Teleoperated Sensing by Grasping: Robot Sensors and Human Psychophysics

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Abstract—An interesting problem for a robot that is manipulating an object in the environment, either directly or by using a tool, would be to perceive the length of the object and/or tool. This paper addresses the problem of length perception in a teleoperation context, using the sense of touch alone. To establish a relation between the forces acting on the robot gripper and the length of the gripped object, a rigorous mechanical analysis of the gripper-object system is performed. With regard to robotic length perception, a novel sensor that derives directly from the results obtained from the mechanical analysis is proposed. The mechanical analysis is also applied to the question of how humans perceive the length of a rod held stationary in the hand, and tested experimentally in a sequence of psychophysical investigations. The implication of this study for design of teleoperated systems under human force-reflection control is discussed.

1. Introduction

Teleoperated tasks often involve manipulation of objects in the environment, either directly or through tool use. In haptic manipulations involving unconstrained grasping of tools, we ask whether the human operator (or an autonomous robot system) can determine the characteristics of a tool simply by holding it. Rods may be viewed as one of the simplest tools a human operator might be asked to control remotely. In this paper, we address the task of determining the length of a uniform rod by grasping it.

We approach this problem in a series of four steps:

1. define the required task that needs to be accomplished
2. study the physical and other constraints that apply
3. determine a system that satisfies both the task and constraints
4. evaluate system performance.

We have chosen the task-driven model for teleoperation, rather than the technology-
driven approach that attempts to determine the usefulness of a system developed from an existing equipment base, because a task-driven model better addresses the human-interface issues that arise in teleoperation.

2. Haptic perception of length by grasping

For a remote robot controlled by a human operator, accurate length perception may be important in situations where the object is manipulated in space-constrained environments: if the dimensions of the object are known, then the object can be manipulated (reoriented, relocated, etc.) without causing damage to other surrounding objects or to the robot itself. Perceiving length may also be required in situations where it is important to know the location at which the object is grasped, or in tasks that require further manipulation based on the knowledge of length (e.g., assembly of components of a space-station structure).

In the haptically teleoperated task, an object is grasped by a remote robot at the slave end. The forces are presented to the hand of a human operator, who controls the task at the master end. Thus, to fully understand the problem of haptic length perception within the teleoperation context, it is necessary to:

1. understand the nature of the interaction of the remote robot with the environment, particularly the effects of the environment on the robot due to the interaction, and

2. determine the human’s ability to accomplish the task of estimating tool length when provided with appropriate haptic feedback.

The first goal lies within the domain of machine perception or robotics, while the second goal within the domain of experimental psychology. Thus, what links the seemingly diverse fields of experimental psychology and robotics is the more general goal of telesrobotics (or more generally, teleoperation) whereby a human operator must control the activities of a robot in a remote workspace.

We approach this problem by first performing a force analysis based on the general principles of mechanics, devising a suitable system (for the remote robot) that fulfils all the mechanical constraints specified in the analysis, extending the results of the force analysis to the human haptic subsystem, and finally evaluating the performance of both systems.

2.1 Force analysis of the gripper-object system with respect to length perception

In order to perceive the length of a gripped object, it is necessary to begin by establishing the relation between the forces acting on the gripper and the length of the object. The term 'gripper' refers either to the end-effector of the remote robot
In the force analysis of the gripper-object system, we make the following assumptions:

1) the gripped object is made of homogeneous material such that any element cut from the body possesses the same specific properties of the body.

2) the gripped object is uniform, i.e., it has the same geometric properties throughout its length.

3) the angle or orientation of the object with respect to the ground plane is assumed to be known.

4) the gripper-object system is at rest and in a state of static equilibrium where there is no macroscopic motion. This assumption excludes any situation where damage or permanent deformations may occur to either the object or the gripper due to excessive forces and torques.

