The Length Perception via Dynamic Touch with Undefined Inertia

A DISSERTATION

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Thomas A. Stoffregen, Advisor

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Abstract

Perception of object length arising from manual wielding is powerfully influenced by the inertia tensor of wielded objects (e.g., Solomon & Turvey, 1988). In solid objects the inertia tensor is a fixed quantity which can be computed, and whose responses to torques are stable. By contrast, when I lift a glass to drink, I am wielding (in addition to the glass) a liquid, whose dynamics (including the inertia tensor) vary as a function of movement. In this study I asked whether judgments of object length during manual wielding would be influenced by the presence of liquid mass in the wielded object. In Experiment 1, the type of weight was manipulated (liquid and solid weights). In Experiment 2, I manipulated the type of weight and movement of liquid by orienting the cylindrical weight horizontally or vertically. In both experiments, judgments of length were strongly correlated with the weight position, and changing dynamics of liquid weights did not reduce the accuracy of length perception. On the basis of these results I argue that the inertia tensor is not likely single unique mechanical information to be detected for the haptic length perception.

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Introduction

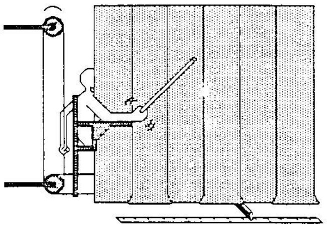
When I was growing up, I practiced kendo, Japanese martial art of sword fighting. One of the hardest things about kendo was everything had to be accurate and precise. In order to earn the points, I had to strike an opponent's particular body parts with particular part of the shinai. Therefore, I had to maintain a keen awareness of the tip of the shinai (mocked sword made of bamboo) throughout the match. Worst of all, I had to wear all the protective gear, which include a helmet that severely obstructed the field of view. It was very difficult to even to see my hands with the helmet. It was not unusual to see people, including me, during the match, slightly wield the shinai up and down to "feel" the length of shinai. Although only a shinai's handle was grasped, the simple wielding motion gave an impression of spatial dimension of shinai. It was very intuitive to wield the shinai to perceive its spatial dimension, but how was I able to haptically perceive such information? Variety of object properties, not limited to length, such as texture, weight, and hardness can be perceived by manual exploration. There are also variety of modes of manual exploration are available including hefting, wielding, hammering, rubbing, etc, and these are part of everyday actions.

Haptic Perception: Dynamic Touch

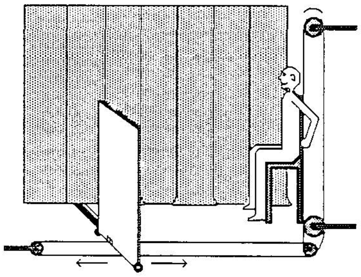
In general, haptic perception can be characterized by three different forms of touch, cutaneous, haptic, and dynamic touch. Cutaneous touch is referred as haptic experience when the objects contact the skin, and haptic touch is experience when the hands are moved over the surfaces. In general, references to touch are these two. Dynamic touch refers to haptic perception that gives us perceptual access to properties of objects through the combination of stimulation of the receptors in the skins and articulation of joints (Gibson, 1966). Although it is not apparent, dynamic touch is most commonly used haptic touch, and dynamic touch enabled me to perceive the length of shinai. In general, the length perception through dynamic touch has been studied extensively followed by the landmark study by Solomon and Turvey.

Landmark Study by Solomon and Turvey

Series of studies by Solomon and Turvey (1988) examined the haptic perception of object length. In their studies, participants were asked to wield the rod with right arm that was occluded by a curtain. A planar surface mounted on a dolly was visible to the participants, and their task was to judge the reaching distance of the rod by positioning the planar surface to the point where the tip of the rod would touch the surface (Figure 1). In their first experiment, the length of aluminum rods was manipulated ranging in length from approximately 0.3 m to 1.2 m in increments of 0.15 m. Total of seven rods were used, and all rods had equal radius (0.635 cm) and density (2,700 kg/cm^3). The perceived length of rods was a linear function of the actual length of rods, and participants tended to overestimate the shorter rods and underestimate the longer rods. In the following experiments, material of rods (experiment 2), wielding body position (experiment 3), and frequency and amplitude of swing (experiment 4) were manipulated. Perceived lengths maintained the linear relation to the actual length and were comparable to the result from the experiment 1.



EXPERIMENTER'S VIEW



SUBJECT'S VIEW

Figure 1. Experimental setup from Solomon & Turvey (1984).

Since the haptic perception of differences in the length of rods was constant across experiments 1 – 4, Solomon and Turvey suggested that mechanical force, moment of inertia (*I*) was likely influencing the length perception, not rod length itself. Moment of inertia (*I*) is the rod's resistance to being rotated, and Solomon and Turvey believed that the moment of inertia I_1 which is the moment of inertia about x-axis (Figure 2) was the unique source of length perception.

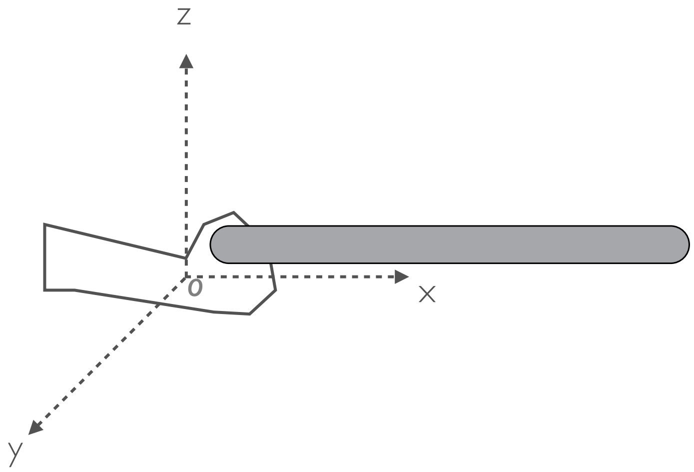


Figure 2. A rod wielded at a fix point *o* (wrist) around perpendicular to the longitudinal axis (x-axis).

I_1 can be calculated as, $I_1 = \frac{m}{12}(3a^2 + L^2) + m(r^2 + d^2)$ where m is rod of mass, L is length of rod, a is radius of the rod, r is the distance between center of mass and the end of the rod, and d is the distance between wrist (defined as rotation point) and center of the rod. I_1 can increase or decrease by increasing or decreasing an object’s mass, and if I_1 is responsible for the length perception, it would make sense that length perception was not affected by the material of rods, body orientation, and amplitudes or frequencies of wielding. I_1 also increases as the center of mass (CM) moves further away from the rotation point and deceases as CM shifts closer to the rotation point. To confirm I_1 is a base for the length perception, I_1 was manipulated by attaching a small aluminum block (m = 127 g) to the aluminum rods. The block was attached at three different locations (1/4, ½, and ¾ of rod length) for each of three different rod lengths (0.61 m, 0.76m, and 0.91 m). When the block was attached to the further from the wrist, perceived length was greater (experiment 5 – 6). I_1 increased as the aluminum weight was attached to further distal to the rotation point of rod (in their study, the fixed rotation point was defined at wrist). In addition, when the participants held the rod at different positions, perceived length was greater when the participants held the rod further from the center of rod (experiment 7 – 8).

