A Comparison of the Force Dynamics of the Precision Grip of Humans and Robots

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Abstract

In the field of robotics, many of studies have been published addressing the issue of grasping in robotic manipulators. A number of these discuss grasp force and present algorithms aimed at achieving the 'optimal' grasp force for given tasks. This paper seeks to make a comparison between these algorithms and the human grasping function.

An apparatus and experimental protocol were designed to allow for the gathering of grip force data from human subjects presented with the task of keeping an object within a two-finger pinch grasp (between the thumb and index finger). This object was connected to the stylus of a PHANToM robot, which was programmed to apply various magnitudes of 'step' loads at random times and intervals throughout an individual trial. The object contained force sensors to measure the grip force employed by the human subject during each stage of the task. This data has been analyzed and compared to the results of the robotics algorithms for the specific task.

The paper begins with background on the physiology and motor control of the hand, moves to relevant experiments in biomechanics, then touches upon some areas of cooperation between the fields of biomechanics and robotics. After this, research in robotics addressing the issue of grasping and grip force is reviewed. Finally, original research on the grip force response of human subjects to various step loads is presented and a comparison of the results to the relevant robotics algorithms is made.

Introduction

Few people would argue with the statement that the human body has adapted amazingly well to behave and perform tasks that are regularly required in daily life. Many machines have been designed that are better suited for a specific task than humans (e.g. a computer for fast and accurate calculations), however none are as versatile as the human machine. So much so, that a field of study has been developed that takes leads from the human body (or other living organisms) to solve various engineering problems – Biomimetics (literally 'mimicking life').

Particular to this literature review, a biomimetics approach has been adopted by a number of researchers in the field of robotics to attempt to solve the problem of developing stable grasping and manipulation of a desired object. People are incredibly adept at picking up and moving around an object of any reasonable size and shape without dropping or crushing it. The function of many robots is similar to the human function: an object must be grasped and manipulated to accomplish a desired task.

Let us consider a potential application for a robotic manipulator – in a hen house. The robot is to be configured to pick up eggs after they are laid and place them gently on a conveyor belt. It has been decided that the robot will have a simple, two-fingered end-effector with soft fingertips (e.g. covered with rubber) and has already been programmed and configured for everything except the grasping and manipulating of the egg. A number of factors immediately come to mind that might affect the way the robot is to behave. First, how is it to approach the egg to initially grasp it? It is a simple task for humans to perform, but not as elementary for robots who need to be programmed through every step of the process. If the egg is grasped too close to the ends, it may slip out of the robot hand and create a mess in the hen house. And after a suitable grasp position has been found, how much force should be applied by the robot fingers? It is clear what will happen if too much or too little force is used when grasping the egg. Where, then, is the appropriate middle?

The following literature review investigates the human grasping function, focusing on a simple two-finger pinch (thumb and index finger). This narrowed topic is particularly interesting because it is analogous to the common two-fingered pinch in robotic grasping and manipulation. The goal of this section is to provide the background necessary understand the human pinch function enough to compare it to the algorithms that have been developed in the field of robotics that describe the appropriate grasp force to ensure the stable grasp of a given object. This 'understanding' will be gotten through a discussion of the anatomy and physiology of the thumb and index finger pinch, overview of the analogous robot function, review of relevant experimental research, and the cooperation of the two fields.

Overview of the Human Pinch Function

Grasping an object isn't a task that we generally think about before doing. But there are many factors that are taken into consideration (perhaps subconsciously) that lead to our choice of a specific grasp configuration for the job at hand. These factors serve as a basis for the classification of human grasp choices as presented in Cutkosky and Howe [9].

The authors present a taxonomy for grasp classification that begins with general function (power or precision) and continues the subclassification based on the geometry of the object being grasped and manipulated. Power grasps can be recognized by the usage of a large contact surface area, typically involving the palm, and precision grasps by mostly fingertip contact. According to their system, the thumb-index finger pinch is the most dexterous precision grasp for the most detailed task and geometry, but also for the smallest object size [9].

Although it is the simplest grasp, as far as number of fingers, and therefore muscles and degrees of freedom, it is still relatively complex. The index finger has seven muscles, three joints, and four degrees of freedom. The thumb has eight muscles, two joints, and three degrees of freedom (some sources argue for a extra degree of freedom in the "roll" of the thumb and index finger around its length). Because there are more muscles than degrees of freedom, fingers are redundant systems, and therefore difficult to analyze. For instance, a number of different muscle coordination strategies can result in the same output force from a finger, and determining which muscles are contributing and to what extent becomes challenging [2].

Embedded in the dermis (inner layer of the skin) are mechanoreceptors that provide the sensory information that the central nervous system needs to respond to stimuli and allow for the completion of a desired task. These mechanoreceptors are the human equivalent to strain gauges, force transducers, accelerometers, and other types of sensors used to gather information about the mechanical properties of a stimulus. In the human fingerpad, these receptors are classified as FA and SA (fast and slow adapting) types I and II, and send information to the central nervous system (afferent) [4]. The surface area of the cerebral cortex devoted to the control of the fingers and hand is about as large as that for entire body (other than the hands) from the head down! [10]

In muscles there are also a variety of mechanoreceptors that provide information about the muscle's position and force development, termed muscle proprioceptors. These mechanoreceptors do not respond to external stimuli, but sense the internal mechanical behavior of the muscle, hence the term 'proprioceptors' as opposed to 'exteroceptors'. In the muscle tendons, Golgi organs provide the sense of muscle force by increasing frequency of action potential firing with increased displacement. In the muscle, spindle organs provide a strain gauge type of signal that tells the CNS information about the length of the muscle [10].