When the object is gripped at one extreme end, the force, $F$, and torque, $T$, acting on the gripper are:

$$F = \rho_A L g$$  \hspace{1cm} (1)

$$T = \frac{1}{2} \rho_A L^2 g \cos(\theta)$$  \hspace{1cm} (2)

where, $\rho_A$ is the mass per unit length of the object, $L$ is the length of the object, $g$ is the gravitational acceleration, and $\theta$ is the orientation of the object with respect to the ground plane. When the object is gripped at an intermediate location, the torque is given by:

$$T = -\frac{1}{2} \rho_A [(L-x)^2 - x^2] g \cos(\theta)$$  \hspace{1cm} (3)

where $x$ is the distance of the grip location from one end of the object. The gravitational acceleration $g$ and the orientation of the object $\theta$ with respect to the ground are known quantities, the force $F$ and torque $T$ are measured quantities. The quantities $\rho_A$, $L$ and $x$ must be deduced.

The force analysis reveals that the length of the object becomes indeterminate when the object is held perpendicular to the ground plane, or at an intermediate location. To overcome the latter problem, it is proposed that two force-torque measurements be obtained by gripping the object at two independent locations simultaneously. If the two force-torque measurements are physically close to each other, the system can
be easily split into two independent subsystems, and the length of the grasped object can be determined individually for both sides by using equations (1) and (2).

3. Robotic perception of length

The results of the force analysis implied the need for further sensor development since the existing gripper and tactile technologies were inadequate. For references and reviews of current technology in tactile sensing, see Ellis, et. al. [4], Regtien [11] and Nicholls & Lee [9]. To provide adequate sensing in the gripper, we developed a novel sensor based on thin-plate deformation.

3.1 Design of robotic sensor

The proposed sensor employs detection and use of force information to predict the length (and mass) of the gripped object. For reviews of the detection of force information, the interested reader is referred to Brock [2], Bicchi, et. al. [1], and Okada [10].

The sensor consists of two sets of plate arrangements. Each plate arrangement constitutes two thin plates arranged such that they directly face each other, i.e., one plate is mounted on the top inner surface of the gripper while the other is mounted on the inner bottom. Each plate is a plane structure whose thickness is very small when compared to its other two dimensions, and bound geometrically by straight lines. For ease of design and analysis, only square plates were considered.

The boundary conditions prescribed for the sensor plates were two fixed supports at two opposite edges, with the other two edges simply supported (Fig. 1). Simply supported edges offer adequate sensitivity to the sensor plate and also make it relatively easy to obtain analytical solutions, whereas fixed supports offer ruggedness to the design. Since the analysis is relatively straight-forward when the structure is symmetrical, the boundary conditions for the opposite edges were chosen to be the same.

With the object gripped by the proposed sensor arrangement, the predicted loading pattern on each sensor plate is essentially a non-uniform one (Fig. 2). The sensor plates may be subjected to loads that are present on the entire or partial surface of the plate, or they may be line loads. Here, only the case in which the sensor plates are loaded on the entire surface is considered. For a more detailed discussion of different loading patterns, the reader is referred to Ellis, Ganeshan & Lederman [4].

For a square plate with sides of length 'b', the sides x = 0 and x = b simply supported and the sides y = ±b/2 fixed, the loading function (assuming that the load varies in the x-direction only) may be represented by the following series (Timoshenko & Krieger [14]):
Figure 1 Boundary Conditions for the Proposed Sensor Plate

Figure 2 Predicted Loading Pattern on Sensor Plates
\[ F_z = \sum_{i=1}^{\infty} F_i \sin \left( \frac{i\pi x}{b} \right) \] (4)

where, \( F_z \) is the lateral load acting on the surface of the plate. The strain \( \varepsilon_x (x,y) \) at a particular location on the plate is then given by:

\[ \varepsilon_x(x,y) = \frac{1}{2} \left[ \frac{h \pi^2}{b^2} \right] \sum_{i=1}^{\infty} \left[ \frac{b^4 F_i}{i^4 \pi^4 D} \right] + A_i \cosh \left( \frac{i\pi y}{b} \right) + B_i \left( \frac{i\pi y}{b} \right) \sinh \left( \frac{i\pi y}{b} \right) \sin \left( \frac{i\pi x}{b} \right) \] (5)

where,
- \( \varepsilon_x \) is the strain developed in the x-direction of the plate
- h is the thickness of the plate
- b is the width of the plate
- D is the flexural rigidity of the plate
- \( A_i, B_i \) are the coefficients

\[ A_i = -\frac{b^4 F_i}{i^4 \pi^4 D} \left[ \frac{1}{\cosh(\alpha_i)} + \beta_i \alpha_i \tanh(\alpha_i) \right] \]

\[ B_i = -\frac{b^4 F_i \beta_i}{i^4 \pi^4 D} \]

\[ \alpha_i = \left( \frac{i\pi}{2} \right) \]

\[ \beta_i = \frac{\tanh(\alpha_i)}{\sinh(\alpha_i) + \alpha_i \cosh(\alpha_i) - \alpha_i \tanh(\alpha_i) \sinh(\alpha_i)} \]

If the material and geometric properties of the plate are known, the strain \( \varepsilon_x \) can be determined to a desired level of accuracy by choosing the number of terms required to represent the load equation. For most loading conditions, only the first few terms need to be considered. For four terms, an accuracy of 98% has been reported for the triangular loading pattern, which is similar to the loading pattern prevalent in the present situation (Timoshenko & Krieger [14]). Rearranging the terms, we obtain:
\[ \epsilon = Cf \]

where \( C \) is a constant representing the compliance of the plate. Since, \( C \) is a square matrix, given that its determinant is not equal to zero, the force set \( f \) can be expressed as

\[ f = C^{-1} \epsilon \]

### 3.2 Experimental design and methodology

In this section, the mechanical design and the experimental method used to evaluate the proposed sensor are presented. A strip of low carbon stainless steel was bent at right angles at a chosen distance from both ends. The flat portion was then used as the sensing surface, and the bent portions were used to simulate the fixed boundaries of the sensor plate. For the simple supports, aluminum-channel sections with razor-sharp edges were used. The channel section and the plate arrangement were then screwed to a wooden base block that was attached to a bench vise.

Four electrical strain gauges were used for measuring the strain on each plate. These gauges were mounted on the bottom surface of the plate along the centre line between the simple supports, and the locations (x and y coordinates with respect to the origin) of these gauges were recorded. In order to account for errors in strain gauge installation, such as misalignment, lack of proper bonding, etc., the gauge readings were calibrated against a known value of strain.

Four different objects were used in the experiment. The width of all four objects was the same as that of the plate. Two of the objects were of oak wood, one was of pine and the other was of aluminum. Each of these objects was gripped at an intermediate location between its ends. The total mass for each of the objects, and the lengths extending on the two sides of the plate sensor are shown in Table 1.

When the object is gripped by both the left and right set of plate sensors, each set predicts the overhang length plus the length of the gripped portion of the object. Four different sets of readings were obtained for each rod from different trials, and the mean was used for the length estimates. The adapted strain-gauge calibration method could only provide for force calibration. In order to provide for torque calibration, a least-squares quadratic fit of the data was obtained and the estimated lengths were computed using the empirically derived equation:

\[ \text{CL} = 0.1357 \times 10^{-03} \text{ (PL)}^2 + 0.6852 \text{ (PL)} + 51.78 \]

where, \( \text{CL} \) is the length obtained after the above correction is applied, and \( \text{PL} \) corresponds to the length perceived by the plate sensor.
3.3 Results

The length perception results are shown in Table 2, where the mean perceived length is the mean of the four different trials. After the torque correction was applied, the estimated length yielded an average error of 3.82% (standard deviation = 2.17). The average error in mass perception was found to be 1.6% (standard deviation = 1.14).