Perceiving shape by dynamic touch

Burton, Turvey, and Solomon (1990) also examined if it was possible for us to perceive the shape of objects via dynamic touch. In their series of experiments, participants were asked to compare the objects to determine if wielded objects were same (experiment 1) or different (experiment 2). In experiment 3 and 4, participants were asked to match the wielded objects (invisible) and objects on the table (visible). Five different shapes (hemisphere, cylinder, parallelepiped, cone, and pyramid) were used, and size of wielded objects were different from the visible objects. Burton, Turvey, and Solomon (1990) computed the greatest and least principle moments of inertias for each shape, and the ratio of greatest/least was referred as inertia index. The participants were able to distingue the shapes based on the inertia index, but when the shapes had similar inertia indexes, they could not differentiate them. The results indicated that participants were able to detect a pervasive property of object shape, but not properties localized at salient vertices, edges, and faces. In other words, participants were able to tell how wide or narrow the object was, but not able to detect if the object had round or square edge.

Heaviness perception

It is well known phenomena that when two objects with equal masses, but different volumes/sizes, larger object with same mass is usually perceived lighter. Amazeen and Turvey (1996) proposed that this so called, size-weight illusion could be predicted by the inertia model. By changing the width and length of objects while keeping the objects' volume constant, they manipulated I_1. When there was no visual information, perceived heaviness decreased with an increase in width and increased with an increase in length.

Liquid as medium

Pagano and Donahue (1999) asked participants to wield a rod in the air or in the water and found on average, the perceived length was 5.5cm longer when participants wielded a rod in water compared to when they wielded it in air. Since the density of water is 830 times more than air, water resistance was taken as object's inertia and disturbed the length perception. However, when the participants were informed about the medium of wielding in the beginning of trials, they were able to differentiate the drag and inertia tensor, and the perceived lengths were equivalent between wielding in water and in air (Pagano & Cabe, 2003).

The Present Study

Recall that the inertia tensor is characterized as a resistance to the rotation of the rigid object. Calculating inertia tensor is based on the assumption that the rod has continuous mass distribution. For this reason, the rods and weights being manipulated in the dynamic touch studies have been always solid objects, and inertia tensor hypothesis is exclusively applied to the solid object. However, in everyday activities, dynamic touch is a common form of perceptual activities, and they are not limited for just rigid objects, but also non-rigid objects such as drinking a bottle of water. Furthermore, people with visual impairment are still able to perceive the size of the cup and drink from it without a spill. Thus, the question rises, how do we perceive the properties of non-rigid object when the visual information is not available? Can we still perceive the length of object via dynamic touch even though the inertia tensor will not be well defined with non-solid object?

To answer this question, non-rigid body was used as weights for the series of two experiments. In experiment 1, the solid and liquid weights were attached to a wooden rod, then participants were asked to wield the rod and judge the length of the rod. I used hollow plastic sphere half-filled with water as a liquid weight and a baseball as a solid weight. The mass distribution of the liquid weight continuously changed during the wielding movement, and this resulted continuous shifting of the center of mass. Consequently, changes in the center of mass would vary the inertia tensor. If the inertia tensor is the sole basis for length perception, then continuous changes in the inertia tensor would have significant impact on perceiving an object's length. In the experiment 2, I manipulated the liquid motion by using the hollow cylinders to create weights. The motion of liquid in the cylindrical encloser was varied by changing the orientation of the long axis relative to the plane of wielding movement in the way the same wielding movement generated the different liquid dynamics.

This study was the first dynamic touch study that used non-rigid material to examine the length perception. Due to complex physical event associated with liquid weight, I did not attempt to evaluate the perceived length that was based on the moment of inertia. The purpose of this study was to evaluate if people could perceive the length of non-rigid objects in the same fashion as rigid objects.

Experiment 1

Experiment 1 addressed whether or not liquid weight would alter the haptic length perception. For the solid objects, the inertia tensor is believed to be the solo underlying principle for the length perception. However, with liquid weight, the center of mass would be constantly changing every time the object is wielded. Changing the center of mass would significantly impact the value of inertia tensor, therefore, length perception with liquid weight may differ from one with solid weight. My assumption was that even though liquid dynamics would continuously change the mass distribution of weight, perceived length would not be affected by such change because haptic length perception is not solely specified by the moment of inertia. It was important that the liquid be free to move relative to the rigid rod that participants wielded. This relative motion would not be possible if the liquid completely filled its container. Accordingly, I used containers that were approximately half full, such that participant’s wielding movements would produce a sloshing sound that would impact haptic stimulation and shift the center of mass as the rod was wielded. My methods and procedures were closely modeled based on Solomon and Turvey (1988).

Methods

Participants

Ten undergraduate students (5 men, 5 women) at University of Minnesota participated in the study. The students were recruited from Kinesiology courses, and they were naïve regarding the purpose of the study. Students were volunteers who received extra credit for their participation. Each participant reported no history of neurological or skeletal-muscular disorders or any previous injuries.

Apparatus and experimental setup

Participants were asked to wield wooden dowels with weight attached (Figure 3). The dowels were 90 cm in length, 1.25 cm in diameter, and weighed 80 grams. I attached weights to the dowels in five different locations, measured from the end that was gripped: L1 = 23 cm, L2 = 34 cm, L3 = 46 cm, L4 = 57 cm, and L5 = 69 cm. All weights were spheres with a diameter of 10 cm and total weight of 180 grams. The solid weight was a regulation softball. The liquid weight was a hollow plastic sphere weighing 40 grams. The sphere contained 140 grams of water, which filled it about halfway, thereby permitted free movement of the water in response to wielding movements. The combined mass of wooden dowel and the attached weights was 260 grams.

A black curtain was used to partition the experimental space. The participant was seated on a height adjustable stool and placed his or her right arm through a hole in the black curtain (Figure 1). A table was placed on the experimenter's side of curtain, and the participant was asked to adjust the position of their arm so that the elbow was positioned by the side of the chest and the wrist was aligned with the edge of the table. Once the participant adjusted the arm position, he or she was asked to fix the elbow against the table.

Throughout the experiment, the wooden dowel was occluded from the participant’s view. A square of grey cardboard that measured, 60 cm × 125 cm, was attached to a dolly, and the dolly was connected to a system of ropes and pulleys.

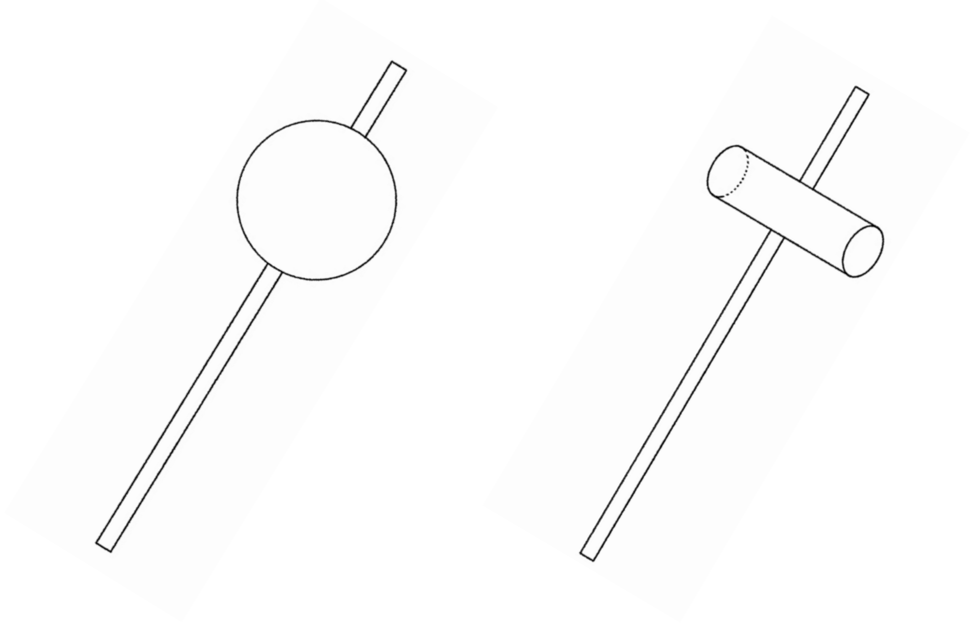


Figure 3. Right: the wooden dowel with weight attached used in Experiment 1. Left: the aluminium rod with cylindrical weight attached used in Experiment 2

