97	4.41	3.18	3.28	3.75	3.40

Table C.3: Activities of daily living time data for subject #1

	Anatomical hand (sec)				Hook (sec)				Hook with fingertips (sec)			
Task	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
Coins	4.01	3.44	3.73	3.73	17.95	13.09	12.37	14.47	29.02	15.82	15.49	20.11
Undo buttons	7.11	4.42	6.58	6.04	15.54	19.18	17.72	17.48	0.00	0.00	0.00	0.00
Food cutting	3.05	3.17	2.41	2.88	0.00	0.00	0.00	0.00	24.47	0.00	0.00	0.00
Page turning	1.70	1.54	1.51	1.58	5.08	4.90	5.24	5.07	5.93	4.90	5.33	5.39
Jar lid	1.65	1.57	1.77	1.66	32.40	11.48	21.18	21.69	7.23	4.87	6.93	6.34
Jug pour	3.69	3.57	3.72	3.66	12.13	9.68	11.84	11.22	15.09	8.55	8.34	10.66
Carton pour	7.98	7.33	7.25	7.52	14.69	13.29	13.80	13.93	14.98	14.70	13.55	14.41
Full jar	1.53	1.45	1.46	1.48	5.32	4.94	5.46	5.24	4.39	3.37	4.02	3.93
Empty tin	1.55	1.41	1.55	1.50	4.17	4.57	3.93	4.22	3.17	3.49	3.11	3.26
Tray	2.93	2.77	2.74	2.81	9.57	9.19	9.82	9.53	9.62	9.60	7.95	9.06
Turn a key	1.32	1.17	1.25	1.25	3.43	3.47	3.44	3.45	3.57	3.59	3.55	3.57
Zipper	2.26	2.09	2.05	2.13	7.07	5.45	4.69	5.74	11.99	6.72	6.46	8.39
Screw	3.27	2.90	3.19	3.12	10.23	10.63	8.12	9.66	8.87	9.44	8.03	8.78
Door handle	1.47	1.40	1.35	1.41	2.78	3.22	3.12	3.04	2.97	2.97	2.72	2.89

Table C.4: Lightweight abstract objects time for subject #2

	Anatomical hand (sec)				Hook (sec)				Hook with fingertips (sec)			
Task	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
Spherical	2.33	2.59	1.75	2.22	4.04	4.57	4.21	4.27	4.28	4.13	4.65	4.35
Tripod	2.38	2.02	2.19	2.20	5.07	4.43	4.80	4.77	3.82	4.22	5.22	4.42
Power	2.01	1.92	2.00	1.98	4.10	4.31	3.73	4.05	3.68	3.25	3.49	3.47
Lateral	2.17	2.14	1.83	2.05	4.90	4.86	3.99	4.58	5.39	4.91	6.13	5.48
Tip	1.96	2.00	1.74	1.90	5.57	5.23	4.36	5.05	4.02	4.29	4.84	4.38
Extension	2.20	2.42	2.22	2.28	5.05	5.44	5.04	5.18	4.71	4.61	5.03	4.78

Table C.5: Heavyweight abstract objects time for subject #2

	Anatomical hand (sec)				Hook (sec)				Hook with fingertips (sec)			
Task	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
Spherical	2.26	2.40	2.49	2.38	4.35	4.20	5.15	4.57	4.72	4.11	4.23	4.35
Tripod	1.62	1.83	1.93	1.79	3.21	3.45	4.18	3.61	3.54	3.17	3.01	3.24
Power	1.89	2.23	1.99	2.04	5.23	3.89	4.15	4.42	3.89	2.93	3.97	3.60
Lateral	2.13	1.89	2.23	2.08	4.36	4.39	4.28	4.34	3.97	3.84	3.08	3.63
Tip	1.80	1.82	2.24	1.95	3.44	3.27	4.03	3.58	3.07	3.10	3.02	3.06
Extension	2.40	2.04	2.09	2.18	5.39	5.28	5.69	5.45	5.26	5.34	4.85	5.15

Table C.6: Activities of daily living time for subject #2

	Anatomical hand (sec)				Hook (sec)				Hook with fingertips (sec)			
Task	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
Coins	6.37	5.42	5.37	5.72	19.42	19.29	15.30	18.00	29.96	22.59	22.14	24.90
Undo buttons	8.77	6.53	5.87	7.06	25.69	17.09	28.30	23.69	24.48	32.73	28.97	28.73
Food cutting	5.07	5.42	5.33	5.27	32.11	37.01	19.50	29.54	0.00	0.00	0.00	0.00
Page turning	2.68	2.65	2.65	2.66	9.09	6.68	4.72	6.83	5.68	6.14	5.41	5.74
Jar lid	3.19	2.70	3.14	3.01	0.00	0.00	0.00	0.00	5.95	6.20	5.03	5.73
Jug pour	5.28	5.16	5.24	5.23	16.52	11.34	11.77	13.21	13.45	10.52	9.22	11.06
Carton pour	8.59	8.25	9.12	8.65	14.87	14.93	16.21	15.34	14.37	14.28	12.67	13.77
Full jar	2.84	3.09	2.97	2.97	6.68	6.22	6.72	6.54	6.38	7.15	4.91	6.15
Empty tin	2.30	2.35	2.37	2.34	5.06	5.78	5.60	5.48	4.59	3.45	3.50	3.85
Tray	4.29	3.97	3.57	3.94	10.65	11.23	9.89	10.59	8.16	8.42	8.53	8.37
Turn a key	1.62	1.80	1.84	1.75	5.84	4.37	4.97	5.06	3.78	3.67	3.22	3.56
Zipper	4.47	4.50	3.13	4.03	10.57	13.22	11.29	11.69	0.00	0.00	0.00	0.00
Screw	4.69	4.69	4.13	4.50	12.40	10.30	11.15	11.28	11.52	7.83	9.85	9.73
Door handle	1.97	1.92	2.09	1.99	5.20	5.38	5.59	5.39	4.63	3.59	3.89	4.04

Table C.7: Lightweight abstract objects time for subject #3

	Anatomical hand (sec)				Hook (sec)				Hook with fingertips (sec)			
Task	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
Spherical	3.09	2.49	2.14	2.57	5.16	3.74	3.78	4.23	4.69	4.25	3.19	4.04
Tripod	1.71	1.59	1.79	1.70	4.63	3.89	4.62	4.38	3.82	3.85	3.83	3.83
Power	1.62	1.59	1.63	1.61	3.73	3.87	3.67	3.76	3.54	3.47	4.12	3.71
Lateral	2.27	2.17	1.80	2.08	4.62	4.18	4.99	4.60	5.23	5.07	5.24	5.18
Tip	2.19	2.16	1.98	2.11	5.04	4.26	5.57	4.96	4.57	5.17	4.52	4.75
Extension	1.90	1.97	2.21	2.03	4.97	4.99	5.81	5.26	5.37	4.24	6.07	5.23

Table C.8: Heavyweight abstract objects time for subject #3

	Anatomical hand (sec)				Hook (sec)				Hook with fingertips (sec)			
Task	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
Spherical	1.89	2.07	1.94	1.97	0.00	0.00	0.00	0.00	3.73	4.49	4.61	4.28
Tripod	1.38	1.55	1.33	1.42	4.58	3.85	3.52	3.98	3.73	3.60	3.51	3.61
Power	1.67	1.76	1.77	1.73	4.06	4.78	4.35	4.40	4.03	3.64	3.63	3.77
Lateral	1.89	1.62	1.73	1.75	5.17	3.94	3.93	4.35	5.55	4.77	4.61	4.98
Tip	1.63	1.67	1.55	1.62	7.05	5.83	5.14	6.01	5.91	5.11	4.88	5.30
Extension	2.37	1.74	2.03	2.05	6.29	6.80	4.97	6.02	6.49	4.28	4.49	5.09