Thus, rod length can be estimated to within 6% accuracy using the proposed plate sensor; but by downsizing the strain gauge lengths, we expect that measurement error can be further reduced. The results obtained for the 60 mm length were found to be spurious as they deviated greatly from the average results; hence they were discarded as a statistical outlier. The strain developed for the 60mm-length rod was in the low range of 1 - 5 μstrain, and the installed strain gauges were not sensitive enough to record them accurately.

4. Human perception of haptically derived length

Earlier in the paper, we argued that in order to fully understand the problem of length perception within the teleoperation context, it is not only necessary to study the remote robotic system, but to also investigate the human haptic system. A necessary and essential step in this investigation is to determine the human’s ability to accomplish the task of estimating object length by grasping under conditions of restricted exploration. Here, restricted exploration refers to the situation where the objects are held stationary in the hand (no translatory or rotary motion).

The problem of haptic length perception has been approached from various viewpoints by a number of researchers (Jastrow [7], Tehtsoonian and Teghtsoonian [13]). However, a number of more recent experiments directed at the perception of length in humans are based on an entirely different approach. These studies involve wielding or hefting, or just holding the stimulus still in the hand (Carello, et. al. [3], Solomon & Turvey [12]).

4.1 Length Perception - Psychophysical or Cognitive?

When a rod is held in the hand, stresses and strains are developed there due to the effects of the action of forces. These direct physical inputs cause the deformation of the relevant tissues of the haptic system, from which the metric information regarding the forces and torques is transduced. Based on the force analysis presented earlier, we propose that the perceived length of unseen objects held stationary in the hand depends on both the force applied by the rod and on the torque subtended by the rod at the grip (Force-Torque model).

It is important to note that in certain situations, as in the case where the rod is held perpendicular to the ground plane or gripped at its centre of mass, torque is
unavailable; in certain other situations, as in the case where the rod is held at
different orientations with respect to the ground plane, the weight may remain
constant while the torque varies. It is hypothesized that the weight of the rod and the
torque subtended at the grip will both contribute to the perception of the length of
unseen objects, their strengths depending on the extent to which each source is
available.

In the pilot studies that were conducted prior to the actual formal experiment,
subjects asked to provide psychological reports after the completion of the
experiments reported that they first perceived weight, and then used these estimates
to perceive length. These reports suggested that length estimates are probably
derived from the corresponding weight percepts. Since the cue related to weight is
present in every situation, irrespective of the grasp location or the orientation of the
rod with respect to the ground plane, this raises an important question for human
length perception: "Is perception of length affected by the perception of weight?".One possible hypothesis is that length percepts are associated with the corresponding
weight percepts. This approach to the problem of length perception is based on a
more cognitive approach to perception that hypothesizes that perception of a certain
quality of the object is based on the computations performed on other perceptions
(Percept-Percept model). Thus, we approach the problem of human length
perception from two theoretical viewpoints - the psychophysical approach that is
based on the force/torque analysis, and the cognitive approach that is based on the
theory that one percept is derived from another percept.

4.1.1 Experimental Methodology

In this human psychophysical study, subjects assigned numerical estimates in
proportion to the perceived length of different statically grasped rods. In the
experiment, the effects of different stimulus parameters were systematically
assessed, including material composition of the rods, mass of the rod and orientation
of the rod.

Subjects were presented with visually occluded rods of widely varying masses to
obtain a broad range of values for the force and torque. Rods of three different
lengths and three different masses were used. This design allows us to study the
effect of the mass of the rods on perceived length, when actual length remains a
constant; in other words, it allows us to see if different rods having the same length
but different mass (due to different densities) are perceived as having the same
length. To decorrelate the weight of the rods from the torque subtended at the grip,
each rod was also presented in three orientations - vertical, horizontal or at 45
degrees to the ground plane. In addition to the length estimates, subjects also
responded with weight estimates. The lengths, masses, forces and torques for each
of the nine different stimulus rods, each held at three different orientations, are as
shown in Table 3.
4.1.2 Results