It is the entire system – bones, joints, muscles, skin, receptors, and central nervous system control that determine the way the hand and fingers behave in various conditions. The research that will be discussed next seeks to further understand and classify this behavior during the two-finger pinch task.

Interesting Experiments

Roland Johansson has worked on the subject of human grip force dynamics since the mid-1980s and is responsible for many of the significant advances in the field. In a series of three papers (only two are reported here), Johansson et al. [6,7] present research that was specifically designed to give insights on the sensory control of the human precision grip.

A significant obstacle to research in this area is the fact that much of the control of precision grip is based on the sensorimotor memory that people develop from years of experience performing these types of tasks. These experiences develop an internal representation of the expected properties of the object we wish to manipulate. In order to get rid of this sensorimotor memory, an 'active' object is restrained between the thumb and forefinger, rather than the standard 'passive' object encountered in everyday life. This 'active' object is a pair of parallel grip surfaces, fitted with strain gauges and accelerometers to measure grip force and acceleration, and attached to a torque motor. The motor delivers loads to the object at unexpected times, thereby making the object 'active.'

Subjects who were prevented from seeing the object chose to utilize the precision grip (thumb and forefinger pinch) to restrain it. The rest of the arm was constrained by a vacuum cast and the bottom three fingers grasped a post to further constrain the arm. EMG electrodes were attached to the interossei (muscles between the thumb and the hand) and the antagonist muscle group attached to the other side of the thumb.

The overall results of the research are significant, in that it is the first time the grip force dynamics of the precision grip were outlined, opening the way for further research in this area. First, it was found that the grip force was initiated after a brief delay (presumably the time it takes for a signal to travel to the CNS, be processed, and come back). During the ramp loads, the force was characterized by a sharp increase, greater than that of the load rate, a sort of catch up for the delay. If the load was still increasing after catch up, the grip force rate tracked the load rate, moving in parallel with it. During the plateau, or hold phase, the grip force also moved in parallel with the load rate, a nearly horizontal line, with a bit of a safety margin to ensure secure grasp. During the unloading phase, the grip force exerted by the subject followed a smooth, bell-shaped path. It is believed that this path has been "programmed" for the inter-trial grip force (not zero), and is based on the quick learning of the subject. A diagram of the load and grip forces is located below in figure 1.

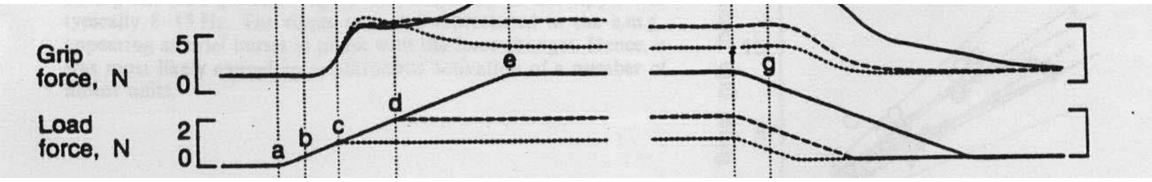

Figure 1: Plot showing the load forces (bottom) and the resultant grip forces

Other interesting results are presented by Johansson et al. The authors identify safety margins used by humans in the precision grip (i.e. the grip force employed is greater than the minimum required to restrain the object). These safety margins, believed to be based on the objects physical properties (weight, density, friction), were found to be about 50% of the minimum force required [6,7].

Macefield et al. [4] present research done in investigation of the 'responses of cutaneous afferents' during the restraint of an object held in a thumb and index finger pinch. The authors utilize the same experimental setup as Johansson et al. [6,7] without the EMG electrodes. Instead, tungsten microelectrodes are inserted percutaneously into the median nerve to record the activity of 10 FA I and 13 FA II "fast adapting" afferent (to the spinal cord) nerves and 12 SA I and 18 SA II "slow adapting" afferent nerves, all "low-threshold" mechanoreceptors. The goal of the research was to determine the role that the different classes of mechanoreceptors play in the restraint the object in the two-finger pinch.

The results show that the FA I afferents are the first to respond to external stimuli. These afferents begin firing before the fingers respond by increasing grip force, suggesting that these are the ones responsible for this initial detection. This class of afferents responds to changes in stimuli, such as the ramp portions of the loading, and remain fairly inactive during constant stimulus application, such as the plateau phase applied after the ramp loading. The activity of the FA I afferents seemed to be suppressed during instances of high force application, as if these were being 'choked'. The FA II afferents were only active during instances of high loading rates, such as step loads. They didn't seem to respond to the ramp or plateau loads, and therefore were only active during a small portion of the trials.