Table C.9: Activities of daily living time data for subject #3

	Anatomical hand (sec)				Hook (sec)				Hook with fingertips (sec)			
Task	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
Coins	5.29	5.53	5.06	5.29	19.87	15.34	16.81	17.34	36.40	26.03	21.53	27.99
Undo buttons	6.75	6.69	4.87	6.10	25.33	19.68	12.93	19.31	0.00	0.00	0.00	0.00
Food cutting	5.72	5.29	4.09	5.03	52.52	31.47	34.80	39.60	0.00	0.00	0.00	0.00
Page turning	1.99	2.15	2.62	2.25	7.47	6.43	8.21	7.37	9.32	10.69	8.83	9.61
Jar lid	3.07	2.19	2.61	2.62	0.00	0.00	0.00	0.00	11.54	8.28	8.24	9.35
Jug pour	5.35	4.77	3.82	4.65	14.28	9.59	7.21	10.36	11.91	15.91	7.32	11.71
Carton pour	8.92	8.31	7.69	8.31	18.27	21.07	18.28	19.21	16.47	14.09	16.50	15.69
Full jar	2.12	2.29	2.31	2.24	6.93	4.70	5.53	5.72	4.76	4.53	5.88	5.06
Empty tin	1.80	1.93	1.91	1.88	3.99	3.87	3.67	3.84	4.07	4.09	3.77	3.98
Tray	3.42	3.64	3.33	3.46	11.58	8.09	8.94	9.54	9.35	9.88	11.28	10.17
Turn a key	1.96	1.61	1.65	1.74	5.21	4.14	3.97	4.44	6.16	5.77	6.73	6.22
Zipper	2.64	2.79	2.75	2.73	7.28	20.56	13.33	13.72	22.36	20.13	20.99	21.16
Screw	3.88	4.33	4.00	4.07	18.34	11.27	8.02	12.54	13.52	10.04	10.48	11.35
Door handle	1.99	1.88	2.12	2.00	3.28	3.42	3.53	3.41	4.03	3.63	3.00	3.55

Table C.10: Lightweight abstract objects time for subject #4

	Anatomical hand (sec)				Hook (sec)				Hook with fingertips (sec)			
Task	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
Spherical	2.11	1.92	1.97	2.00	4.55	4.74	4.26	4.52	4.18	4.19	4.74	4.37
Tripod	2.18	2.49	1.93	2.20	5.18	4.33	5.11	4.87	3.21	2.99	3.30	3.17
Power	2.19	2.15	1.95	2.10	4.85	4.03	4.55	4.48	3.48	3.59	3.97	3.68
Lateral	2.01	2.30	1.75	2.02	5.17	4.38	6.59	5.38	4.78	3.67	3.69	4.05
Tip	1.91	1.83	1.90	1.88	5.11	5.75	5.87	5.58	5.14	4.11	3.59	4.28
Extension	2.53	2.83	2.65	2.67	5.32	4.24	4.20	4.59	4.47	3.83	3.78	4.03

Table C.11: Heavyweight abstract objects time for subject #4

	Anatomical hand (sec)				Hook (sec)				Hook with fingertips (sec)			
Task	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
Spherical	1.96	2.02	2.14	2.04	5.11	4.31	4.01	4.48	4.84	4.14	4.02	4.33
Tripod	1.93	1.73	1.97	1.88	4.29	4.73	5.08	4.70	3.26	3.24	2.97	3.16
Power	2.19	2.04	2.01	2.08	6.34	5.33	5.07	5.58	4.49	4.76	4.14	4.46
Lateral	2.03	2.39	2.04	2.15	5.31	4.63	4.90	4.95	4.03	3.80	5.23	4.35
Tip	2.09	1.88	2.29	2.09	7.27	6.71	7.42	7.13	6.77	5.70	5.78	6.08
Extension	2.04	2.02	2.42	2.16	5.48	5.32	4.93	5.24	4.45	4.32	4.61	4.46

Table C.12: Activities of daily living time data for subject #4

	Anatomical hand (sec)				Hook (sec)				Hook with fingertips (sec)			
Task	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
Coins	5.02	5.08	4.96	5.02	23.97	15.61	15.18	18.25	17.52	17.39	15.47	16.79
Undo buttons	8.56	8.13	7.30	8.00	27.54	101.46	123.23	84.08	41.58	48.66	51.04	47.09
Food cutting	7.07	4.93	4.79	5.60	24.92	43.49	26.63	31.68	30.13	27.44	18.71	25.43
Page turning	2.63	2.34	1.83	2.27	8.03	4.59	5.61	6.08	4.99	4.44	4.98	4.80
Jar lid	3.13	2.65	2.73	2.84	16.33	7.11	8.61	10.68	6.54	7.00	5.27	6.27
Jug pour	7.07	6.20	5.65	6.31	16.64	12.30	12.67	13.87	14.37	12.70	9.89	12.32
Carton pour	9.51	9.82	8.44	9.26	15.27	16.20	15.00	15.49	17.99	17.83	18.33	18.05
Full jar	2.40	2.14	2.34	2.29	5.30	4.45	4.53	4.76	5.77	5.97	4.53	5.42
Empty tin	1.93	2.03	1.87	1.94	3.69	3.83	3.66	3.73	3.52	3.20	3.29	3.34
Tray	3.83	3.69	4.03	3.85	14.71	11.92	10.29	12.31	12.28	9.17	8.63	10.03
Turn a key	2.07	1.93	1.69	1.90	5.83	4.80	4.39	5.01	4.28	4.11	4.33	4.24
Zipper	3.25	2.71	2.92	2.96	7.66	16.73	10.77	11.72	14.40	10.14	7.99	10.84
Screw	4.61	4.17	4.06	4.28	13.99	12.44	17.07	14.50	10.72	9.20	8.38	9.43
Door handle	2.07	1.97	1.92	1.99	2.88	4.05	3.12	3.35	3.80	3.82	3.55	3.72

Table C.13: Lightweight abstract objects time for subject #5

	Anatomical hand (sec)				Hook (sec)				Hook with fingertips (sec)			
Task	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
Spherical	1.43	1.33	1.11	1.29	3.13	2.93	2.68	2.91	3.90	3.50	3.63	3.68
Tripod	1.63	1.26	1.13	1.34	3.80	3.27	2.85	3.31	4.63	3.76	3.30	3.90
Power	1.18	1.11	1.09	1.13	2.99	2.69	2.68	2.79	4.05	3.36	2.73	3.38
Lateral	1.49	1.83	1.46	1.59	3.73	3.59	3.47	3.60	3.92	3.88	3.95	3.92
Tip	1.41	1.41	1.03	1.28	3.67	3.85	4.07	3.86	3.42	3.90	3.65	3.66
Extension	1.64	1.90	1.94	1.83	5.07	3.99	4.23	4.43	3.50	3.16	3.05	3.24