The length estimates and weight estimates were initially transformed logarithmically (base 10) as human psychophysical functions are usually best described by a power function. Length estimates increased with increasing length and decreasing orientation (vertical, oblique and horizontal). They also varied consistently with material increasing in the following order: wood, plastic and aluminum. In other words, rods of the same length but different materials were perceived to be of different lengths: the wooden rods were perceived to be the shortest, while the aluminum rods were perceived to be the longest. It was also found that the effect of rod orientation was smaller for shorter, wooden rods. The linear equation obtained for the psychophysical model that predicts $\log_{10}$ perceived length from $\log_{10}$ actual weight and torque (since simple correlations with perceived length were a little higher when these parameters were used) is as follows:

$$PL = 1.23 \log \text{Force} + 0.26 \log \text{Torque} + 0.26$$

where PL is the perceived length.

Weight estimates similarly varied with material, in the order wood, plastic, and aluminum. Overall, the weight estimates varied in strikingly similar fashion to the length estimates ($r = 0.984$). Also, both length and weight magnitude estimates were more strongly related to the logarithmically transformed values of weight ($r = 0.93$ and 0.95, respectively) than to torque ($r = 0.74$ and 0.75, respectively).

To evaluate the percept-percept model, a multiple regression was first performed in which log weight estimates were predicted from log weight and torque:

$$PWT = 1.23 \log \text{Force} + 0.26 \log \text{Torque} + 0.26$$

where PWT represents the weight estimates. The $R^2$ value was found to be 0.965. The phenomenological reports of the subjects also suggested a dependency of length estimates on perceived weight. Eleven out of fifteen subjects volunteered that they based their judgements of length on the estimated weight of the object, while the other four suggested that they were influenced by the twisting effect felt at the grip.

The results of the experiment suggest that both models - the force-torque model based on the psychophysical approach and the percept-percept model, can predict the length estimates exceptionally well, although the latter model may be marginally better.

4.2 Pitting the Force-Torque Model against the Percept-Percept Model

To differentiate between the relative effectiveness of the force-torque model and the percept-percept model, another experiment was conducted to effectively assess the role of the weight percept over and above the forces and torques in judging rod
length. The technique we used involves inducing a static version of the haptic size/weight illusion in the subject. When subjects were presented with two objects of the same weight but different sizes, Ellis & Lederman [5] have reported that the larger one when hefted felt lighter than the smaller one. This illusion has been termed the haptic size/weight illusion. In order to pit the force-torque model against the percept-percept model, the subject was asked to statically grasp rods whose diameters (size) varied, while the physical length, weight and torque subtended at the grip remained unchanged (Ellis & Lederman [5]). The percept-percept model would predict that subjects should estimate the narrower diameter rod to weigh more than the larger diameter rod, and consequently, should further estimate its length to be longer. The force-torque model would predict no such differences as the force and torque at the grip remain unchanged.

4.2.1 Experimental Methodology

Blindfolded subjects were presented with rods that were held in a steady, horizontal position relative to the ground plane. One group assigned numerical estimates in proportion to the perceived length of the grasped rods, while another group made only weight estimates. Three pairs of rods were used in the experiment, with pair lengths of 22.9 cm (8"), 27.9 cm (11") and 35.6 cm (14"). The outer diameters of the small and large rod of each pair were 1.75 cm (11/16") and 76.3 cm (3"), respectively. The masses for each pair of rod lengths were 384, 525, and 666 g, respectively. The torques subtended at the grip by each pair were 431.3, 719.8, and 1162.9 N-m respectively.

4.2.2 Results

Subjects from the weight estimation group judged the narrower diameter rod to weigh more than the wider diameter rod. In the other group, subjects judged the narrower rod to be longer than the wider rod. The simple correlation coefficient between the perceived length and perceived estimates was higher (0.99) than with log force or log torque. The subjects' estimates of length were almost perfectly correlated with the weight estimates. Thus, we conclude that the percept-percept model explains the estimation of the perceived length of statically held rods best.