Procedure

During the trials, participants were handed the wooden dowels with solid or liquid weight attached to the one of five locations by the experimenter. Participants were asked to judge the maximum distance reachable with the dowel (a point where the dowel would touch the target), and to express their judgments by using the rope to slide the target to the appropriate position. A scale was placed alongside the dolly on the experimenter's side, so that the experimenter could record the target position for each judgment. The instructions for the participants were as followed:1. Feel free to wield the dowel in any direction and at any speed in order to feel the length of dowel, 2. To take as much time as needed to express their perceptual judgment, 3. To maintain a firm grip of the dowel and not to re-grip or move the dowel within the hand, 4. To maintain the arm position throughout the trials. In other words, the wielding was limited to rotations around the wrist, 5. Avoid touching the curtain, 6. Feel free to continuously adjust the dolly throughout the trials. The experimenter demonstrated the task using a rod that was not used in the actual trials. This demonstration rod had different length, diameter, material, weight, and shape from the dowels used in the trials. After the demonstration, the participants were seated and were not able to see the experimenter's side of the room until all trials were completed. In the beginning of trial, the experimenter handed the dowel with the liquid or solid weight attached to the one of the five locations. During the trials, the experimenter monitored the participant's arm movement to ensure he/she was following the instruction. If the participant hit the curtain, the trial was repeated, and the judgement data from the repeated trial was used instead of the data from the initial trial. There were no practice trials, and throughout the trials, the participants were not given any feedback on the accuracy of their judgements. Experimental sessions were approximately 30 minutes in duration. Once participant was satisfied with the judgment, the trial was ended, and the participant passed the dowel to the experimenter. At the end of each trial, the experimenter measured the distance between the edge of table where the participants rested their wrist and the cardboard that was attached to the dolly. Each condition was repeated three times, totalling 30 trials, and the order of conditions were randomized and counterbalanced. Participants were permitted to take a break if they felt fatigued, or for any other reason. I used a 5 (weight location) x 2 (solid versus liquid) x 3 (trials), within-participants design.

Results & Discussion

A 2 (type of weight) x 5 (weight position) x 3 (trials) repeated measures ANOVA revealed significant effects for weight locations, F(4, 36) = 31.9, p < .001, η^2 = .40 (Figure 6). Effect size was estimated by using η^2statics, and the value of .40 indicates that 40% of the variance is accounted for by weight position.

The average perceived lengths of the rod for each participant are shown in Figure 4, and Figure 5 shows the average perceived length of solid and liquid weights for each weight location. For the solid weight, the average perceived length for L1, L2, L3, L4, and L5 were, 60.9cm, 69.5cm, 75.9cm, 81.4cm, and 88.7cm respectively. The average perceived lengths for liquid weight were 57.8cm, 65.5cm, 70.5cm, 78.4cm, and 88.7cm respectively. This indicates that although perceived lengths were tended to underestimated for all weight positions comparing to the actual length, the subjects were able to differentiate the location of the weights in both liquid and solid weight. The trend analysis revealed that there was a strong linear relation between perceived length and weight position (solid weight: $y = 6.7x + 55$ $R^2 = 0.99$, liquid weight: $y = 7.5x + 50$ $R^2 = 0.99$).

There was no significant effect for type of weight. In addition, there was no significant effect for interactions.

The absence of a main effect for solid vs. liquid and the absence of a significant interaction between weight location and material suggests that subjects were influenced by the location of both liquid and solid weights. This raised the question that why the length perception did not influence the types of weight. One of the possible explanations is that the liquid movement was not significant enough to have an impact on the length perception. The change in the moment of inertia was still in the within range of the solid weight's moment of inertia and did not reach the threshold to shift the length perception. Thus, in the experiment 2, liquid weight was designed to generate more of a sloshing sound by using the cylindrical container.

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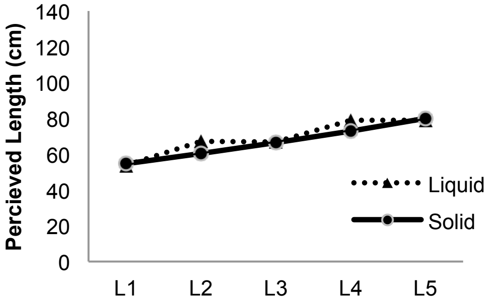

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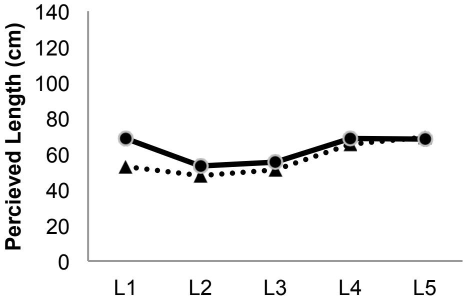

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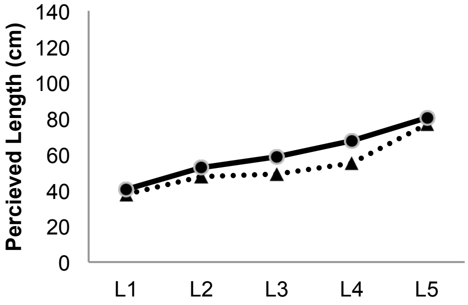

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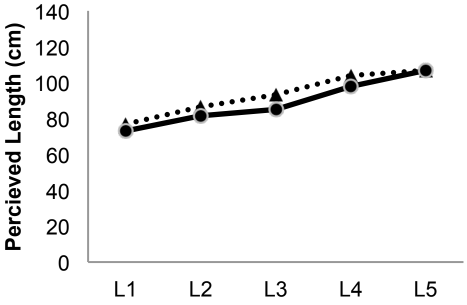

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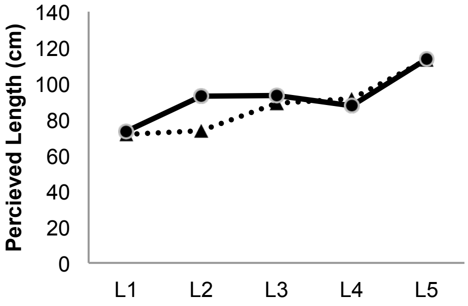

