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ORIGINAL PAPER

Perceptually salient haptic rendering for enhancing kinesthetic perception in virtual environments

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Abstract Kinesthetic or dynamic touch involves the use of muscle sensitivity to perceive mechanical properties of objects that are gripped in the hand and wielded in space. Many previous studies with real objects have investigated the mechanical properties that underlie human haptic perception. Few virtual environments, however, have systematically incorporated the relevant mechanical parameters underlying kinesthetic perception. In this study, the ability of a haptic device to render kinesthetic information regarding the inertial properties of virtual objects was tested. Results suggest that users were able to perceive length of rendered virtual objects via the haptic device. Further, users can be trained using the haptic device to increase sensitivity to specific mechanical parameters (like inertia) that are perceptually salient in perceiving properties of rendered objects. The primary implication of this finding is that rendering kinesthetic parameters and employing feedback in a systematic manner may increase the realism of virtual environments and also improve haptic perception.

Keywords Kinesthetic haptic rendering · Haptic environment design · Haptic perception in virtual environments · Haptic skills training in virtual environments

1 Introduction

1.1 Kinesthetic rendering in virtual environments

The traditional paradigm for haptic interaction in virtual environments is point based, with the user feeling vibrations or forces at one or more points of intersection between a haptic device *avatar* and a simulated object. While point based interaction is common in the real world, there is another pervasive form of touch that involves muscular effort via kinesthetic and proprioceptive mechanisms during the manipulation of hand-held objects. Consider, for example, the wielding of a stick or the lifting of a coffee cup by its handle; even without visual feedback humans can perceive certain properties of hand held objects, including their length, orientation, and heaviness. This kind of touch, which involves the perception of object properties via motions of the object, has been called "dynamic" or "kinesthetic" touch [1–3]. Currently, very few virtual environments incorporate kinesthetic haptic feedback [4]. However, as haptic interfaces evolve in their rendering capabilities, the inclusion of this type of haptic feedback seems plausible and desirable. In this study, we examined the effectiveness of rendering kinesthetic touch via a haptic device for perceiving a certain physical property of rendered virtual objects using a skills training paradigm. Human users interacted with virtual "sticks" using the haptic interface (virtual environment) and were trained to report the felt lengths of the virtual sticks.

Despite a large body of work demonstrating the perceptual capabilities of kinesthetic touch in the real world, few virtual environments have been designed to convey haptic information through this mode of interaction [5]. As virtual haptic environments increasingly focus on more realistic and perceptually "smart" interaction methods, we believe that kinesthetic feedback explicitly modeled after dynamic touch may provide for richer, truly multimodal, interactions. Including this mode of haptic feedback may enable users to more easily perceive properties of objects rendered virtually and use this information for skilled action. Virtual environments designed with kinesthetic interaction can be employed in a variety of applications useful for haptic skills training, skills transfer,

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virtual prototyping, etc. (applications will be more fully discussed in the Conclusions section) [6].

The primary objective of this study is to examine how effectively a haptic device can be used to render kinesthetic feedback for efficient perception of rendered virtual objects. The paradigm used to assess this is to train users to perceive the lengths of virtual sticks from felt haptic feedback rendered by the device, and experimentally determine mechanical quantities underlying their perception. In other words, we seek to test whether or not a haptic device can be used to train users to perceive rendered objects by increasing their reliance on mechanical quantities.

This paper is organized as follows: in Sect. 1, we introduce the theoretical foundations of kinesthetic perception, including the perceptual processes involved in sensory training. We then provide a synthesis of the state-of-the-art for kinesthetic perception in multimodal environments, and place the current work in context. In the next section, we detail the experimental procedures used in this study, including participants and protocol, the algorithm used for rendering relevant mechanical parameters and the three phases of the experiment. The results section discusses both overall and individual participant results for perceptual attunement and calibration. We conclude the article by discussing the various implications of the study results.

1.2 Perceptual basis for kinesthetic perception

It has been hypothesized that kinesthetic information perceived about held objects is related to the dynamics of the object. Several candidate mechanical quantities, sometimes called "invariants" that are associated with the objects' dynamics have been suggested to be the basis upon which humans perceive object properties [1,7]. These quantities include the mass (m) of an object and its first moment (M). A mechanical quantity of particular interest is the second moment of an object's mass distribution, its *inertia* ($\boldsymbol{I}$) [8].