Table C.14: Heavyweight abstract objects time for subject #5

	Anatomical hand (sec)				Hook (sec)				Hook with fingertips (sec)			
Task	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
Spherical	1.27	1.29	1.28	1.28	5.93	3.90	3.65	4.49	5.21	4.69	3.43	4.44
Tripod	1.28	1.09	1.07	1.15	3.07	2.73	2.61	2.80	3.29	3.33	3.19	3.27
Power	1.50	1.55	1.63	1.56	4.59	4.63	3.87	4.36	3.33	3.10	2.97	3.13
Lateral	1.83	1.53	1.43	1.60	4.02	4.07	4.02	4.04	3.72	3.79	4.11	3.87
Tip	1.20	1.11	1.29	1.20	3.32	3.69	3.44	3.48	4.18	3.17	3.59	3.65
Extension	1.64	1.57	1.77	1.66	6.23	5.93	5.54	5.90	4.81	3.69	3.50	4.00

Table C.15: Activities of daily living time data for subject #5

	Anatomical hand (sec)				Hook (sec)				Hook with fingertips (sec)			
Task	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
Coins	4.69	4.29	3.66	4.21	16.68	20.87	15.23	17.59	12.17	15.27	11.03	12.82
Undo buttons	5.96	4.77	4.02	4.92	22.57	15.99	31.10	23.22	40.37	31.79	28.37	33.51
Food cutting	3.76	3.69	3.53	3.66	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Page turning	1.74	1.69	1.46	1.63	8.42	4.76	4.48	5.89	3.97	3.78	3.17	3.64
Jar lid	2.18	2.11	2.05	2.11	22.19	8.73	11.23	14.05	4.69	4.56	3.01	4.09
Jug pour	4.27	4.33	3.79	4.13	17.23	11.10	13.53	13.95	6.83	6.97	7.42	7.07
Carton pour	8.93	8.93	3.79	7.22	12.98	11.26	11.42	11.89	12.51	15.09	12.14	13.25
Full jar	2.14	1.73	1.88	1.92	4.33	4.97	3.97	4.42	4.13	3.77	3.36	3.75
Empty tin	1.56	1.57	1.51	1.55	3.56	3.32	3.00	3.29	3.61	3.67	3.15	3.48
Tray	3.75	2.59	2.67	3.00	8.35	11.36	9.61	9.77	8.33	8.09	7.09	7.84
Turn a key	1.47	1.39	1.58	1.48	3.84	3.59	3.10	3.51	3.23	2.79	2.48	2.83
Zipper	2.17	1.67	1.62	1.82	13.51	6.83	4.23	8.19	7.39	8.35	4.78	6.84
Screw	3.78	4.57	3.30	3.88	6.45	4.92	8.30	6.56	7.83	5.99	6.97	6.93
Door handle	1.19	1.12	1.23	1.18	3.72	3.39	3.45	3.52	3.17	2.83	2.54	2.85

Table C.16: Lightweight abstract objects time for subject #6

	Anatomical hand (sec)				Hook (sec)				Hook with fingertips (sec)			
Task	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
Spherical	0.99	0.83	1.03	0.95	4.32	4.36	3.19	3.96	3.02	2.53	2.63	2.73
Tripod	0.87	0.87	0.92	0.89	3.61	2.64	2.52	2.92	3.37	2.90	3.37	3.21
Power	1.20	1.15	1.12	1.16	3.32	3.07	2.83	3.07	2.80	2.51	2.51	2.61
Lateral	1.20	1.24	1.12	1.19	3.69	3.21	2.67	3.19	3.99	4.27	4.21	4.16
Tip	1.76	1.34	1.26	1.45	4.25	3.64	3.24	3.71	3.77	2.93	2.69	3.13
Extension	1.83	2.00	1.63	1.82	4.05	2.83	3.39	3.42	3.20	3.18	2.64	3.01

Table C.17: Heavyweight abstract objects time for subject #6

	Anatomical hand (sec)				Hook (sec)				Hook with fingertips (sec)			
Task	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
Spherical	1.09	1.14	1.07	1.10	4.78	5.73	5.55	5.35	2.87	3.08	2.89	2.95
Tripod	0.95	0.79	0.98	0.91	3.43	3.21	2.65	3.10	3.20	3.40	3.33	3.31
Power	1.12	1.13	1.11	1.12	11.88	5.23	7.61	8.24	3.08	3.10	2.77	2.98
Lateral	1.42	1.20	1.26	1.29	4.40	4.51	3.77	4.23	4.09	4.35	3.69	4.04
Tip	1.53	1.27	1.26	1.35	3.99	4.14	3.77	3.97	3.43	3.86	3.35	3.55
Extension	1.67	1.67	1.74	1.69	3.92	3.60	3.71	3.74	2.76	3.20	2.90	2.95

Table C.18: Activities of daily living time data for subject #6

	Anatomical hand (sec)				Hook (sec)				Hook with fingertips (sec)			
Task	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
Coins	3.94	3.89	4.03	3.95	18.33	20.14	24.92	21.13	17.69	18.40	17.79	17.96
Undo buttons	6.97	6.25	6.57	6.60	32.23	22.12	22.56	25.64	44.99	21.80	22.37	29.72
Food cutting	3.75	2.75	3.60	3.37	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Page turning	1.23	1.30	1.69	1.41	4.77	3.64	4.57	4.33	5.87	5.24	5.53	5.55
Jar lid	1.74	1.81	1.67	1.74	5.76	8.21	8.37	7.45	5.89	4.97	4.99	5.28
Jug pour	3.80	5.27	4.02	4.36	17.01	12.99	13.00	14.33	9.34	7.85	9.15	8.78
Carton pour	7.95	8.68	7.94	8.19	41.47	16.93	17.37	25.26	17.16	16.59	16.53	16.76
Full jar	1.93	1.87	1.69	1.83	6.38	4.97	4.96	5.44	3.35	4.14	3.93	3.81
Empty tin	1.54	1.42	1.22	1.39	5.28	4.97	5.29	5.18	2.77	2.63	2.84	2.75
Tray	2.87	2.91	2.97	2.92	10.21	10.65	8.88	9.91	11.89	9.17	9.72	10.26
Turn a key	1.07	0.77	0.89	0.91	4.17	4.01	3.38	3.85	4.35	4.59	3.86	4.27
Zipper	1.68	1.97	1.83	1.83	9.58	7.70	8.21	8.50	0.00	0.00	0.00	0.00
Screw	3.45	3.00	2.84	3.10	6.29	10.18	7.13	7.87	7.68	6.88	7.29	7.28
Door handle	1.15	1.01	0.89	1.02	1.59	1.37	1.24	1.40	2.49	2.44	2.22	2.38

Table C.19: Lightweight abstract objects time for subject #7

	Anatomical hand (sec)				Hook (sec)				Hook with fingertips (sec)			
Task	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
Spherical	1.25	1.17	1.39	1.27	6.19	4.88	4.87	5.31	5.93	4.88	4.65	5.15
Tripod	1.15	1.12	1.07	1.11	5.61	4.09	3.69	4.46	5.11	7.67	4.59	5.79
Power	1.37	1.31	1.23	1.30	4.47	4.95	5.87	5.10	4.93	6.60	7.08	6.20
Lateral	1.53	1.50	1.84	1.62	5.73	4.57	4.44	4.91	9.31	8.24	4.88	7.48
Tip	1.37	1.36	1.15	1.29	6.41	5.93	4.36	5.57	4.66	5.02	5.63	5.10
Extension	1.67	1.56	1.17	1.47	7.57	5.47	4.13	5.72	7.43	7.32	8.37	7.71