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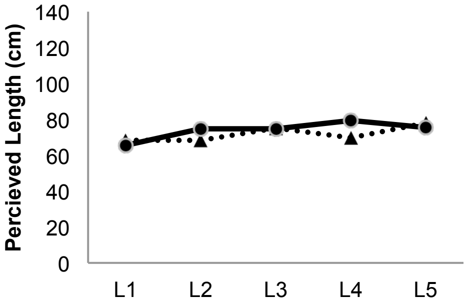

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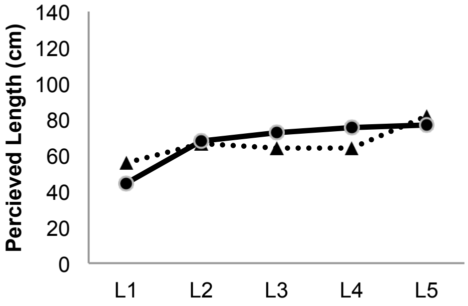

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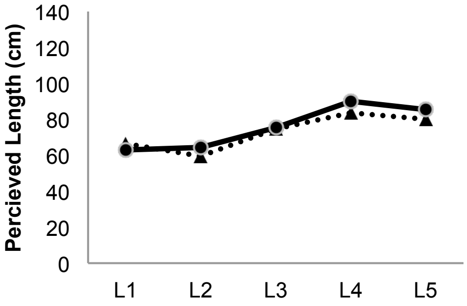


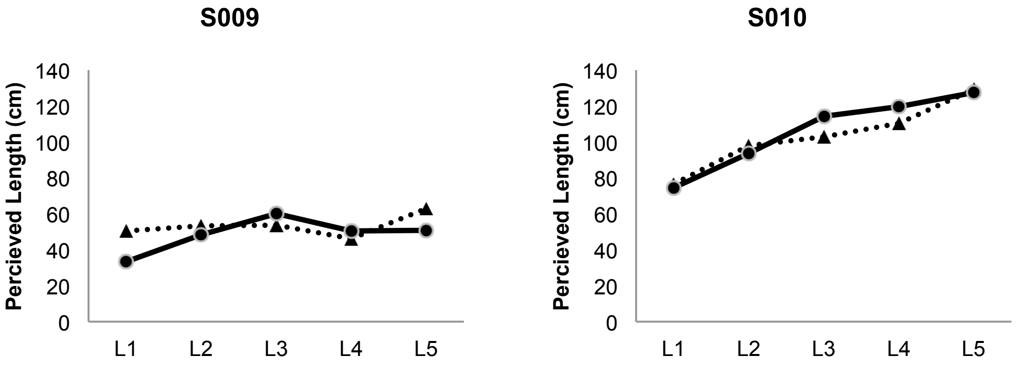
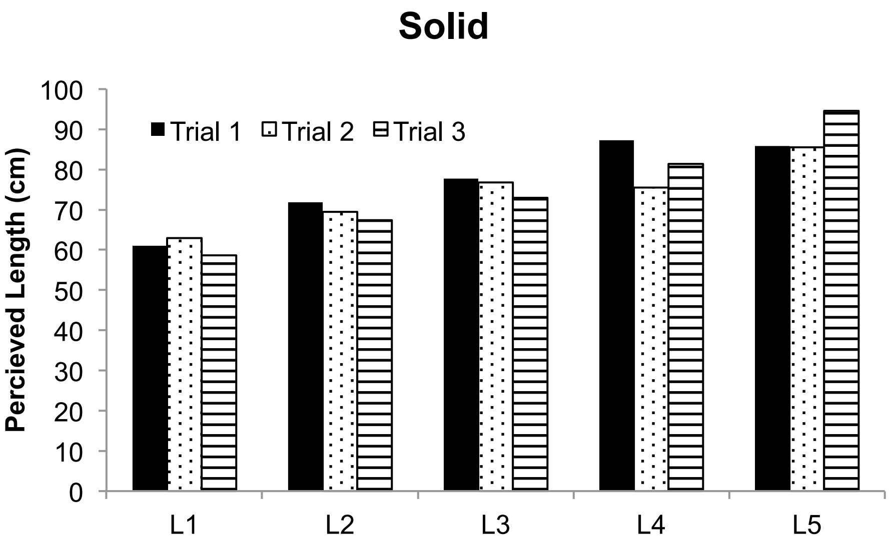


Figure 4. Perceived length of solid and liquid weights as a function of weight location, L1, L2, L3, L4, and L5 for each subject.



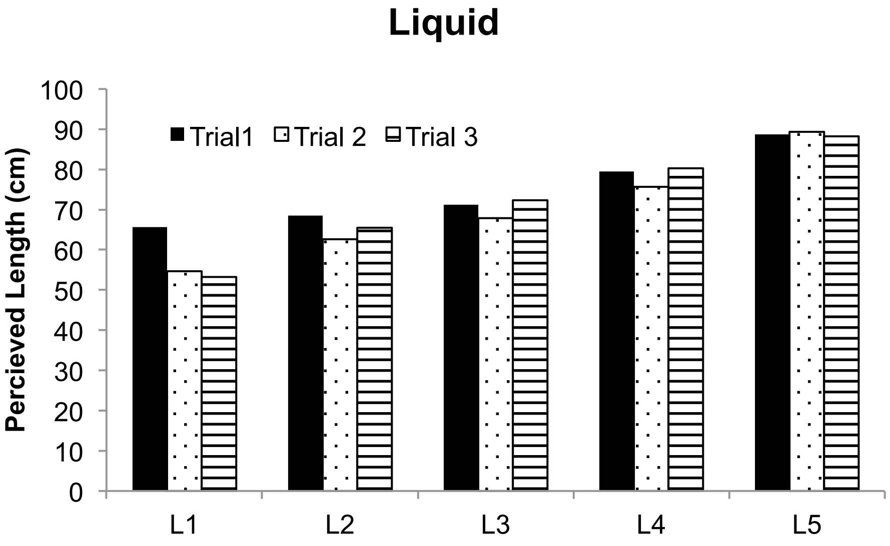


Figure 5. Average perceived length of solid and liquid weights for each weight location.