During the past two decades, nearly one hundred publications have reported studies on haptic perception with real objects using the kinesthetic or "dynamic touch" paradigm [8]. In a vast majority of these studies the role of the inertia tensor was found to be central to the haptic perception of occluded objects that are held and manipulated. Inertia has been found to be related to perceived length [9,10], width [11], height [12], shape [19] and weight [13,14]. Thus, in addition to the mass of an object, the perception of geometric properties, such as length, height, width and shape, are apprehended on the basis of mass-based properties. Specifically, the perception of these properties seems to be based on the object's inertial eigenvalues rather than on its actual geometric dimensions [15]. In addition, it has been demonstrated that the perception of object properties via dynamic touch is a function of mechanical "invariants", rather than the continuously changing forces and torques during object manipulation [9]. While the haptic system is sensitive to time-varying forces and torques, it seems to use them to register mechanical quantities that remain invariant, like $\boldsymbol{I}$ [16]. In fact, evidence suggests that dynamic touch functions by producing muscle forces and torques that set an object in motion in order to produce reactive forces and torques corresponding to the object's mass distribution. As "invariants" must be defined with respect to quantities that change, mechanical invariants such as $\boldsymbol{I}$ only manifest themselves when an object's disposition is changed (e.g., when forces produce changes in position, velocity or acceleration). It follows that the time-varying forces and torques produced by the muscles serve to reveal the time invariant mechanical quantities to which the haptic system is sensitive [2,7,9,16,17]. Even when the point of rotation is not fixed, an invariant form of $\boldsymbol{I}$ can be quantified which is employed during dynamic touch to perceive properties of hand-held objects [18].

1.3 Perceptual processes in haptic learning

We employ the perceptual framework of *attunement* and *calibration* to study this research question. *Attunement* is the process by which users learn to identify an object property by basing their perceptual judgments on specific mechanical quantities (or "variables") that are available to the perceptual system and correspond with the property in question. For example, since the amount of liquid remaining in an opaque beverage can correspond directly to the weight being hefted, a user can simply lift the can and sense the amount of liquid by becoming attuned to weight (though the perception of weight is itself based upon an attunement to a specific set of invariant mechanical parameters [2,14,19]). During the process of attunement the user converges on the perceptual variables that are correlated with the object property to be perceived and makes judgments based on them. This process occurs only in the presence of feedback, since without feedback one or more uncorrelated or imperfectly correlated variables may be employed [20,21]. The user senses multiple mechanical variables during haptic interaction with objects, variables that are correlated with the property, called *specifying* variables, and variables that are ambiguously related to the property, called *non-specifying* variables. Before feedback, the user perceptually estimates an object property based on a combination of variables, both specifying and non-specifying. However, as feedback about the object property becomes available, the user will converge on the variables that are most correlated with the object property and which accurately predict it. This feedback process has been termed the "education of attention," or simply "attunement" [20,22,23].

During every-day perception in the real world one naturally receives feedback that allows one to become attuned to specifying variables. In simulated or remote environments, however, the specifying variables may not be rendered or feedback may be unavailable. In such cases the user may attune to non-specifying variables. In some cases, the nature of the displays, either haptic, visual, or some combination of the two, may inadvertently provide feedback that encourages the use of non-specifying variables. In theory, it should be equally possible to train the use of either non-specifying variables or specifying variables, depending on the feedback that is given. In artificial systems, where feedback concerning specifying variables may be absent or less salient, the non-specifying variables may be favored. However, to improve the perceptual efficacy and realism of artificial displays, systematic investigation into the higher order invariants (or variables) used for perceiving certain properties, as well as evaluating the suitability of devices to render these invariants need to be considered. In this study we employed a haptic device to render virtual objects that can be interacted with kinesthetically and we measured its efficacy by testing if users show improved attunement (sensitivity) to mechanical quantities after training.