Table C.20: Heavyweight abstract objects time for subject #7

	Anatomical hand (sec)				Hook (sec)				Hook with fingertips (sec)			
Task	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
Spherical	1.37	1.19	1.30	1.29	5.42	4.47	4.54	4.81	5.57	9.83	8.53	7.98
Tripod	1.08	1.02	1.06	1.05	5.05	5.41	4.81	5.09	5.03	3.67	7.20	5.30
Power	1.30	1.20	1.33	1.28	11.82	0.00	0.00	3.94	7.06	5.69	6.12	6.29
Lateral	1.57	1.53	1.57	1.56	5.09	4.94	3.25	4.43	7.12	5.73	8.15	7.00
Tip	1.36	1.20	1.42	1.33	4.70	4.45	3.68	4.28	7.03	5.89	10.02	7.65
Extension	1.57	1.62	1.60	1.60	6.91	4.97	4.54	5.47	6.87	4.21	4.93	5.34

Table C.21: Activities of daily living time data for subject #7

Task	Anatomical hand (sec)				Hook (sec)			
	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
Coins	5.99	5.02	4.29	5.10	18.85	16.17	15.14	16.72
Undo buttons	9.06	6.86	5.08	7.00	20.61	33.53	15.22	23.12
Food cutting	6.75	3.89	6.78	5.81	26.93	21.45	18.13	22.17
Page turning	2.03	1.77	1.65	1.82	6.54	5.29	5.34	5.72
Jar lid	1.89	2.24	1.85	1.99	19.60	7.79	6.64	11.34
Jug pour	6.60	5.43	5.31	5.78	10.69	9.8	11.54	10.68
Carton pour	8.60	9.95	9.21	9.25	17.13	18.48	13.9	16.50
Full jar	1.94	1.89	1.46	1.76	4.68	4.16	3.33	4.06
Empty tin	1.18	1.21	1.24	1.21	2.88	2.34	2.79	2.67
Tray	3.09	3.68	2.97	3.25	10.87	11.36	6.65	9.63
Turn a key	1.24	1.38	1.43	1.35	3.61	2.97	2.67	3.08
Zipper	2.18	1.86	1.77	1.94	17.49	9.47	13.6	13.52
Screw	3.68	3.07	4.03	3.59	17.63	10.59	8.19	12.14
Door handle	1.32	1.32	1.19	1.28	2.09	1.67	1.59	1.78

Task	Hook with fingertips (sec)			
	Trial 1	Trial 2	Trial 3	Average
Coins	35.92	18.55	16.65	23.71
Undo buttons	0.00	0.00	0.00	0.00
Food cutting	24.53	30.92	20.86	25.44
Page turning	8.42	7.55	5.69	7.22
Jar lid	8.65	16.87	7.34	10.95
Jug pour	10.83	9.48	8.97	9.76
Carton pour	15.26	14.71	10.26	13.41
Full jar	6.03	8.57	6.8	7.13
Empty tin	6.04	3.67	3.05	4.25
Tray	16.53	10.59	8.79	11.97
Turn a key	3.97	3.49	3.00	3.49
Zipper	14.83	5.37	5.94	8.71
Screw	10.94	9.26	8.63	9.61
Door handle	2.57	3.13	2.59	2.76

Table C.22: Lightweight abstract objects time for subject #8

	Anatomical hand (sec)				Hook (sec)				Hook with fingertips (sec)			
Task	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
Spherical	1.53	1.73	1.43	1.56	3.41	3.38	3.08	3.29	3.02	3.26	2.73	3.00
Tripod	1.93	1.78	1.60	1.77	3.81	3.00	3.43	3.41	2.84	2.69	2.42	2.65
Power	1.39	1.26	1.34	1.33	2.63	2.88	2.94	2.82	2.69	2.65	2.34	2.56
Lateral	1.66	1.58	1.33	1.52	3.44	2.58	2.37	2.80	2.46	3.00	2.15	2.54
Tip	1.37	1.77	1.29	1.48	4.12	3.50	4.30	3.97	2.17	1.98	2.24	2.13
Extension	0.99	1.43	1.11	1.18	2.97	2.67	3.03	2.89	1.96	2.02	2.15	2.04

Table C.23: Heavyweight abstract objects time for subject #8

	Anatomical hand (sec)				Hook (sec)				Hook with fingertips (sec)			
Task	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
Spherical	1.73	1.66	1.60	1.66	4.16	4.23	3.57	3.99	3.75	3.51	2.95	3.40
Tripod	1.33	1.37	1.36	1.35	2.61	3.21	2.63	2.82	2.71	2.57	2.55	2.61
Power	1.33	1.43	1.20	1.32	4.22	4.30	3.69	4.07	2.76	2.50	2.51	2.59
Lateral	1.43	1.43	1.23	1.36	3.21	2.85	2.83	2.96	2.65	2.73	2.60	2.66
Tip	1.29	1.29	1.13	1.24	3.76	5.48	3.26	4.17	4.53	2.46	2.12	3.04
Extension	1.28	1.38	1.61	1.42	3.06	2.92	4.87	3.62	2.41	2.40	2.23	2.35

Table C.24: Activities of daily living time data for subject #8

	Anatomical hand (sec)				Hook (sec)				Hook with fingertips (sec)			
Task	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
Coins	5.45	6.18	4.99	5.54	16.64	20.69	12.85	16.73	19.87	14.93	23.13	19.31
Undo buttons	9.12	4.92	6.46	6.83	23.36	27.12	16.18	22.22	49.00	52.61	35.22	45.61
Food cutting	3.17	2.52	2.26	2.65	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Page turning	1.58	1.50	1.32	1.47	3.92	3.09	2.73	3.25	4.51	3.76	3.40	3.89
Jar lid	1.58	1.39	1.49	1.49	3.37	4.29	2.80	3.49	5.63	5.27	3.62	4.84
Jug pour	3.47	4.50	3.83	3.93	11.98	13.98	9.67	11.88	9.65	6.58	5.65	7.29
Carton pour	6.05	5.15	4.55	5.25	12.43	17.24	12.77	14.15	15.29	15.84	11.86	14.33
Full jar	1.67	1.51	1.42	1.53	5.83	6.38	5.56	5.92	3.46	3.95	3.29	3.57
Empty tin	1.27	1.26	1.24	1.26	2.86	2.57	2.28	2.57	2.55	2.69	2.27	2.50
Tray	3.14	2.49	2.66	2.76	10.38	10.05	7.04	9.16	8.28	8.93	6.51	7.91
Turn a key	1.10	1.03	1.01	1.05	3.02	2.97	2.62	2.87	2.30	2.72	2.46	2.49
Zipper	1.60	1.62	1.50	1.57	4.59	3.91	4.21	4.24	24.47	11.94	12.07	16.16
Screw	2.83	2.89	2.48	2.73	10.12	8.28	8.68	9.03	15.53	12.65	8.21	12.13
Door handle	0.98	0.82	0.87	0.89	1.37	1.30	1.19	1.29	1.87	1.69	1.56	1.71

Table C.25: Lightweight abstract objects time for subject #9

	Anatomical hand (sec)				Hook (sec)				Hook with fingertips (sec)			
Task	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
Spherical	1.48	1.51	1.33	1.44	6.53	5.89	7.47	6.63	5.01	4.91	5.02	4.98
Tripod	1.94	1.84	1.79	1.86	4.33	5.93	5.91	5.39	4.64	5.47	5.00	5.04
Power	1.62	1.81	1.73	1.72	5.29	4.84	5.06	5.06	4.19	5.04	4.90	4.71
Lateral	1.96	1.93	2.07	1.99	4.30	5.05	4.39	4.58	3.97	4.92	4.09	4.33
Tip	1.91	2.11	2.13	2.05	6.73	4.69	4.03	5.15	5.66	5.41	5.07	5.38
Extension	2.54	2.48	2.57	2.53	5.27	4.89	6.12	5.43	5.18	5.43	6.75	5.79