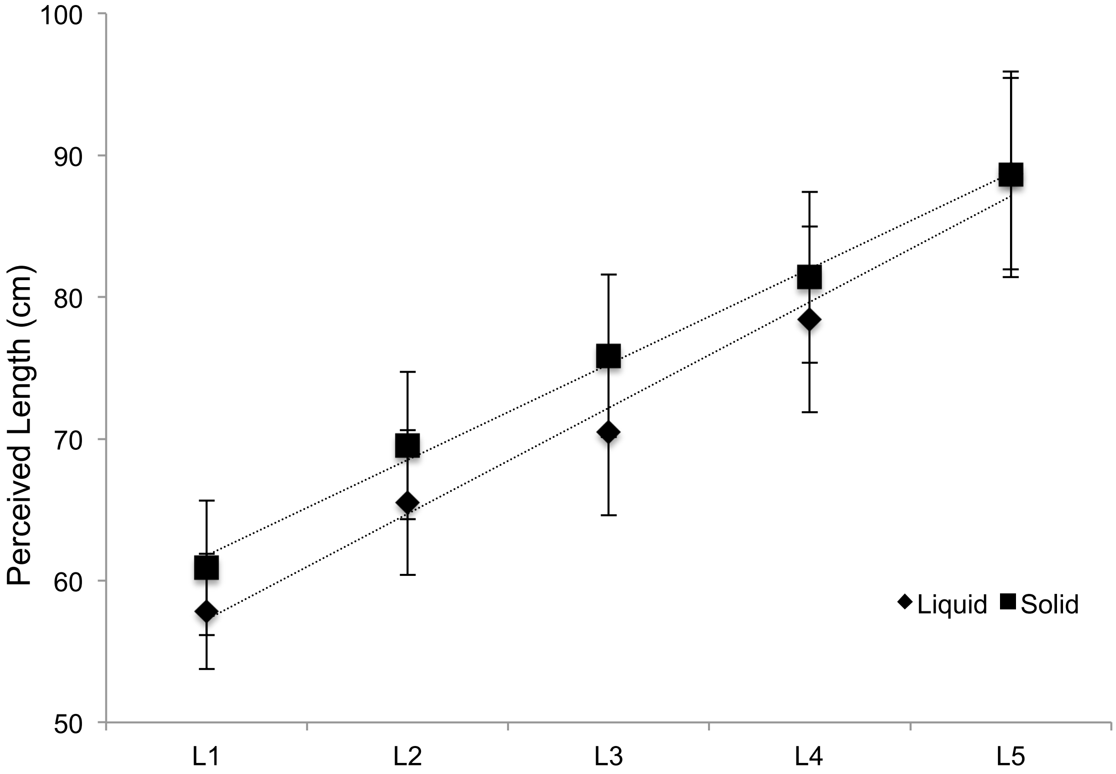


Figure 6. The average perceived length as a function of weight location, L1, L2, L3, L4, and L5. Error bars represent standard errors.

Experiment 2

In the experiment 1, I did not find significant effect of the types of weights. Both weights were spheres, such that motion of the liquid (relative to the container/rod) would be equivalent for rotations of the rod around any axis. In the experiment 2, my goal was to vary the relation between wielding movements and liquid motion (and, consequently, the relation between wielding movements and haptic stimulation). To do this I used weights that were cylindrical (Figure 1: right), and I varied the orientation of the cylinder's long axis relative to the plane of wielding movements.

Methods

Participants

12 undergraduate students (three male, nine female) at University of Minnesota participated in the Experiment 2. The students were recruited from the intermediate Kinesiology course, and they were naïve regarding the purpose of the study and did not participate in the Experiment 1. Students were given the extra course credit by participating in the study. All participants reported no history of neurological or skeletal-muscular disorder or any precious injuries.

Apparatus and experimental set-up

In Experiment 2, participants wielded aluminum rods (Figure 3). The rods were 90 cm in length, with diameter of 1.9 cm, and weighing 165 grams. I attached weights to the dowels in five different locations, measured from the end that was gripped: L1 = 23 cm, L2 = 34 cm, L3 = 46 cm, L4 = 57 cm, and L5 = 69 cm. The weights consisted of cylinders 15 cm in length with diameter of 10 cm and weighing 90 grams, cut from lengths of PVC pipe. Cylinders were filled with solids or liquids. For solid weights, the cylinders were filled with a mixture of polystyrene pieces and glass marbles, which were packed tightly so that they did not move (relative to the cylinder) when the rod was wielded. For liquid weights, 130 grams of water were added to the cylinder, which filled it about halfway such that the water was free to move (relative to the cylinder) when the rod was wielded. The ends of the cylinders were sealed with plastic caps weight 5 grams. The total mass of each weight was 395 grams.

The experimental setting was the same as in Experiment 1. In Experiment 1, some participants reported they could hear sloshing sound during the liquid weight trials. Therefore, in Experiment 2, I asked participants to wear a headphone throughout the trials to prevent them from hearing sloshing in the liquid weight conditions. During trials, white noise was played through the headphone, and the experimenter provided instructions to the participants through a microphone.

Procedure

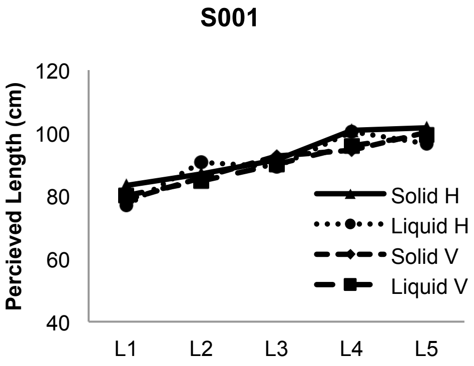
As in Experiment 1, participants were handed each rod and were asked to judge the length of rods by moving the cardboard panel back and forth by using the pulley system. The motion of liquid was manipulated by changing the orientation of the weight when the experimenter was handing the rod to the participants. Given the wielding movement would produce more motion of the liquid in the vertical condition than in the horizontal condition. The instructions to the participants were same as Experiment 1, except that participants were asked to only wield the rods along the sagittal plane (up-down wielding, no side wielding was allowed) to control the movement of the liquid within the cylinder. Before the trials, the experimenter demonstrated the procedure, using a demonstration rod that was not used in the trials. In the beginning of the trial, the experimenter oriented the weight horizontally or vertically and handed the rod to the participant. During the trial, the experimenter monitored the movement of rod and ensured the intended orientation was maintained. When the participant did not maintain the intended orientation of the weight, the trial was repeated. As in Experiment 1, participants were not given feedback about the accuracy of their judgments. Each condition was repeated three times for two different weight orientations for a total of 60 trials. The entire experiment approximately lasted 60 minutes. The participants were free to take a break anytime during the trials to avoid fatigue.

Results & Discussion

I conducted a 2 (types of weight) x 5 (weight position) x 2 (weight orientation) x 3 (trials) repeated measure of ANOVA on the judgment data. As in Experiment 1, the main effect of weight position was significant, $F(4, 44) = 40.98$, $p < .001$, $\eta^2 = .31$ (Figure 8). Average perceived lengths with horizontal and vertical weight orientations for all subjects are presented in figure 7. The main effect of orientation was also significant, $F(1, 11) = 8.19$. $p < 0.05$, $\eta^2 = .003$ (Figure 8, top). Participants perceived the rods to be longer when the weights were oriented horizontally than when their orientation was vertical. In addition, there was significant interaction between weight and orientation, $F(1, 11) = 6.37$, $p < 0.05$, but the effect size, η^2 was less than .001. Although the effects of orientation and interaction between orientation and type of weight were significant, those two variables only accounted for less than 1% of the variance combined. No other significant interactions were observed.

Simply inspecting the figure 7 shows differences in slopes and intercept among participants. The intercepts of the solid weight with horizontal orientation, liquid weight with horizontal orientation, solid weight with vertical orientation, and liquid weight with vertical orientation ranged from 50.41 to 88.14, 43.96 to 79.28, 45.38 to 85.77, and 38.64 to 85.95, and slopes ranged from -.91 to 8.94, 2.01 to 8.14, -1.37 to 8.92, and -.45 to 9.11 respectively. To evaluate the characteristic of regression line differences, I calculated the correlation between the slop of each participant and the within-cell standard deviation of each participant's perceived length for liquid and solid weight conditions with vertical or horizontal weight orientation. Highly positive correlation was observed for all four weight/orientation conditions (solid/horizontal: r = .9, liquid/horizontal: r = .97, solid/vertical: r = .95, liquid/vertical: r = .95). This means that the steeper regression line tended to have more dispersion, and the flatter regression line tended to go with less dispersion. Participants were able to distinguish the weight location, but some participants estimated the differences more conservatively, and others exaggerated the differences.