The SA class of afferents wasn't significantly active during the loading and unloading portions of the trials, but seemed to be the source of information about the states of constant stimulus application. The SA I afferents were found to be influenced by the grip force employed by the subject during the holding phase. It was found that the SA

II afferents gave information about the load force applied by the stimulus and the corresponding direction of the load application.

In "Precision Grip Force Dynamics: A System Identification Approach," by Fagergren et al. [1], the authors take a 'black box' approach to classifying the human two-finger pinch system. This approach involves the development of a model based purely on experimental data, and is preferable in a biological system involving too many parameters to model effectively using theoretical methods.

The authors describe a series of two experiments used to accomplish their task: a reaction experiment in which an object is dropped onto a receptacle that the subject restrains with a precision grip, and an active experiment, nearly identical to the one used by Johansson [6,7] and Macefield [4]. Both of these result in nearly the same grip force dynamic response, but the inputs to the CNS are generated differently. Since these type of experiments only allow the measurement of the system output (i.e. the grip force dynamics as opposed to the signals input to the CNS), the two different experiments are used as a check to the estimation that the input is simply a step function.

Based on the shape of the force output seen in the experiments done by Johansson [6,7] (see figure 1), it is easy to see that the grip force response system behaves somewhat as a typical linear system (although their input is a ramp force function). This was taken as an assumption by Fagergren et al. in the development of a transfer function to model this system. From these assumptions, and combining the transfer functions estimated based on the two experiments, the authors present a transfer function:

$$H(s) = \frac{280}{s^2 + 22s + 280}$$

to model the dynamics of the precision grip force system, which includes the "isometric linearized dynamics of the motorneuron pool, muscles and the biomechanical system configuring the precision grip.[1]" A plot of the system as modelled by the the above transfer function is located below in figure 2, for a step input of one.

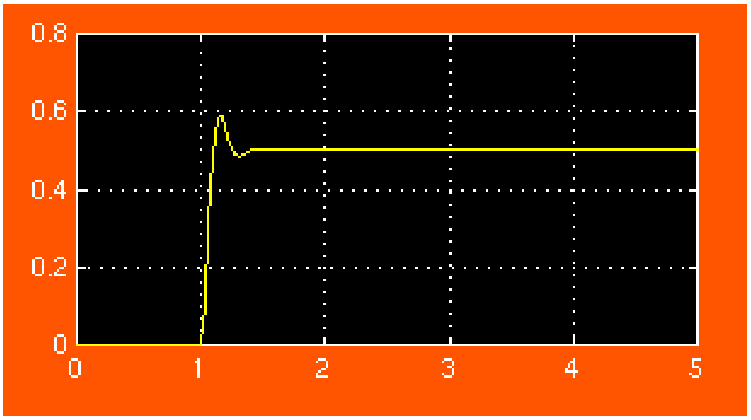

Figure 2: Step response of the Grip force dynamics system for a step input of one

Although the authors present the nice transfer function that looks very close to the actual grip response of the subject, they do not seem to describe the result very well. For instance, how does the step input relate to the force applied to the object?

Cooperation with the Field of Robotics

In the literature reviewed for this study, many papers were identified that, to some extent, merge the study of human precision grip (and grasping in general) to the study of robotics and robotic control. It is interesting to see the two fields working together. In some instances, researchers in robotics take leads from the study of human grip force dynamics, while some researchers investigating the human hand have taken leads from developments in the field of robotics (although the former seems to be more frequent than the latter).

In a series of papers, H. Inooka and I. Kim [3,5] describe a control strategy for robot hands based on the human precision grip dynamics. An advantage of this technique is the employment of the carefully chosen safety factor used by humans, which serves to minimize the force (and therefore torque requirements) needed to adequately restrain a desired object. The authors needed to compensate for a lack of sensing technology in robotic hands, and do so by determining the onset of slip based on the change in velocity of the object being grasped. They develop a control scheme very close to that presented by Macefield et al. [4], and implement the findings. The resultant behavior of the robot hand is deemed effective and the control strategy validated.

John Hollerbach, one of the major players in robotic hand research, authored a chapter in *Vision and Action: The Control of Grasping* entitled "Grasping in Human and Robot Hands [8]." From the title the interaction between the two fields is evident. In the chapter, Hollerbach gives an overview of the state of the research (in 1990) including grasp geometry, path planning, fine motion control, regrasping, finger and hand control, tactile sensing, and ending with robotic hand design. This final section deals with the research interest in robotics that is based on the previously presented subjects, particularly in the areas of sensing and control.

Interesting research is presented by Valero-Cuevas in "Applying principles of robotics to understand the biomechanics, neuromuscular control and clinical rehabilitation of human digits. [2]" As the title suggests, the author uses robotics to study biomechanics. Due to the complexity of the human hand and the redundancy of the muscle control (as discussed in a previous section of this review), the author takes simplifications developed in the study of robotics to make discoveries about the biomechanics of the human fingers. Particularly, the human digits are viewed as serial manipulators and the Jacobian defining their motion was determined (after a number of constraints and simplifications were introduced). The constraints and simplifications were based on clear definitions of mechanical tasks as would be performed in a robotic manipulation. Valero-Cuevas' motivation is to understand the biomechanics to aid in clinical rehabilitation of the hand, but the application of such understanding goes far beyond that specific arena.