Table C.26: Heavyweight abstract objects time for subject #9

	Anatomical hand (sec)				Hook (sec)				Hook with fingertips (sec)			
Task	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
Spherical	2.19	2.40	2.25	2.28	0.00	0.00	0.00	0.00	6.02	5.79	6.28	6.03
Tripod	1.98	2.01	1.89	1.96	5.53	5.09	5.59	5.40	5.03	5.07	5.22	5.11
Power	2.26	2.47	2.38	2.37	0.00	0.00	0.00	0.00	4.98	4.69	5.01	4.89
Lateral	2.23	2.60	2.81	2.55	6.44	5.26	6.21	5.97	6.16	6.83	6.54	6.51
Tip	2.37	2.63	2.20	2.40	6.45	5.13	5.54	5.71	9.28	8.13	8.42	8.61
Extension	3.26	2.60	2.96	2.94	7.82	4.83	5.35	6.00	9.22	7.59	7.05	7.95

Table C.27: Activities of daily living time data for subject #9

	Anatomical hand (sec)				Hook (sec)				Hook with fingertips (sec)			
Task	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
Coins	6.49	5.93	6.43	6.28	25.33	24.95	18.49	22.92	19.25	18.92	24.53	20.90
Undo buttons	7.53	7.11	6.92	7.19	34.24	30.35	31.29	31.96	39.27	35.96	29.03	34.75
Food cutting	7.43	7.49	7.54	7.49	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Page turning	2.43	2.33	2.28	2.35	7.83	7.98	7.07	7.63	6.41	5.92	5.22	5.85
Jar lid	2.83	2.89	2.82	2.85	17.43	11.80	10.63	13.29	8.33	6.99	5.69	7.00
Jug pour	6.59	5.84	5.63	6.02	13.44	10.90	10.19	11.51	12.39	11.24	10.19	11.27
Carton pour	8.74	9.24	9.36	9.11	18.72	19.65	18.82	19.06	21.56	21.38	20.31	21.08
Full jar	2.74	2.82	2.95	2.84	6.27	6.31	5.98	6.19	5.88	6.32	6.24	6.15
Empty tin	2.48	2.62	2.53	2.54	4.86	4.55	4.89	4.77	5.19	5.51	4.55	5.08
Tray	5.21	4.83	4.51	4.85	10.23	9.89	12.35	10.82	18.42	12.25	16.92	15.86
Turn a key	1.79	1.97	1.65	1.80	3.14	4.09	3.35	3.53	4.50	3.85	3.87	4.07
Zipper	3.55	3.87	3.14	3.52	11.68	9.67	8.59	9.98	15.61	9.58	11.67	12.29
Screw	5.57	6.02	5.22	5.60	10.39	11.49	10.41	10.76	11.65	10.69	11.17	11.17
Door handle	2.00	2.05	1.71	1.92	3.24	3.22	2.67	3.04	3.86	4.03	3.92	3.94

Table C.28: Lightweight abstract objects time for subject #10

	Anatomical hand (sec)				Hook (sec)				Hook with fingertips (sec)			
Task	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
Spherical	1.47	1.45	1.59	1.50	7.42	6.54	6.42	6.79	6.37	5.31	4.76	5.48
Tripod	1.84	1.61	1.63	1.69	9.28	8.23	7.35	8.29	7.31	5.37	5.21	5.96
Power	2.07	1.93	2.05	2.02	9.42	7.69	8.58	8.56	5.39	5.04	5.17	5.20
Lateral	2.27	2.24	2.27	2.26	10.85	8.69	8.97	9.50	7.03	8.03	5.91	6.99
Tip	2.23	2.34	1.99	2.19	8.72	7.11	7.32	7.72	7.93	10.17	7.96	8.69
Extension	2.76	2.97	2.84	2.86	6.87	7.28	7.04	7.06	6.67	6.17	6.23	6.36

Table C.29: Heavyweight abstract objects time for subject #10

	Anatomical hand (sec)				Hook (sec)				Hook with fingertips (sec)			
Task	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
Spherical	1.87	1.85	2.05	1.92	9.70	9.12	15.00	11.27	6.37	7.38	5.47	6.41
Tripod	1.71	1.59	1.87	1.72	7.75	7.14	7.76	7.55	5.47	5.48	4.39	5.11
Power	2.01	1.95	2.05	2.00	11.23	9.86	8.49	9.86	6.83	5.18	5.21	5.74
Lateral	2.62	2.67	2.53	2.61	8.67	8.01	6.99	7.89	0.00	0.00	0.00	0.00
Tip	2.03	2.19	2.17	2.13	9.19	6.84	7.59	7.87	7.37	8.63	8.23	8.08
Extension	2.63	3.19	2.65	2.82	7.77	7.36	7.07	7.40	12.87	11.53	8.33	10.91

Table C.30: Activity of daily living time data for subject #10

	Anatomical hand (sec)				Hook (sec)				Hook with fingertips (sec)			
Task	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
Coins	7.12	6.37	6.03	6.51	30.43	29.00	25.78	28.40	33.43	28.78	29.82	30.68
Undo buttons	10.49	9.03	8.57	9.36	41.83	23.07	24.68	29.86	0.00	0.00	0.00	0.00
Food cutting	7.90	7.61	6.05	7.19	32.59	52.34	0.00	28.31	0.00	0.00	0.00	0.00
Page turning	2.62	2.67	2.44	2.58	9.29	9.50	7.41	8.73	9.36	9.85	7.93	9.05
Jar lid	3.28	3.21	3.29	3.26	0.00	0.00	0.00	0.00	8.49	7.94	7.49	7.97
Jug pour	6.99	6.29	5.72	6.33	24.67	18.49	15.66	19.61	15.57	26.27	17.18	19.67
Carton pour	10.37	9.49	9.28	9.71	28.56	31.21	25.68	28.48	24.75	28.63	22.63	25.34
Full jar	3.20	3.06	3.07	3.11	12.66	6.89	8.49	9.35	10.34	8.63	7.83	8.93
Empty tin	2.74	2.72	2.57	2.68	7.02	6.63	7.26	6.97	5.90	5.67	5.33	5.63
Tray	4.87	5.22	4.32	4.80	15.93	12.53	11.14	13.20	21.13	14.95	11.26	15.78
Turn a key	2.88	2.63	2.59	2.70	6.83	5.71	5.05	5.86	5.61	4.09	3.37	4.36
Zipper	4.66	4.26	4.89	4.60	19.21	12.53	8.71	13.48	0.00	0.00	0.00	0.00
Screw	6.35	5.53	4.97	5.62	17.86	12.29	14.23	14.79	13.05	13.12	13.86	13.34
Door handle	3.13	3.19	3.03	3.12	6.02	5.62	5.24	5.63	5.00	5.43	4.29	4.91