Attunement to the correlated variables alone does not necessarily produce accurate perceptual judgments. For a perceptual judgment to be accurate, the user must not only *attune* to the specifying variable but also learn the appropriate magnitude of that variable. The variable must be metrically scaled to the property for accurate estimation to occur. This perceptual process, referred to as *calibration*, involves the learning of the correct scaling factor for specifying variables through feedback [24]. Attunement and calibration can occur simultaneously during the same feedback process, where the user learns to weed out non-specifying variables and to scale the specifying variables appropriately for accurate judgments [20,21]. For example, a person may not only learn to attune to weight as a variable that is correlated with the amount of liquid remaining in a beverage can, but via calibration they also learn to scale their judgments to be metrically accurate with regards to the specific amount of liquid remaining. At the conclusion of this process, the perceiver is conscious of a specific amount of liquid remaining in the can, rather than the mechanical parameters underlying the perceptual system's apprehension of weight.

The effect of attunement and calibration on kinesthetic perception of real objects has been previously studied by having users wield physical objects (e.g. cylindrical wooden sticks) and estimating their physical properties (e.g. length) [20,21,25]. Results from these studies confirm that feedback can indeed guide attunement and calibration to one or more mechanical variables. For example, studies have shown that the accuracy of perceptual judgments can be improved by training users to become attuned to specifying mechanical variables through a feedback process [20,21]. In this work, the length of unseen, wielded rods of varying lengths, diameters and densities were to be estimated by users. During a pre-test stage, before any feedback was given, participants wielded a set of rods (the test set) and made perceptual judgments of their lengths. Results showed that during the pre-test the participants were basing their judgments on some mechanical variables that were not highly correlated with the actual length. However, during the feedback stage, training was given using a different set of rods (the feedback set) and the actual length of each rod was shown to the user after each judgment was made. In a subsequent post-training phase, with the original set of test rods, it was found that the feedback training did induce both attunement and recalibration. After feedback the participants made perceptual judgments that were more correlated with actual length of the rods by basing their estimates on specifying variables. Importantly, attunement and calibration was not observed in the absence of feedback [21] (see also [24] for a similar finding in vision).

In experiments such as those described above, the subject's perception of length is based upon mechanical variables such as $\boldsymbol{I}$ [8–11]. In such cases the subjects are perceiving length, not $\boldsymbol{I}$, although their perceptions are based upon $\boldsymbol{I}$ [26]. Visual depth perception, for example, is based in part on convergence; the angles subtended by the eyes as they turn inward to gaze upon an object in near space. When one reaches for an object one is aware of a visually perceived distance without being explicitly aware of angles signaled by the eye muscles, although the signals provide a basis for that perception. Just as experiments have shown that feedback allows subjects to become attuned and calibrated to different sources of information to guide visual reaches [24], and to mechanical variables to haptically perceive the lengths of actual physical objects [8,14,20–22], we aim to demonstrate haptic attunement and calibration to virtual objects.

1.4 Context and contributions of current study

In the last two decades, several new multimodal interface devices and environments have been constructed for 3D interaction for a variety of purposes (simulation, training, CAD design, etc.) [27]. For example, kinesthetic exoskeletons have been developed that augment human capabilities in real and virtual multimodal environments [28]. On the other hand, much smaller, "desktop" haptic interfaces have been developed (e.g., Sensable Inc.'s PHANToM, Novint Inc.'s Falcon) which primarily are used for point-based haptic rendering (i.e., where mass-based properties are not rendered) [29]. Thus, partially due to the traditional limitations in device rendering capabilities, virtual haptic perception of mass-based properties of objects has not been widely studied. Some recent studies, however, in this area are that of Gosselin and coworkers [30], who developed "programmable inertia generators" by configuring various masses in 3D space to respond to user motion. In the same vein, Amemiya and coworkers [31] developed a hand-held haptic device that simulated a pulling or "lead-me" sensation. As the capabilities of haptic devices (and multimodal environments) improve, more insight will be gained in this area.

Some of the most extensively studied multimodal environments have been in the medical arena, owing to the positive effect these may have on healthcare. Pertinent to this work, haptic interfaces capable of rendering kinesthetic feedback have been implemented to aid surgeons in augmenting tool/tissue interaction [32,33] during surgery and for training haptic skills needed for proficient surgery [34]. These interface devices range from the simple, with just a few mechanical components [35], to very complex multi degree-of-freedom devices with exquisite mechanisms [36]. However, what is currently being debated is how the efficacy of these interfaces and environments can be measured [37]? That is, how can a multimodal system be quantified for its usability to the human?