Survey of Robotics Literature

There has been a significant amount of literature published in the past 20 years or so on the subject of force control and grasp stability in robotic manipulators. As seems intuitive, researchers first focused in on rather simple cases (such as two-fingered robot hands) and then proceeded to deal with more complicated end-effectors. The scope of this literature survey will be the analysis of the simple two-fingered case.

One of the first researchers to address the grasping problem in an exhaustive manner was J. K. Salisbury in his PhD dissertation at Stanford and successive publications, including the book "Robot Hands and the Mechanics of Manipulation" [E]. Chapter six of the book is entitled "Force Application and Velocity Analysis," and proves to be a good jumping off point in a study of this topic.

The main thrust of the chapter concerns the derivation of the grip transform, G, a matrix that "embodies" the static force analysis and the "relationship between forces and velocities in a hand-object system." This matrix allows for the determination of the contact forces and torques needed to result in "net force on and in a grasped object," and is formed by augmenting the matrix W (describing the contact of the hand with respect to the object) with the vectors that span the null space of W. (A nice description of the significance of the null space of W is described in Valero-Cuevas, 2000.) This matrix G allows for the determination of the net "wrenches" applied to the object and the magnitude of the internal forces (f) through the relation:

$$f = G^{-T} F$$

where G^{-T} is the inverse of the transpose of G and F is the vector of contact wrench intensities. These quantities are used extensively throughout the successive literature on the subject.

Chronologically, the next significant research identified in this review is the work done by Kerr and Roth on the "Analysis of Multifingered Hands" [D], claiming to build upon the previous work done by Salisbury. The paper deals with three topics – appropriate force to apply to ensure secure grasp, fingertip motion needed to result in a certain object motion, and the determination of the workspace of the hand. Of these, only the first is of significant relevance to our topic.

The authors begin by defining a stable grasp as one that can withstand "unwanted movements" of the object. They put forth the observation that once the condition for stability is met, there are still a number of statically indeterminant components of the applied wrench vector, handled as the internal forces. The authors proceed to describe a way that those components can be chosen to 'optimize' the stability of the grasped object. After considering the role of friction in the stability of the object (i.e. is it needed?), and the limits of the forces and torques that can be applied by a given manipulator, a graphical representation of those constraints is developed (put into a neat, 3-D image by K. Shimoga, 1996 [A]). This 'graphical' representation manifests itself as a multi-dimensional polygon containing all solutions to the indeterminant components that meet the stability conditions. All values lying outside of this polygon are not solutions. Kerr and Roth define the 'optimal' grasp force as the solution that lies furthest from the boundaries of this polygon.

The work done by Salisbury [C] and Kerr and Roth [D] provides a sound mathematical derivation of the force that should be applied to an object once a particular grasp has been chosen. Van-Duc Nguyen presents simple algorithms for determining acceptable grasps based on the geometry of the part being grasped in "Constructing Force-Closure Grasps" [Nguyen, 1988]. Section 4 is an especially helpful section describing the conditions that must be met for a grasp consisting of only two point-contacts. Corollary 3 states that "two point contacts with friction...form a planar force-closure grasp if and only if the segment (connecting the two points) points strictly out of and into the two friction cones" of the separate points. It is also important to note that two contact points with friction can be reduced to four contact points without friction, by a "well-known fact of planar mechanics." Corollary 3 is also valid for a 3D grasp with two "soft-finger contacts." In a later publication [Nguyen, 1989], the author describes the "easiest way" of achieving a stable grasp is by covering the fingertips of the robotic hand with soft rubber.

David Montana describes a new condition for stability in "Contact Stability for Two-Fingered Grasps" [B]. He describes previous work on the subject of stability in robot grasps as having dealt with the case of "spatial" stability, and puts forth a new measure that he calls "contact grasp" stability. To motivate the research, Montana begins by providing a number of examples of "unstable" grasps that would be considered stable when evaluated using the existing stability analysis algorithms. He then derives the 8x8 matrix A, which describes the "evolution" of the object during manipulation. This matrix is based on the derivation of the dynamics of two-fingered grasps and the kinematics of contact, resulting in a model that is a system of linear equations. Stability is therefore defined when the eigenvalues of the matrix A have negative real parts, or lie in the "left half-plane."

One of the most helpful pieces of published literature that was identified in this review is an overview of the topic by K. Shimoga called "Robot Grasp Synthesis Algorithms: A Survey" [A]. As is appropriate for survey articles, the paper gives a concise summary of the significant advances in the study of robotic grasps in years previous. The article covers, to some extent, the four articles discussed above, and many more. Sections three and four deal with grasp equilibrium and grasp stability, respectively, and were found to be especially helpful in explaining these concepts more clearly than other literature. Unfortunately, Shimoga seems to break from the notation selected by the researchers he is reviewing and opts for yet another set of notation that must be decoded. As the term "survey" suggests, nothing new is presented in the article, just a succinct summary of existing literature.