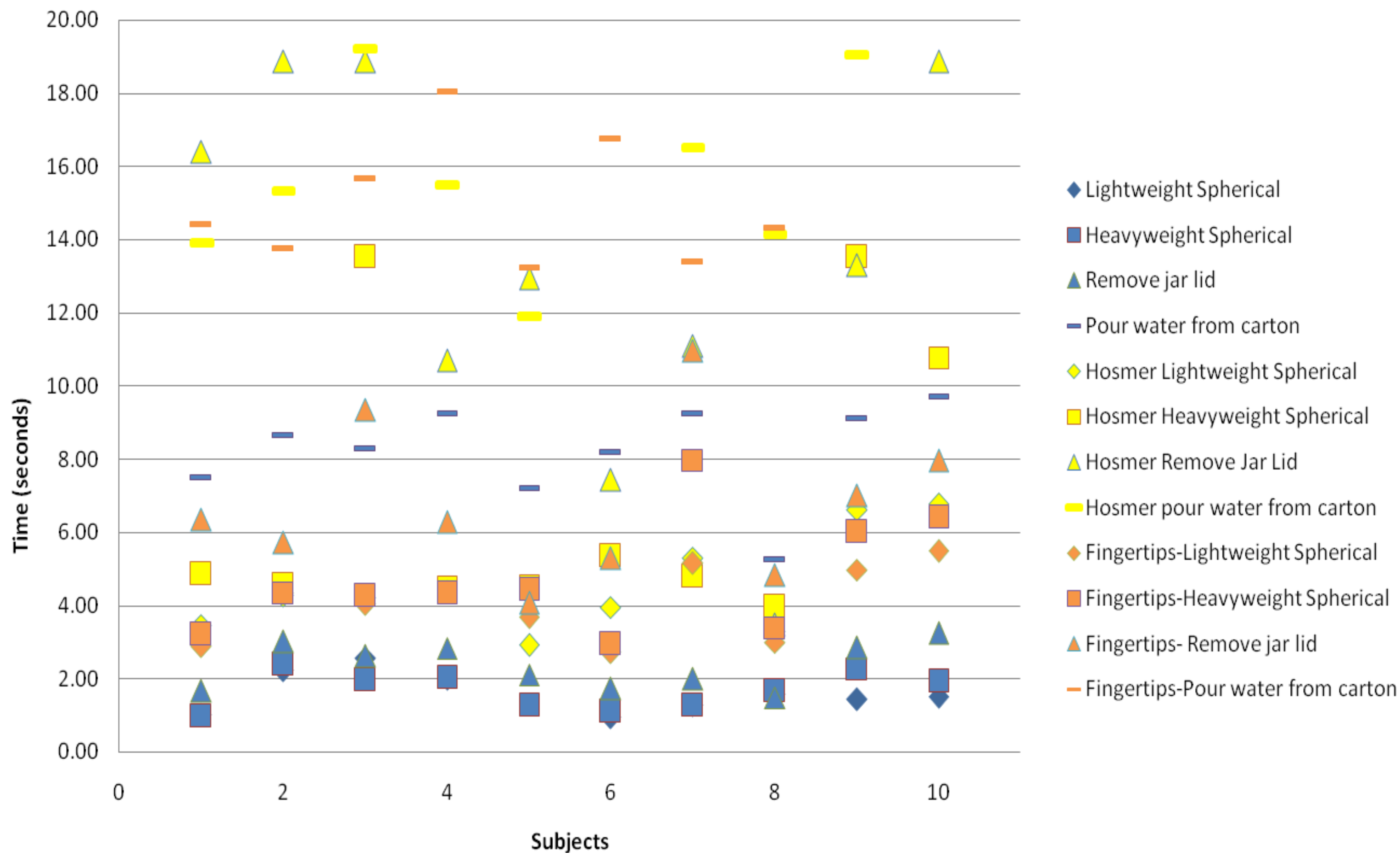

Figure D.1: Mean values of the spherical prehensile pattern for each subject

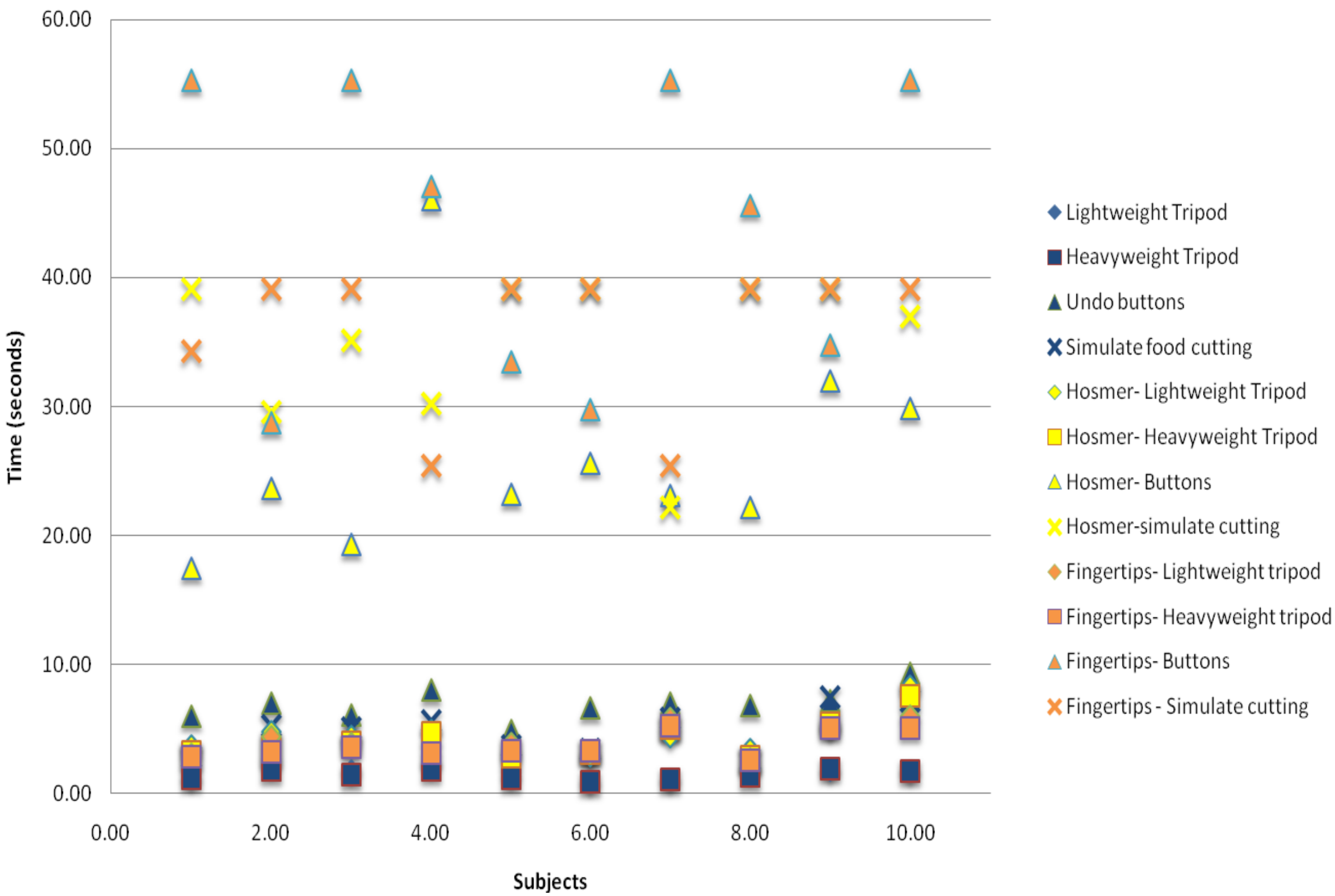

Figure D.2: Mean values of the tripod prehensile pattern for each subject