We suggest that the perceptual salience approach is one method to holistically design and test multimodal interfaces for their efficacy. For instance, using the framework of perceptual salience, we developed haptic interfaces devices to primarily render the stiffness of virtual tissues using custom-designed hardware [38]. We later tested if rendered stiffness (K) of virtual tissues could be used in differentiating skill levels of experts from novices and, if complete novices to surgical training can be trained to apply controlled forces using the device. Our research yielded promising results: first, by the system differentiating experts from novices just based on their interaction with the salient parameter, K [39]. Second, our approach also demonstrated that training does occur using the perceptual framework of attunement and calibration to the salient parameter [40].

This approach has also been taken by other researchers in identifying and implementing perceptually useful virtual environments. For example, Edmunds and Pai [41,42] analyzed a haptic simulator to train human skill by identifying what aspects of the skill were salient and, later, rendering these salient aspects on a simulator. Also, Vicentini and coworkers [43] had worked on identifying what mechanical parameters are salient through curve-fitting techniques for a virtual haptic probing task. Their subsequent work also demonstrates that even low fidelity haptic rendering can achieve significant results as long as useful parameters are carefully rendered [44]. Thus, as device and computing technology matures, the attention will invariably turn to designing, optimizing and evaluating virtual environments for maximum benefit to humans.

The primary contribution of this paper is two-fold: first, we use a relatively novel haptic interface, the five degree-of-freedom Haptic Wand, to render the dynamics of virtual sticks. (The Appendix includes the dynamic model used to simulate these virtual materials, which may be used with other devices.) Based on decades on work with real rods, we demonstrate that comparable results may be obtained virtually with haptic interfaces. Secondly, we illustrate that subjects may be trained to base their perceptual judgments on specific mechanical quantities, in this case, inertia. It is our hope that this work will inspire further investigation into perceptually salient rendering in multimodal environments.

2 Materials and methods

2.1 Experimental design

In the present work, following the procedure employed by Withagen and Michaels [20] using real rods, we employed a subset of their sticks to be rendered with the haptic device. Users were asked to estimate the length of these virtual rods without visual feedback. This task has been employed in scores of experiments involving haptic perception of real rods, and is easily understood by participants [2,7–10,17–19]. The experiment is divided into three phases: *pre-test*, *feedback* and *post-test* (see Fig. 1). In all three phases the participants were asked to wield virtual rods with a haptic device that was completely occluded by a black screen (to remove visual feedback). After wielding, participants reported the length estimate of the virtual rod on a reporting scale apparatus. Two sets of rods, one for testing and another for training with feedback, were simulated to have the mechanical properties listed in Table 1. During feedback the participants were given visual feedback about the accuracy of each of their judgments, immediately after each judgment was made.

In the *pre-test*, participants simply wielded each of the simulated rods from the test set and estimated the length of each rod. No feedback was given during this stage (i.e,

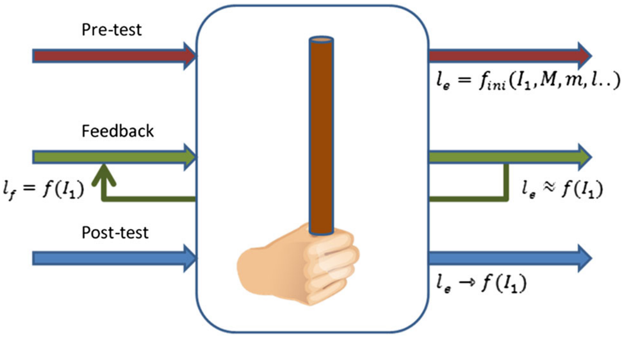

Fig. 1 The experiment was divided into three phases. During the pre-test, it was expected that users make length estimates using individualized functions of mass moments. During Feedback, it was expected that users attuned their length estimates to inertia and learned to calibrate their estimates to a scale. During Post-test, it was hypothesized that users would make length estimates based on inertia and accurately report them on the learned scale. The variables l_f denotes the length of the virtual rod communicated to the participant visually. The variable l_e denotes the estimated length of the rod in each phase

Table 1 Properties of the simulated rods used in the experiment and the artificial, inertia-based feedback training function