The short literature review presented above is by no means comprehensive. The previous research discussed here is that which seems (at least at this stage) directly applicable to the experimental work covered in this report. There are many other researchers who have studied these and similar topics and gone further in depth than the scope of this paper. A number of these publications have been identified and are referred to in the "other publications" section at the end of this report.

Human Grip Response Experiment

An experiment was designed and conducted to measure the grip force response of human subjects to various step loads. The experiment was modeled after those conducted by Johansson et al. [6,7] and similarly, Macefield et al. [4]. Subjects were instructed to use the precision grip to restrain an object fitted with a unidirectional force sensor. Various step loads were applied to this object a direction normal to the grip force and the response recorded. A total of four subjects (two males, two females) were tested.

Experimental Procedure

Each experimental trial began with the determination of the coefficient of friction of the subject's fingers and the grasped object. The parallel surfaces of the object were covered with a paper sticker to help in the regulation of the coefficient. Paper was choen because of its absorptive properties and relatively high coefficient. The object was fitted with a Kistler type 9212 unidirectional force sensor with a maximum measuring range of 5000 lbf and a sensitivity of –53.40 pC/lbf. A picture of the object, fitted with the force sensor is shown in figure 3.

Figure 3: Close-up of the manipulandum object fitted with force sensor

A layer of plexiglass was inserted on both sides of the sensor for insulation, as it is very temperature sensitive.

To determine the coefficient of friction, a 1kg weight was attached to the bottom of the object and the subject was instructed to pick the object up (using the parallel grip surfaces) and release the grip force gradually until the object slipped out. The force at which slip occured was measured (for 5 trials), and the coefficient of friction determined. A picture describing this process is shown in figure 4.

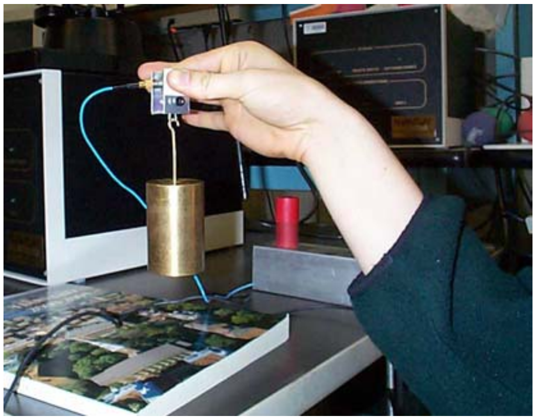

Figure 4: Method of determining coefficient of friction

The weight was then removed and the object was connected to the stylus of a PHANToM robot. The robot was programmed in C++ to apply a step load in the vertical direction to the object being restrained. The experimental apparatus is shown in figure 5 below.

Figure 5: Experiment test-bed – PHANToM robot atop its amplifier, sensing object attached to the stylus, and the block and peg to standardize arm and hand position

Each subject rested their forearm on the aluminum block (clamped to the table), and were instructed to wrap their bottom three fingerd around the post inserted into this block, standardizing the postion of the subject's hand and arm. The manipulandum was placed between the subject's thumb and index finger to be grasped. A picture showing this is shown below in figure 6.

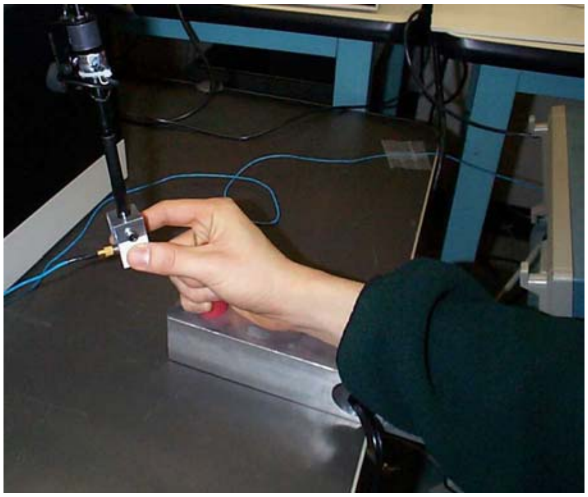

Figure 6: Picture showing the forearm, hand, and object position during disturbance trials

Each load trial began with placing the PHANToM stylus in the home position and resetting the force sensor. The program was then started, and the object placed within the subject's grasp. Grip force was measured both before and after the step load was applied. The force sensor was connected to a Kistler 5004 dual mode amplifier which output current to a Tektronix TDS 420 four channel digitizing oscilloscope. The voltage corresponding to the grip force was read directly from the scope display. A picture of the objects used in the data collection is shown in figure 7 below.

Figure 7: Data collection apparatus – scope (left), amplifier (middle), and computer (for manual recording)

This ‘correspondence’ between grip force and voltage output was gotten through a pre-experimental calibration in which various weights were placed on the object and the voltage output recorded. A line with an intercept of zero was fit to this data, the slope of which was in units of grams per millivolt. The calibration plot is shown in figure 8.