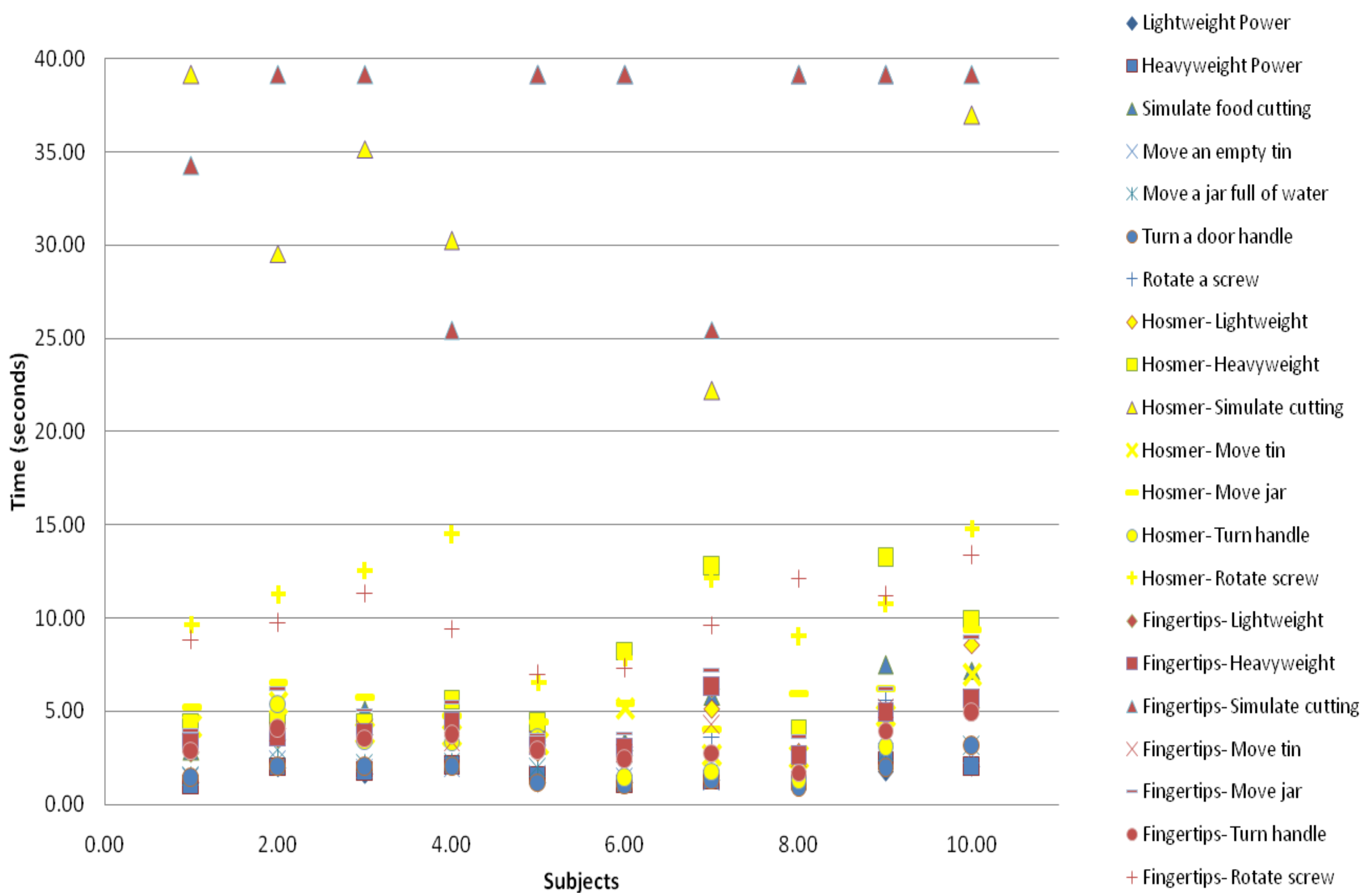

Figure D.3: Mean values of the power prehensile pattern for each subject

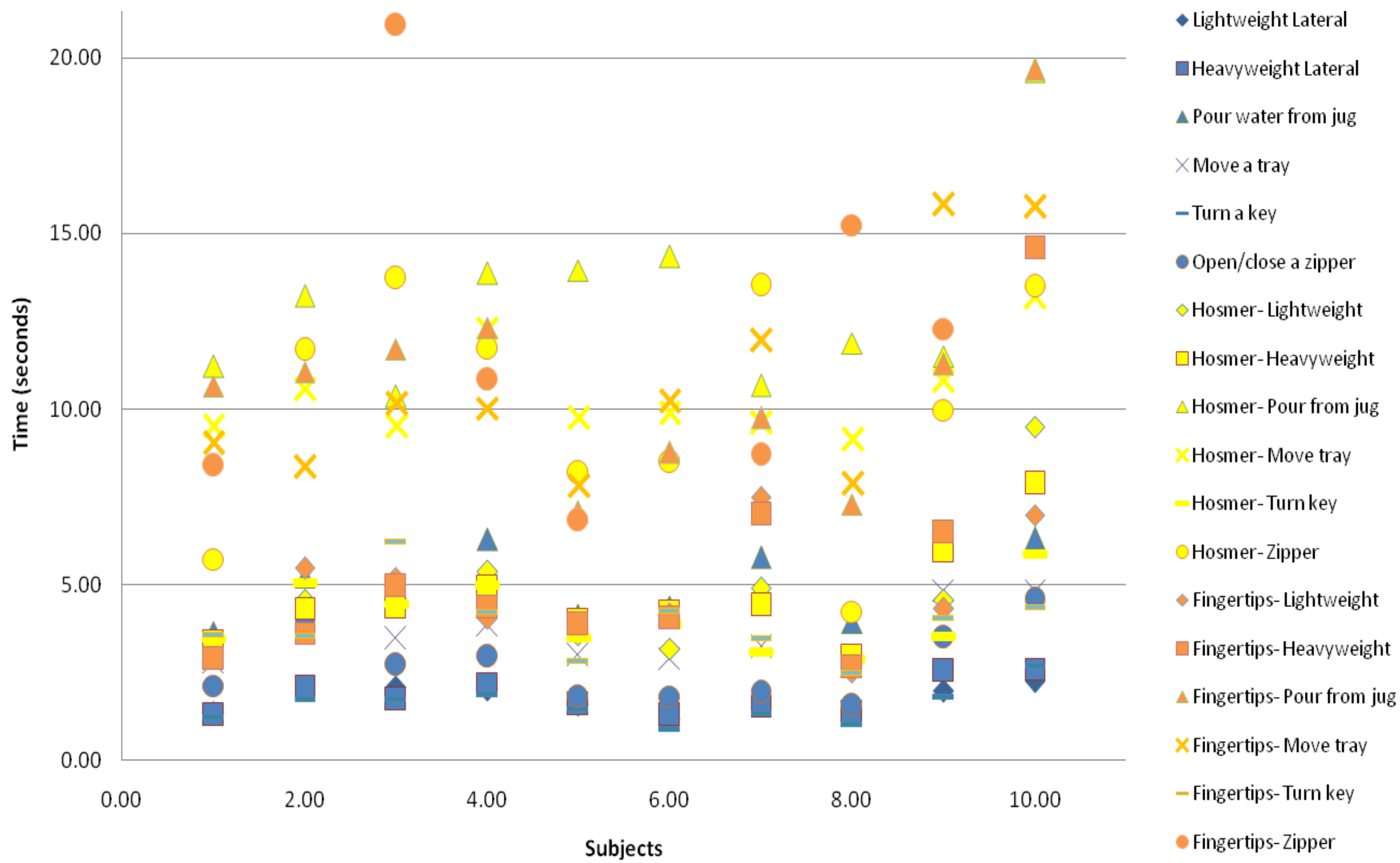

Figure D.4: Mean values of the lateral prehensile pattern for each subject