In Experiment 1, I observed the types of weight had no effect on the haptic length perception, and participants were able to differentiate the position of weight for both liquid and solid weights. It was possible that changes in the center of mass with liquid weight was not significant and had no impact on the length perception. To further examine this issue, cylindrical weights were used for Experiment 2 since such shape would be able to generate both large and small liquid movements depending on the orientation of the cylinder. However, again, the magnitude of liquid movement did not affect the length perception, and the participants were able to differentiate the locations of liquid weight as well as solid weight.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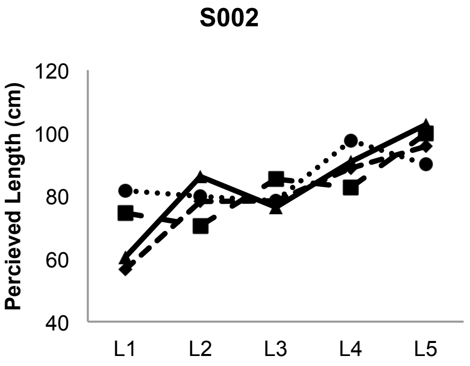
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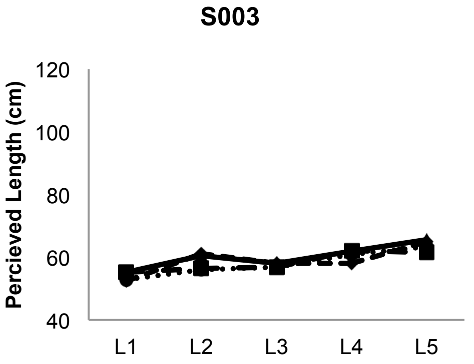
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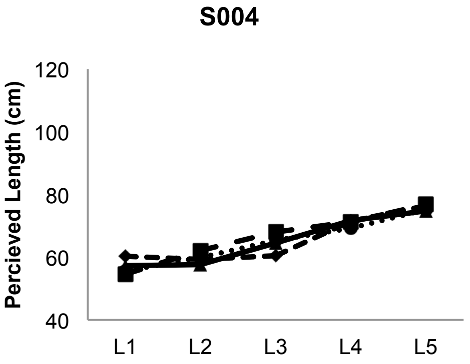
80
60
40
L1
L2
L3
L4
L5


S004
Percieved Length (cm)
120
100
80
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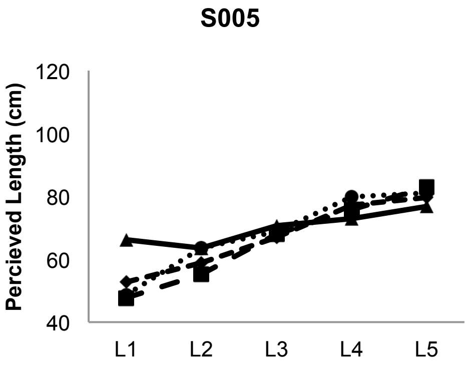
40
L1
L2
L3
L4
L5


S005
Percieved Length (cm)
120
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L1
L2
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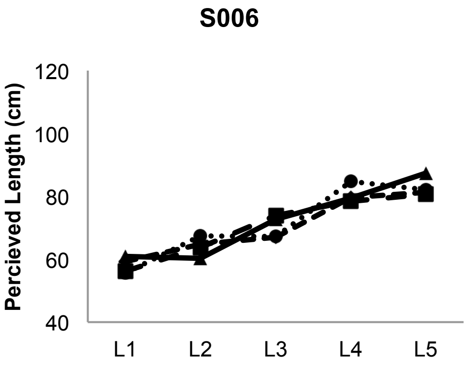
L5


S006
Percieved Length (cm)
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L1
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L5

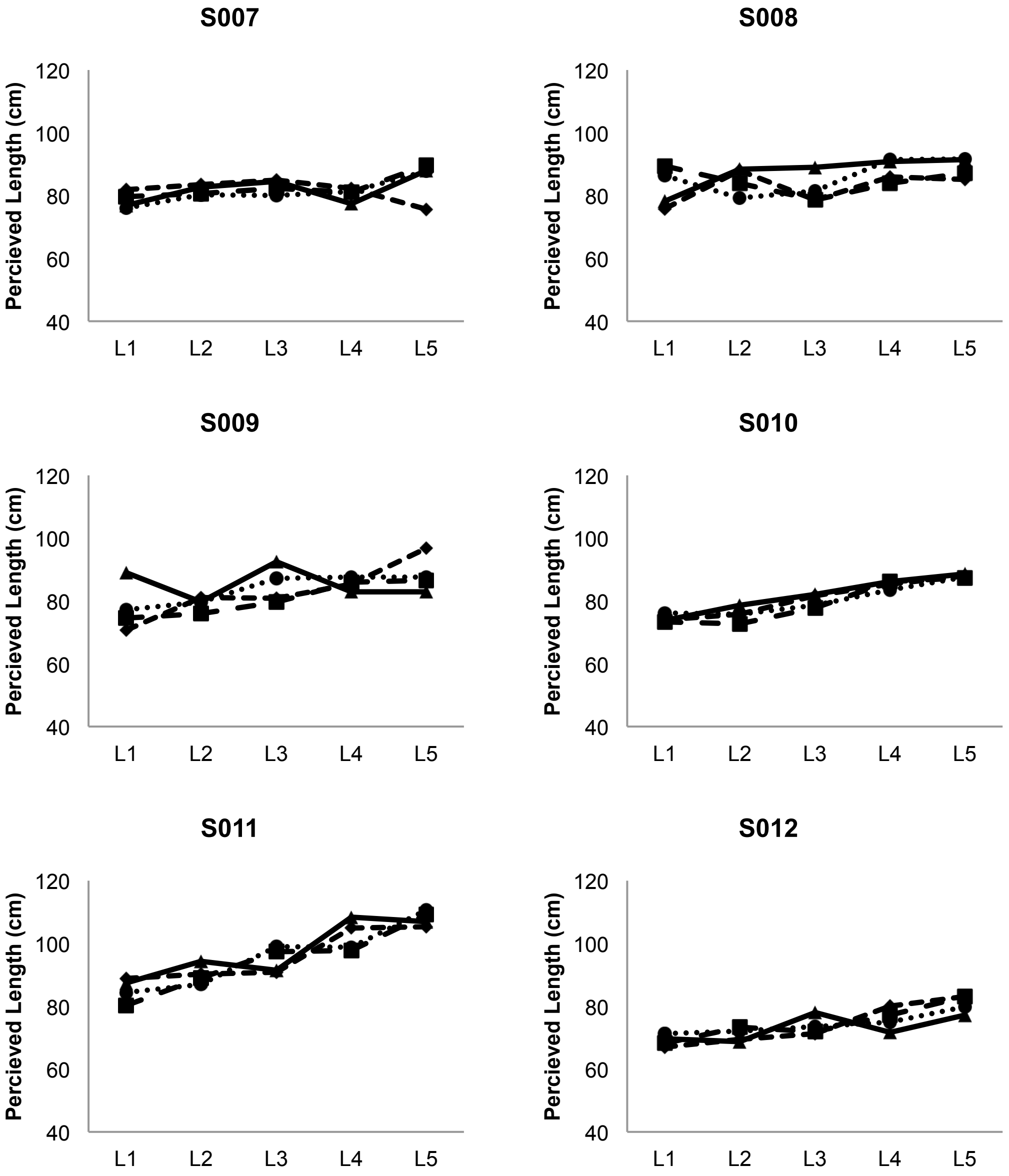

Figure 7. Perceived length of four conditions as a function of weight location, L1, L2, L3, L4, and L5 for each subject.