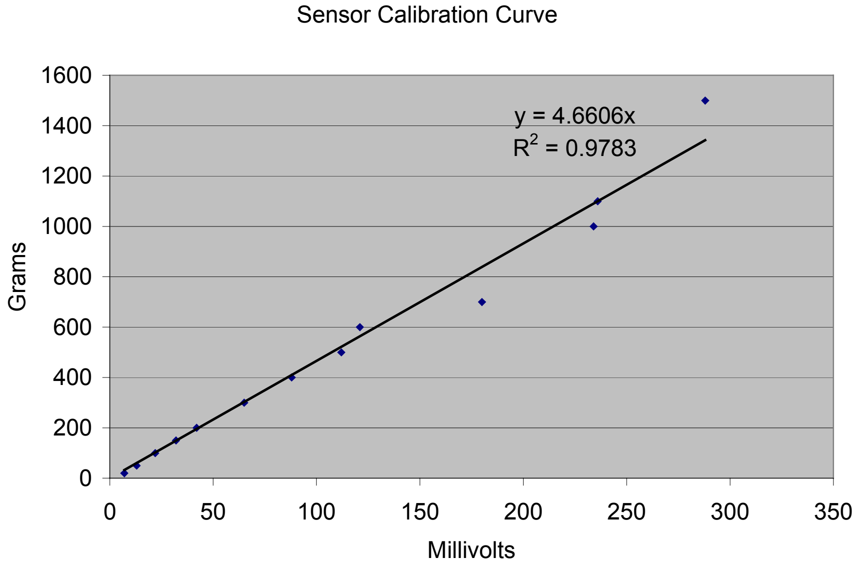

Figure 8: Sensor calibration curve (slope of 4.66 grams per millivolt) and R-squared value of .978

Each subject was presented with three magnitudes of step loads (1, 2, and 3 Newtons) five times each, for a total of fifteen trials. These loads were applied in varing order to the subject, each application seven seconds from when the program was started. This time does not correspond to seven seconds for the subject however, as the time between the start of the program and the secure placement of the object in the subject’s grasp varied with each trial.

The last part of each experiment consisted of a measurement of the maximum grip force that could be applied by each subject. Five trials were conducted in which the subject was instructed to squeeze the object as hard as possible a hold this force constant. A measurement was taken directly from the oscilloscope.

Analysis

A number of assumptions and simplifications were made during the analysis of the experimental results. These include:

- The friction between finger and object surface was modeled as static coulomb friction (i.e. Friction force = normal Force*coefficient)
- Coefficient of friction is the same for all loads. In reality, the harder the subject squeezes, the more contact surface area, and higher coefficient.
- The load actually applied by the PHANToM is assumed to be constant and equal to that which was commanded. (Although a quick experiment in which weights were hung on the stylus revealed that the output force is very close to the desired output.)
- The force values (or corresponding voltages) were read directly off of the scope. The resolution of the scope limits accuracy, but more significant is the method of estimating a value for force based on a very noisy output. An average of the force data was simply ‘eyeballed’ from the scope screen.

Also significant in determining the results are the ‘psychological’ factors involved in the experiment. Based on the previous trial, subjects tended to ‘expect’ a certain load to be applied in the next trial and would modulate their grip force based on this expectation. For instance, almost every trial in which a three newton load was applied directly after a one newton load, the resting grip force employed by the subject was not large enough for stability, and the object was pulled from the subject’s grasp. In the very next trial, the subject would use a much larger resting grip force and subsequent safety factor to ‘make up for’ the previous slip. These types of changes resulted in very inconsistent results between trials and, therefore, a large spread in the data.

Results

The table in figure 9 below shows the results of the average coefficient of friction (over five trials) for each subject, as well as the average across subjects and standard deviation.

Subject	Coeff.
1	0.6161
2	0.6188
3	0.6093
4	0.623
average	0.6168
st. dev.	0.0057

Figure 9: Average coefficient of friction between precision grip and object

The results of this portion of the experiment were very consistent across subjects, as the low standard deviation suggests.

Figure 10 shows the average grip force employed per subject for each load value.

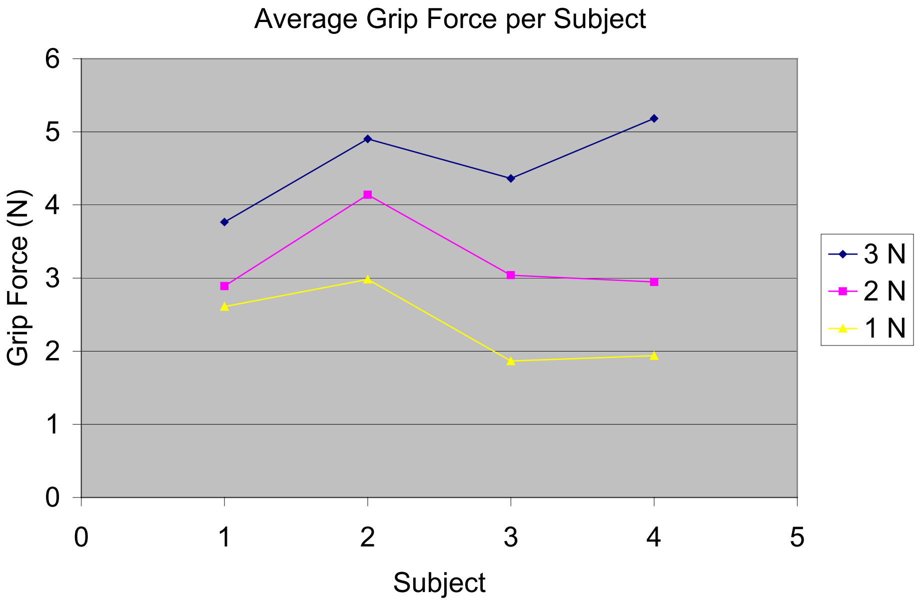

Figure 10: Average grip force per subject for each of the three disturbance loads