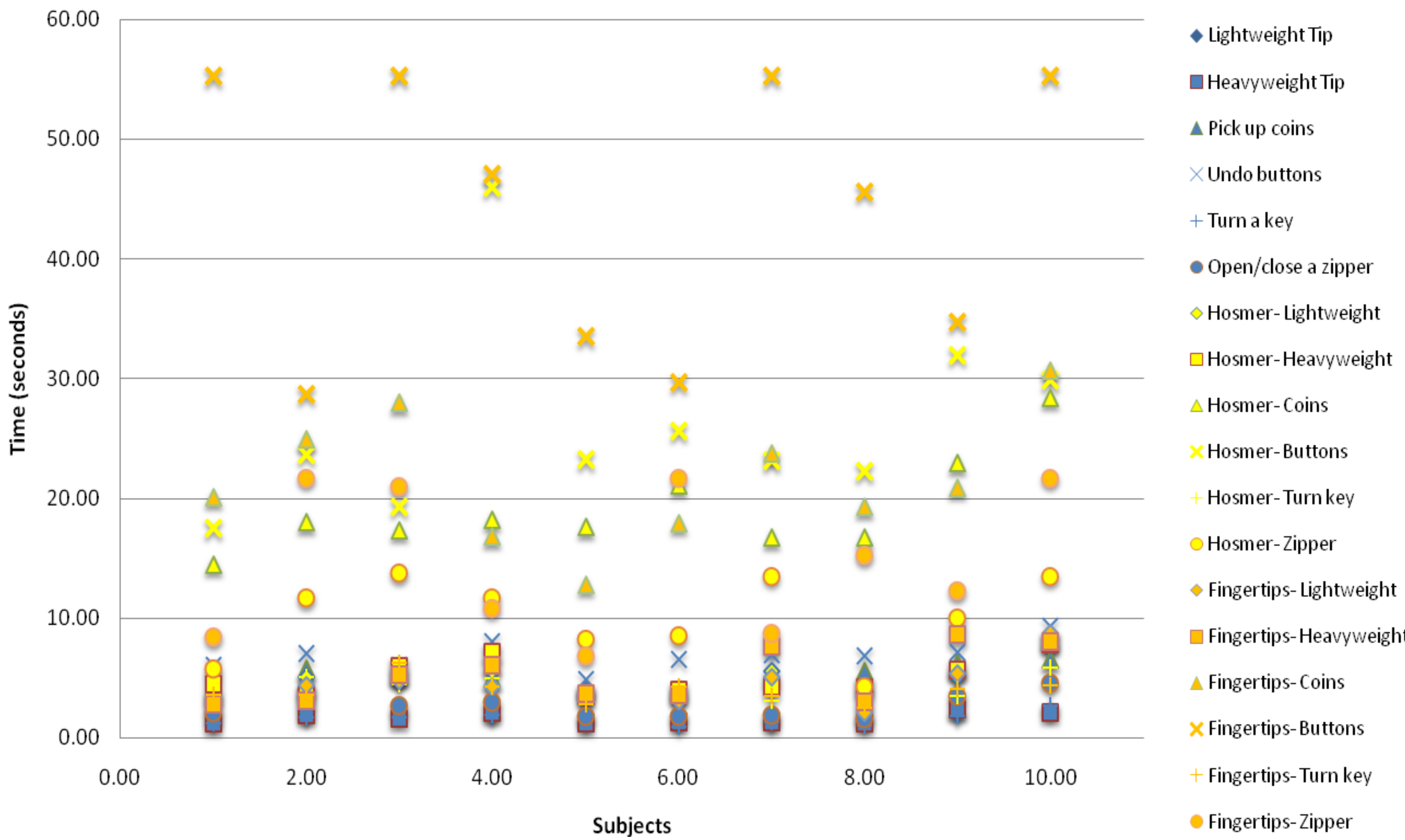

Figure D.5: Mean values of the tip prehensile pattern for each subject

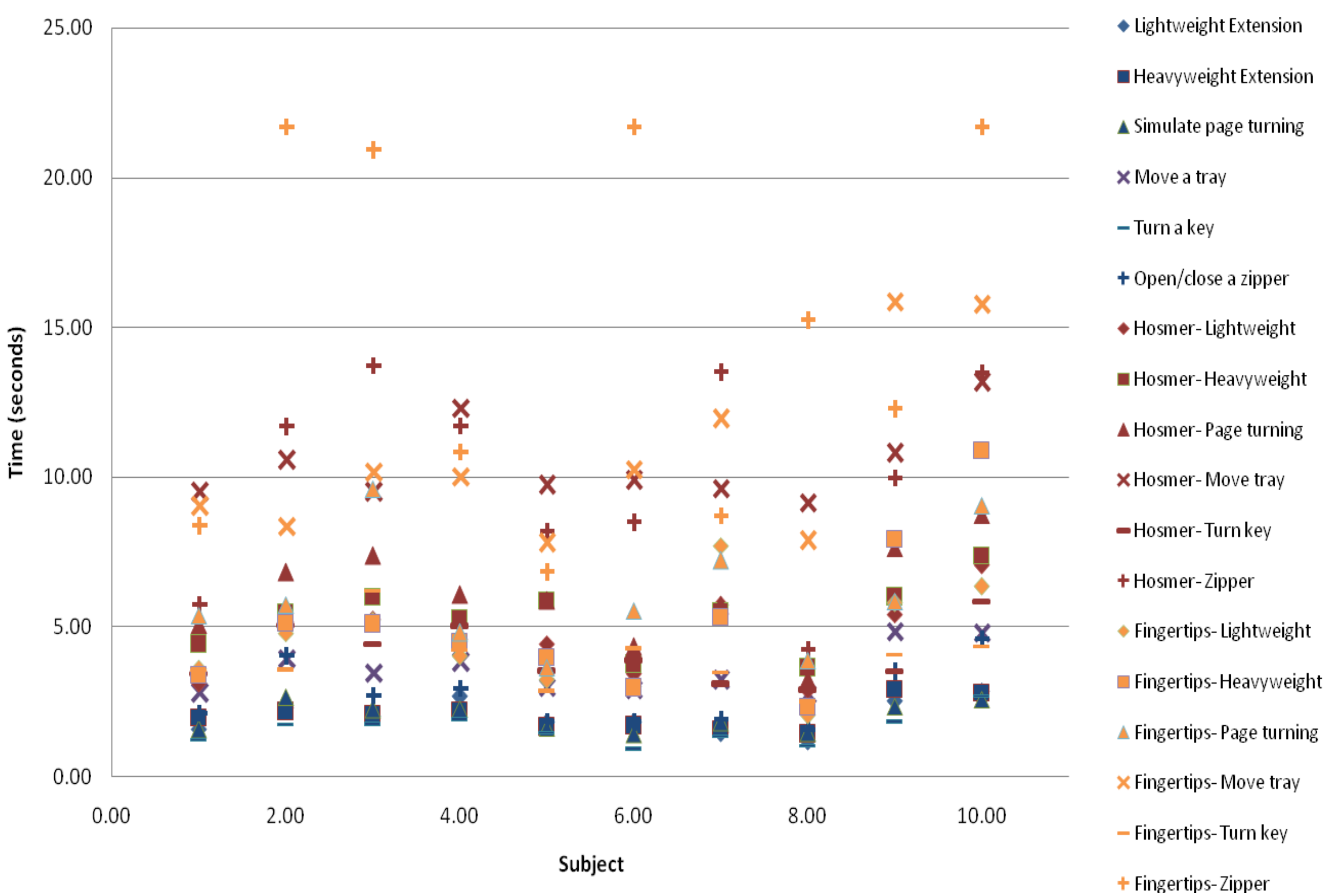

Figure D.6: Mean values of the extension prehensile pattern for each subject