5. Discussion

Haptically teleoperated tasks are usually based on the contact paradigm, for example, inserting a peg in a hole. Another haptic manipulation task arises in the unconstrained grasping of tools, where we ask whether the human operator (or an autonomous robot system) can determine characteristics of a tool simply by holding it. This paper addresses a particular problem in machine and human perception concerned with acquiring the necessary information to determine the length of a gripped object by static contact. We believe the current task also poses interesting questions for a robot that must manipulate objects in the environment, whether
directly or through the use of a tool. With regard to machine perception, we address the "forward" problem, namely how can a machine perceive the length of a statically gripped rod? In contrast, the question posed of human perception addresses the "inverse" problem: what environmental properties determine or contribute to length perception of statically held rods?

A mechanical analysis of the system consisting of the gripper and the object was first performed using the general principles of statics. Here, the term "gripper" refers to either the hand or the end-effector of a robot. The results obtained from the mechanical analysis revealed that the length of a gripped object is indeterminate when the object is held perpendicular to the ground plane or when it is gripped at a single intermediate location. To overcome the latter limitation with regard to robotic perception, we proposed that two simultaneous and independent force-torque measurements be obtained.

With respect to robotic length perception, this result implied that existing gripper and tactile technologies were not adequate, indicating the need for further sensor development. We proposed a unique and novel sensor design based on the theory of thin plates, using strain-gauge technology. Some of the advantages of this plate sensor are as listed below:

1. The sensor is designed to establish direct contact with the environment. Since forces and torques are transduced directly from the parameters of contact interaction between the sensor and object, measurement error is minimized.

2. The design provides economical and simple alternatives for transducing forces and torques.

3. The proposed sensor is sophisticated in design, requiring few modifications for directly mounting on the inner sides of the robot gripper.

4. An experimental evaluation of the proposed sensor suggests that it can be effectively employed to perceive the length of an object that is statically gripped at an arbitrary location.

5. The sensor can be made physically sturdy to withstand rough handling.

The results of the static analysis were also extended to the study of human length perception. Based on the analysis of forces and torques, two different models of length perception were proposed. The psychophysical model uses the forces and torques acting on the hand to predict the length estimates directly in a single processing step, while the percept-percept model uses the forces and torques first to predict the perceived weight, which is then used to predict perceived length.

The first experiment focused on investigating the effectiveness of both the force-
torque and percept-percept models in predicting rod lengths. The results indicated
that perceived length could be predicted by both models remarkably well, although
perhaps the percept-percept model based on weight percepts was marginally better.
The direct assessment of perceived weight was achieved in the second experiment
by successfully inducing a static version of the haptic size-weight illusion. This
technique allowed us to maintain the values of the mechanical variables constant,
while altering the perceived weights of rods of equal length and weight but different
diameters. As predicted, the manipulation produced a corresponding change in the
length estimates: the narrow rod felt both heavier and longer than the
 correspondingly wider one. The phenomenological reports obtained from subjects
also suggested that the length estimates could be derived from the estimates of
weight. The weight percept proved to be a single variable that varied in remarkably
similar fashion to the length percept for the rods of different materials across all
three orientations (in the first experiment) and for rods of all sizes (in the second
experiment). The second experiment pitted the force-torque model against the
percept-percept model by inducing a haptic size/weight illusion: the results indicated
that the perceived weight estimates could account for 98.4% of the variance in the
length estimates. Overall, the percept-percept model can account for length estimates
of rods varying in material, orientation, length and diameter.

The results from these parallel robotic and human psychophysical studies further
suggest that the highly accurate forces and torques sensed by the robot may need to
be appropriately altered when delivered as inputs to the operator’s hand to counteract
the biases documented in human length perception. Otherwise, the operator may
perceive the rod length to change when the robot gripper alternates between tools
of different materials, and when it alters tool orientation. Hence, providing length
information directly in the form of forces and torques at the wrist and elbow of the
human operator - without compensating for the effects of relevant perceived
parameters - is likely to lead to considerable perceived distortion of a rod that is
grasped by a remote teleoperated robot.