It can be seen from the plot that the chosen force applied per load varied greatly across subjects, as well as the range of forces by a particular subject. It is clear that there is no universal rule applied by humans relating chosen grip force to the particular disturbance. The standard deviation of these data points are huge (each around 1 newton), and were left off of the graph for clarity.

Figure 11 shows the average safety factor used by each subject across all load trials.

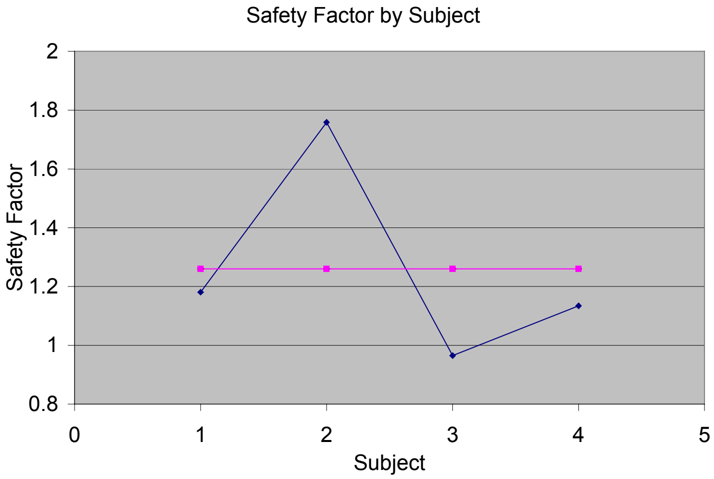

Figure 11: Average safety factor per subject (dark) and across subjects (light)

It can be seen that the safety factor (defined as the grip force divided by the minimum grip force needed for stability all minus one) varies greatly from subject to subject, and ranges from less than one to almost 1.8. Again, there is clearly no universal rule being followed. The standard deviation for these data points is again very large (an average of 1 safety factor), and were left off of the plot for clarity.

Figure 12 shows the average resting grip force (i.e. that which is applied during the times of zero disturbance load application) per subject.

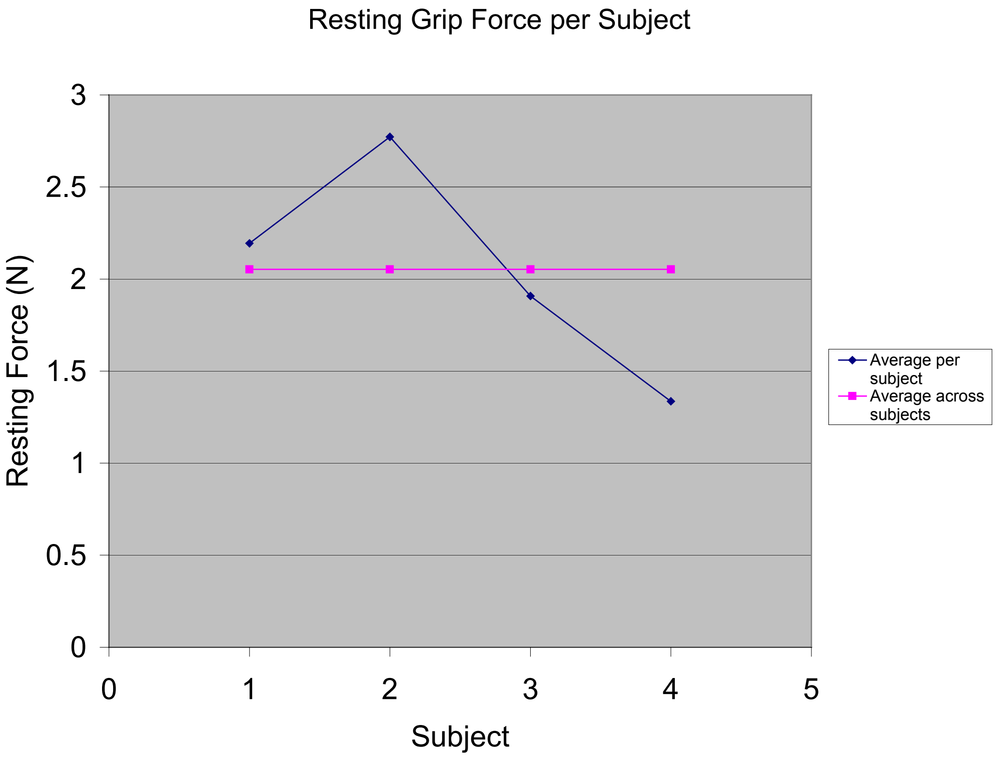

Figure 12: average resting grip force per subject and across subjects

Again, the data varies greatly across subjects and widely spread within subjects (average standard deviation of .8 newtons).