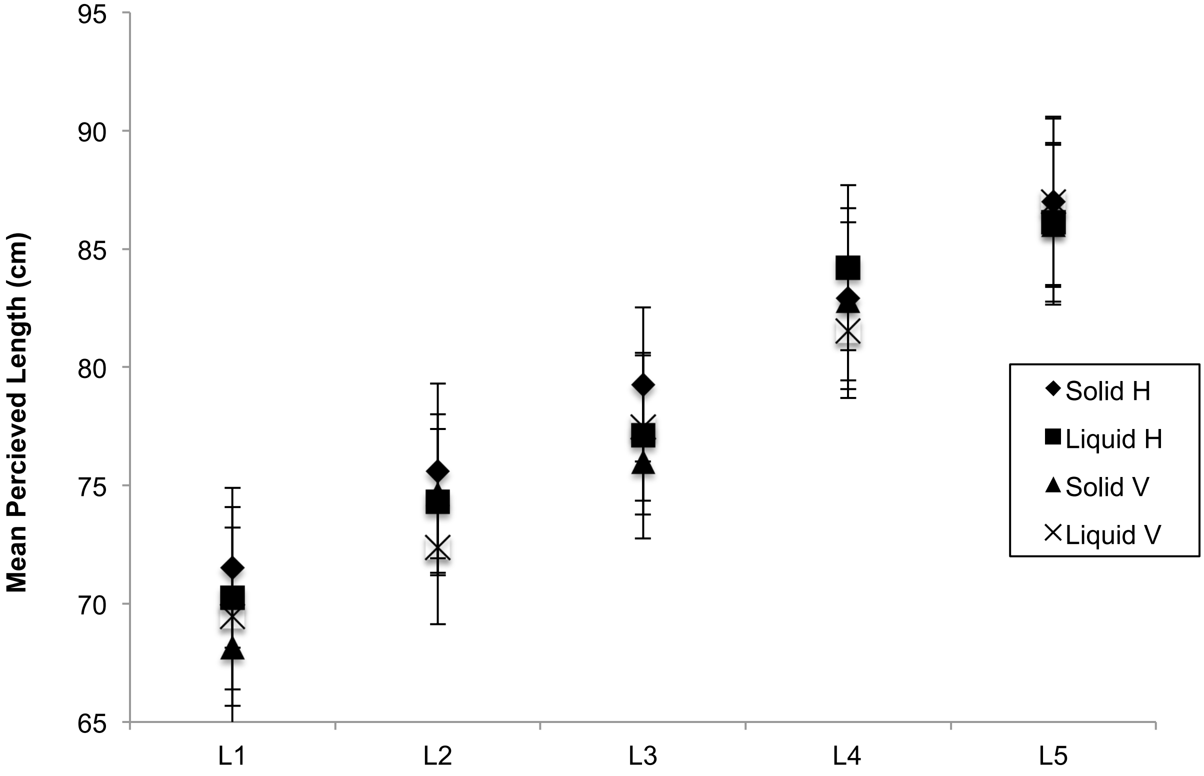

Figure 8. Average perceived lengths as a function of weight locations. Five data points for each condition (total of 20 data points). Error bars represent standard errors.

General Discussion

Although rotational inertia is only defined within the context of rigid body dynamics, and the inertia tensor hypothesis is exclusively applied to rigid objects, the purpose of this study was to determine whether or not the length of non-rigid objects could be perceived via dynamic touch. In Experiment 1, participants wielded a rod to which was attached a spherical container half filled with water. In Experiment 2, a cylindrical contained was used, which entailed differential motion of the liquid when rods were wielded in different axes. When weight was oriented vertically, the liquid could freely move within the 15 cm-long cylinder back and forth whereas with horizontal orientation, the movement of liquid was only limited approximately 7.8 cm. Thus, in the vertical orientation the liquid could have more vigorous back and forth motion than in the horizontal orientation. Most of all, in the vertical orientation liquid movement would be greater than in Experiment 1. It is extremely complicated to measure the rotational inertia with liquid weight since the center of mass constantly changes as a consequence of wielding. In the literature, the moment of inertia is the fundamental principle for length perception with rigid objects. This approach would predict that perception of liquid weights would differ substantially from perception of solid weights. However, in both of the present experiments this was not the case. Therefore, the results of the present study raise new questions about the nature of the information the supports haptic perception through wielding, not only in the context of liquid weights but in general.

Length perception with minimum movement of rod

Previous studies have argued that perceiving the length of rod, the wielding motion might not be required, and the rod length can be perceived by just holding the rod with minimum movement (Burton & Turvey, 1990; Carello et al., 1992). Stroop et al. (2002) further claimed that length perception by static holding is based on moment of inertia. They argued that even the object is held stationary, there is always small movement of object, and this small motion is sufficient to perceive the moment of inertia.

It is possible that participants perceived the objects' length when the objects were stationary with minimum movement. The motion of liquid would be minimum when the rods were stationary, and participants were able to detect fairly stable and defined moment of inertia.

Length perception from static moments?

Kingma et al. (2002) argued that since object's dynamics is fully characterized by the moments of mass distribution, moment of inertia is not the only mechanical information used for the length perception. When the rod was static, the other physical properties of rod was suggested to perceive the length of the rod such as static moment (Burton & Turvey, 1990 & Carello et al., 1992) or the combination of mass of rod and static moment (Chan, 1994 & Lederman et al., 1996). The static moment M is defined as the mass (*m*) times the distance (*d*) between the rotation point and the center of mass of the rod, M = *md*. Kingma, Beek and van Dieen (2002) argued that the previous research on the dynamic touch often neglected other mechanical forces and focused almost solely on inertia tensor. Moment of inertia I_1 is believed to be the principle mechanical force specifies the property of hand-held objects since Solomon and Turvey (1988)'s pioneer work on dynamic touch. However, they pointed out that I_1 is highly correlated with static moment, and previous studies failed to thoroughly evaluate the other mechanical forces such as static moment to establish the claim that the moment of inertia is the exclusive source of length perception. They argued that static moment is also independent of the object's orientation like inertia tensor, and hypothesized that static moment should be considered as the basis for the perception of the length not only when a rod is stationary, but also when a rod is wielded, and Kingma et al. (2004) designed special sets of rods enable to independently manipulate moment of inertia, static moment, and mass. This allowed them to differentiate the effect of moment of inertia and static moment without worrying about confounding covariation. When the rod was wielded, I_1 had a significant effect on the length perception, but also M was independently related to the length perception. For the stationary condition (horizontal holding), the length perception was exclusively correlated with M, and I_1 had no effect, and this finding was contrary to the study by Stroop et al. (2000) that claimed the rotational inertia was only unique source of length perception during the both rod wielding and holding conditions. In the previous studies, M was considered as additional information that was not capable of fully specifying the object properties, and the inertia tensor was the only source of information that was uniquely related to the length perception. However, their result showed that this was not true, and M alone was strongly related to the length perception as well as I_1. Their finding was confirmed by the later study (van de Langenbert, Kingma, & Beek, 2006).