Table 1: Mass and length of objects used to experimentally evaluate the plate sensor

<table>
<thead>
<tr>
<th>Material</th>
<th>Total Mass</th>
<th>Length (left)</th>
<th>Length (right)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pine</td>
<td>229.2</td>
<td>60</td>
<td>1060</td>
</tr>
<tr>
<td>Aluminum</td>
<td>238.6</td>
<td>225</td>
<td>120</td>
</tr>
<tr>
<td>Oak</td>
<td>447.1</td>
<td>510</td>
<td>350</td>
</tr>
<tr>
<td>Oak</td>
<td>796.0</td>
<td>895</td>
<td>650</td>
</tr>
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</table>
Table 2: Results of length perception from plate sensor

<table>
<thead>
<tr>
<th>Actual Length (mm)</th>
<th>Mean perceived length (mm)</th>
<th>Mean Corrected length (mm)</th>
<th>Mean % Error</th>
<th>Standard Deviation (mm)</th>
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</thead>
<tbody>
<tr>
<td>120</td>
<td>102.5</td>
<td>123</td>
<td>+2.5</td>
<td>1.14</td>
</tr>
<tr>
<td>225</td>
<td>223.5</td>
<td>211</td>
<td>-6.22</td>
<td>7.21</td>
</tr>
<tr>
<td>350</td>
<td>433.8</td>
<td>374</td>
<td>+6.86</td>
<td>4.34</td>
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<tr>
<td>510</td>
<td>582.3</td>
<td>497</td>
<td>-2.55</td>
<td>1.35</td>
</tr>
<tr>
<td>650</td>
<td>781.0</td>
<td>670</td>
<td>+3.08</td>
<td>2.22</td>
</tr>
<tr>
<td>895</td>
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<td>-4.69</td>
<td>2.06</td>
</tr>
<tr>
<td>1060</td>
<td>1199.8</td>
<td>1069</td>
<td>+0.85</td>
<td>3.70</td>
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Table 3: Length, mass and values of the relevant mechanical variables pertaining to objects used in the human experiment

<table>
<thead>
<tr>
<th>Material</th>
<th>Length (mm)</th>
<th>Total Mass (kg)</th>
<th>Force (N)</th>
<th>Torque (vert) (N-mm)</th>
<th>Torque (45⁰) (N-mm)</th>
<th>Torque (hor) (N-mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pine</td>
<td>305</td>
<td>0.124</td>
<td>1.216</td>
<td>0</td>
<td>76.0</td>
<td>107.5</td>
</tr>
<tr>
<td>Acrylic</td>
<td>305</td>
<td>0.171</td>
<td>1.678</td>
<td>0</td>
<td>144.4</td>
<td>204.2</td>
</tr>
<tr>
<td>Aluminum</td>
<td>305</td>
<td>0.304</td>
<td>2.982</td>
<td>0</td>
<td>338.0</td>
<td>478.0</td>
</tr>
<tr>
<td>Pine</td>
<td>457</td>
<td>0.144</td>
<td>1.413</td>
<td>0</td>
<td>143.2</td>
<td>202.5</td>
</tr>
<tr>
<td>Acrylic</td>
<td>457</td>
<td>0.224</td>
<td>2.197</td>
<td>0</td>
<td>301.8</td>
<td>426.8</td>
</tr>
<tr>
<td>Aluminum</td>
<td>457</td>
<td>0.418</td>
<td>4.101</td>
<td>0</td>
<td>686.5</td>
<td>970.8</td>
</tr>
<tr>
<td>Pine</td>
<td>610</td>
<td>0.169</td>
<td>1.658</td>
<td>0</td>
<td>244.3</td>
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References