Figure 13 shows the average maximum force that could be applied by each subject.

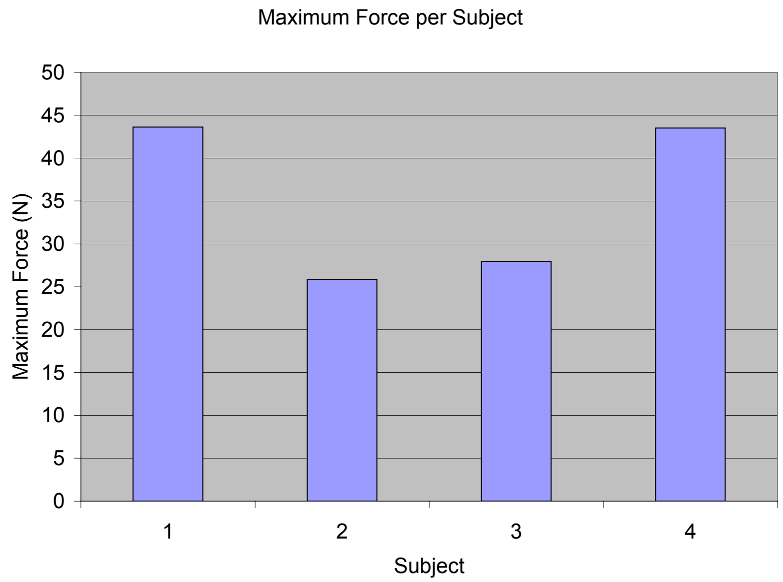

Figure 13: Maximum grip force per subject

Again, the data varies from subject to subject (although subjects 1 and 4 are male and 2 and 3 female).

As described earlier, the results of the experiment were to be compared to robotics algorithms that describe 'optimal' grip force for a given task. Specific to this task, two main ideas exist. The first is that put forth by Kerr and Roth [D] (described previously). The authors state that the optimal force is that which lies furthest from the boundaries of the constraint polynomial. For the task described by the experimental protocol, the constraint polynomial is very simple (one dimensional, in fact). The boundaries are the minimum force necessary to prevent slippage and either the maximum force that can be applied to the object, or the force that would crush it. In this case, the maximum force is less than the crush force, and is therefore the other boundary. Any force value in between the two boundaries is a solution to the problem.

The other idea was put forth by Nakamura, which was not identified in the previous review, but mentioned in Cutkosky and Howe [9]. The algorithm states that the optimum force is the one that minimizes the internal force of the object (which is the minimum grip force needed for stability), plus a factor of safety. This is the method closest to that employed by humans. Obviously, the factor of safety can be different depending on the task.

Discussion

As expected, the method of grip force application chosen by humans is not much like that described by Kerr and Roth [D], but is similar to that described by Nakamura. According to Kerr and Roth, the optimal grip force should be around 17 Newtons (halfway between the minimum force for stability and maximum possible force). This is clearly an unreasonable result, and would yield a safety factor of around 6 for the 3 newton disturbances and 20 for the 1 newton case. But even the safety factor method described by Nakamura is not a good predictor of human behavior, as shown by the enormous standard deviation in this calculation.

The average factor of safety was found to be 1.25 in this research, but was reported by Johansson et al. [6,7] to be 0.5. Why the disparity? The loads applied to the object were in the same range (1 to 4 Newtons in Johansson and 1 to 3 in this study). The most likely explanation is the method of load application. Johansson used ramp loads followed by plateau phases, which allowed subjects to 'track' the load increase with their grip response. However, step loads were applied in this study, thereby making the disturbance even more unexpected.

It seems as though the 'psychological' factors described previously play an enormous role in the grip force responses to external disturbances. The point of using an 'active' object (as described by Johansson et al [6,7]) was to eliminate the 'sensorimotor memory' that is built on years of experience accomplishing these types of tasks. But the resultant 'moment-to-moment' sensing yields inconsistent results.

This brings up the question of whether the results from restraining an active object are applicable to real-world experiences. I can't immediately think of an application in which a robot grasps something that might try to wiggle out of its grip. But it is a possibility. Therefore, the factor of safety applied by the human subjects in this trial seems to be unreasonable for 'real-world' application.

The results of the experiment have begun to open avenues of future research. The most appropriate to shed more light on the topic for application to robotics would be to test for the human grip force in the grasping and manipulation of 'passive' objects. Subjects could be asked to pick up and move around an object fitted with sensors. These results would be more appropriate to practical applications in robotics.

Also, the 'psychological' factors described herein would be interesting to investigate. Can the grip force response during an individual trial be predicted based on the sequence of previous trials? Does the subject's perception of the properties of the object play a role in the grip force response? For instance, what if the object was fragile, such as an egg? Or why and when does slip occur, and is it related to the sensitivity range of the mechanorectors in the fingerpad?

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