If the moment of inertia is not the sole foundation of length perception, and static moment is also perceived via dynamic touch, type of weights would not be an issue because holding the object would be suffice to perceive its length. Kingma, Beek and van Dieen (2002) found the inertia tensor was highly correlated with the length perception, but also that length perception had a strong dependency on the static moment. Because both statistical models derived from inertia tensor and static moment well represented length perception (many previous studies have used simple and multiple regression analysis to construct the statistical models derived from the moment of inertia), it is very difficult to conclude the exclusivity of the model derived from moment of inertia on length perception. Kingma et al. (2002) argued that moment of inertia is often overestimation of coefficients in the regressions and will cause confusion over which invariants are really specifying the length perception. In addition, the static moment is covaried with $I_{1,}$ and it is almost impossible separating and comparing these two to determine each contribution to the length perception. Therefore, it is very likely that the participants were actually detecting static moment, but because of covariation between static moment and moment of inertia, the perceived length was highly correlated with moment of inertia.

In addition, since moment of inertia I_1 is computed with d (distance between center of mass and rotation point) to the power 2, whereas static moment M is computed with simply multiplying d, I_1 is more sensitive to change in the center of mass comparing to M. For liquid weight, the center of mass was dynamically changing whenever the rods were wielded, and this could cause the high fluctuations in the I_1. However, change in d was not reflected in the perceived length in both Experiment 1 and 2. This can be interpreted that participants may be not detecting I_1 to perceive the length, but rather detecting more defined M. However, I cannot confirm this assumption because I_1 is not measurable with liquid weight.

Multiplicity of mechanical information

Recently, it has been proposed that the length perception via dynamic touch is not solely depending on the inertia tensor or static moment. Static moment and combination of static moment and mass have been shown to be highly correlated with the haptic length perception not only when the object is stationary, but also when the object is in motion (Kingma et al, 2004 & 2006; van de Langenberg, 2006). Consequently, the consensus among the dynamic touch researchers appears to be there is no singular invariant information to perceive the object length through dynamic touch.

No significant main effect of weight type can be explained if inertia tensor alone was not based for the length perception. My assumption is that dynamic touch judgments including length perception consist from multiple mechanical information such as inertia tensor, static moment, mass, and gravitational force, and which force to be used in order to perceive the object length is context dependent. My approach to dynamic touch is somewhat similar to dynamical system approach to motor control. In dynamical system approach, the action can be defined by the macro level variables, called order parameters, and coordination between those variables is necessary to accomplish the intended action (Thelen & Smith, 1994). According to this approach, multiplicity of order parameters are emphasized, and taking snap shot of single parameter does not provide full structure of given action. Since there are mounting evidences of multiplicity of mechanical information in dynamic touch judgments, perceiving the length of object can be achieved by detecting them, and these information are coordinated by task (intention) or environmental factors such as different type of weights or different setup for the action. If this assumption is correct, it makes sense that I did not find a significant effect of weight type because the moment of inertia is like one of the order parameters, and length perception is not exclusively based on the moment of inertia.

Orientation of rods

Pagano and Turvey (1993) examined the object orientation and length perception. In their study, the cross shape object was used (Experiment 1) and its orientation was manipulated vertically or horizontally. They did not find any significant effect of orientation on the perceived length. Therefore, I expected no effect of weight orientation for the solid weight, but a significant effect with liquid weights. I found a significant effect of orientation and significant interaction between orientation and weight.

Possible future studies

In this series of study, non-rigid body was used for the first time as a weight. Although the inertia tensor was dynamically changing during the rod wielding, I found no significant main effect of the type of weight on the length perception in the both Experiment 1 and Experiment 2. These results indicate the inertia tensor might not be the exclusive information for the length perception. To further confirm this claim, it would be interesting to manipulate the density of liquid and examine how the length perception would be affected. For example, the mercury's density is more than 13 times higher than water, and change in the moment of inertia will be greater if mercury is used for the liquid weight than liquid weight with water.

Many dynamic touch studies involved the length perception found no effect of exploratory behaviors on the length perception. Manipulation of exploratory behaviors such as frequency of wielding (Solomon & Turvey, 1988), amplitude of wielding (Solomon & Turvey, 1988; Pagano, Fitzpatrick, & Turvey, 1993), and body orientation (Solomon & Turvey, 1988) had no affect on the judgment of object length. These results led to the conclusion that haptic length perception is independent from the exploratory behaviors. Recent evidence suggests that dynamic touch judgments are constrained by exploratory behaviors. For example, length perception by different wielding styles such as static holding or vigorous wielding is associated with different mechanical forces. Also, complexity of exploratory behaviors is also constrained by the intention to perceive particular property of objects (Michaels et al., 2007). Therefore, examining how liquid-specific exploratory behaviors are used to perceive not only object length, but also heaviness and amount of liquid contained as a weight will be interesting. Riley et al. (2002) were able to quantify the differences in the exploratory behaviors across the different perceptual intentions by applying the recurrent quantification analysis to the movement data. Changes in the recurrent structure was observed by changing the intention to perceive the length of object to perceive width of object.

Only a few participants noticed that a liquid weight was used . Most participants had no idea they were wielding liquid weights. Participants were asked to judge only the length of the rods and, typically, were not aware either that there were attached weights, or whether the weights were solid or liquid. By contrast, Jansson, Juslin, and Poom (2006) found that haptic exploration allowed perceivers to distinguish liquid and solid substances and to detect the amount of liquid in a vessel. Critically, however, in that study participants were aware of there would be liquid or solid substance in the vessel. Therefore, different intentions (perceiving the object length or amount of liquid in the vessel) could specify different properties of an object. It seems likely that exploratory behaviors would be significantly different if participants were asked to perceive the length of rod with liquid weight as opposed to perceiving the amount of liquid in the attached weight.

Perceiving the length of objects with liquid weight may be based on how the moment of inertia of the rod changes while during wielding comparing to detecting unchanged moment of inertia with solid weight. Using cylindrical weight or hollow plastic sphere which were symmetrical shapes did generate the dynamic change in the moment of inertia, but the rate of change in the inertia might be predictable due to the symmetrical shape of weight, and perceivers were able to pick up the change and specify the object properties. Thus, generating the less predictable liquid movement by using a asymmetrical weight may have different constraints of the exploratory behaviors and could led to disturbance in specifying the property of object.

In the current study I focused on how length perception was affected by the continuously changing inertia tensor. I questioned whether haptic length perception is solely based on the inertia tensor. The perceived lengths were significantly affected by the liquid weights in a linear fashion consistent with the inertia tensor hypothesis, despite the fact that in the liquid weight condition, the inertia tensor was either highly complex or not defined. Additionally, I did not find a significant difference in perceived length between type of weights in both Experiment 1 and 2, and these results indicated that it is unlikely that the inertia tensor is unique mechanical force which specifies the length perception. Then, I proposed the dynamic touch judgments consist from the multiple macroscopic variables, and constraints such as intentions assemble and coordinate these variables to generate perceptual judgment. I also proposed future studies that will help to confirm my assumption.

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