Rod number	Rod length (m)	Density (kg m)	Inertia, $\boldsymbol{I}_1$ (kg m^2)	Mass (kg)	Moment (kg m)	Feedback length (m)
Feedback rods						
1	0.9	0.05	0.012	0.045	0.020	0.690
2	0.8	0.05	0.009	0.040	0.016	0.613
3	0.8	0.13	0.022	0.104	0.042	0.843
4	0.7	0.13	0.015	0.091	0.032	0.738
5	0.7	0.20	0.023	0.140	0.049	0.852
6	0.6	0.20	0.014	0.120	0.036	0.730
Test rods						
1	1.0	0.05	0.017	0.050	0.025	0.766
2	0.9	0.05	0.012	0.045	0.020	0.690
3	0.9	0.10	0.024	0.090	0.041	0.869
4	0.8	0.10	0.017	0.080	0.032	0.772
5	0.8	0.15	0.026	0.120	0.048	0.884
6	0.7	0.15	0.017	0.105	0.037	0.774
7	0.7	0.20	0.023	0.140	0.049	0.852
8	0.6	0.20	0.014	0.120	0.036	0.730

These rods were originally designed by Withagen et al. [20] in their work on perceptual learning. Specifically, this set of rods was designed to break the co-variation between inertia, mass and moment

participants had no other way of estimating length except from feeling). It was expected that in the pre-test, participants would base their length judgments on some individualized function of mass moments [19–21]. The participant's estimation process, represented as $l_e = f_i(I_1, m, M, l, ..)$ in the pre-test assessment process in Fig. 1, depicts that pre-test length estimates may be based on a custom combination of mechanical variables that may not accurately predict length of virtual objects. Data from this phase served as a reference to compare any improvements after training.

During the *feedback session*, participants wielded simulated rods from the feedback set. After feeling each simulated rod with the haptic device the participants estimated the length of the virtual rod and displayed their estimate on the reporting apparatus. Following this, their estimate was "corrected" by the experimenter pointing to the *inertial length* of the rod (derived from I_1 of the rod, see Sect. 2.5) on the report apparatus. The inertial lengths were based on a pre-formulated function of $\boldsymbol{I}$, denoted as $f(I_1)$ in Fig. 1, and not their actual length. The purpose of using an inertia-based feedback function was to discern if the users can be trained to attune to this mechanical quantity and calibrate their length judgments based on it. Participants were trained using this feedback method for multiple rods. As training progressed, we hypothesized that participants would become attuned to $\boldsymbol{I}$ of felt rods by establishing the correlation between the inertial length (given as feedback) and inertia through felt torque. We also hypothesized that over time the participants would learn to accurately scale their length judgments. Since the inertial length function, $l_f = f(I_1) = 3.0\sqrt[3]{I_1}$, was used during training, we expected that following the feedback session, users would produce length judgments based on this model. It was expected that during the training stage the subject would begin to learn the training function such that $l_e \approx l_f = f(I_1)$.

In the *post-test* session, participants were again given the simulated rods from the test set in random order and asked to estimate their lengths, without feedback (length was not reported visually). It was hypothesized that in the post-test session the participants would base their estimations of length more heavily on $\boldsymbol{I}$. This would demonstrate successful attunement and calibration as governed by feedback [19,20]. That is, it was expected that after the training stage the subject's estimate of length should approach the training function as $l_e \rightarrow l_f = f_f(I_1)$.

2.2 Participants

Ten participants (six male, four female) aged 22–29 years participated in the experiment after providing informed consent in accordance with the local Institutional Research Board (IRB). Participants were recruited primarily by email and were offered ten dollars in compensation for their time. All participants were right handed as determined by a written questionnaire. None of the participants had any previous experience with the haptic device.

2.3 Experiment protocol

After completing informed consent forms the participants were given a standard 3-minute explanation of the experiment, stating the primary goal as estimating length of simulated rods before and after feedback (training). It was never disclosed to the participants that $\boldsymbol{I}$ was the specifying variable to which they were being perceptually trained. Two physical wooden rods were shown to demonstrate the concept of dynamic touch and participants were encouraged to wield the rods and estimate their lengths with eyes closed. Once the participants understood the idea of length perception by dynamic touch, they were instructed on the layout of the sessions; pre-test, feedback and post-test. In all three sessions participants stood in front of a black curtain which occluded the haptic device. The height of the haptic wand was adjusted to suit the height of the standing participant.

During the pre-test session, participants were given eight different test rods in random order, two times each (eight rods in random order, followed by eight rods again in random order). To wield a simulated rod, participants reached under the curtain, placing their arm on an armrest and held the end-effector of the haptic device at its center. After making sure they were within the workspace of the device, they were instructed to wield the rod. Participants were encouraged to wield about one axis (pitch or yaw) for a smooth, continuous feel. At the beginning of the pretest session and during the introduction, it was mentioned that participants were holding the bottom of the simulated rod. Due to design considerations in modeling the rod, participants were instructed to minimize motion of the end of the rod within the hand but were encouraged to wield freely. Since the haptic device has force and torque limitations, if these output values exceeded a threshold, a "beep" sound was produced to warn the subject. If more than four beeps were produced in a trial, it was terminated and restarted again after instruction.

In the feedback session six feedback rods were given three times each in random order. After the subject wielded and reported their length estimate (l_e) of a rod on the report device, the inertial length (l_f) of that rod was then indicated on the reporting rail by the experimenter. For example, if the feedback length is 0.5m then the experimenter moved the indicator to a position that is 0.5 meters from the bottom of the report rail. In this way the experimenter used the reporting device to give length feedback to the subject that was based upon the inertial feedback function, $f(I_1)$. The experimenter alternated using the top and bottom of the indicator as the zero reference (i.e., alternated feedback measurements presented as a distance between the top of the report rail and the indicator with a distance between the bottom of the report rail and the indicator). Thus participants received immediate feedback about the length of the rod while still wielding the rod and could learn from the feedback. This was repeated for all the 18 trials, each trial with the appropriate inertia length value.

In the post-test session the eight test rods were given, two times each in random order. In this session no feedback was given and participants marked the estimated length of the rods on the reporting device (as in the pre-test session).

Participants were offered a break half way through each session. The time needed for each subject to complete the experiment was approximately ninety minutes. Subject 1 completed 24 trials in the pre- and post-tests, but it was decided that since this resulted in a prolonged experimental session the protocol was adjusted to the one described above.

2.4 Haptic system: hardware and software

The experimental setup (cf. Fig. 2) used to render virtual rods included a five degree-of-freedom (5-DOF) Haptic Wand (Quanser Incorporated, Ontario, Canada) with a pen shaped end effector connected to two pantographs (top and bottom). The device sensed position/orientation and rendered forces in the x, y, and z directions and torque about the roll and pitch axes. Yaw torque about the longitudinal axis of the end effector was not measured or rendered. The maximum continuous exertable force is 2.5 N and the maximum continuous exertable torque is 450 N mm. The Haptic Wand was placed on an adjustable table to enable comfortable interaction. The software control platform for this device was WinCon (Version 5.0) used in conjunction with MATLAB®/Simulink® (Version 7.1/6.3). The WinCon toolbox used with Simulink contains software modules for the Haptic Wand which can be used in conjunction with other toolboxes within the MATLAB® environment. The haptic device was occluded from the subject's view by a black, opaque screen.

During each experimental trial participants wielded a simulated rod with the haptic device that was held at the bottom and indicated their estimate of the rod's length on a visible reporting apparatus (cf. Fig. 2). The reporting apparatus was a 1.2-m rail with an adjustable pointer that could be positioned using a string and pulley system that ran along the length of the rail. Participants usually wielded the simulated

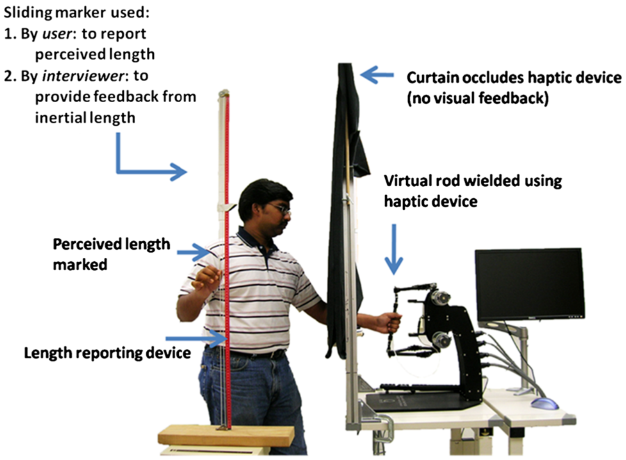

Fig. 2 Experimental setup

rod by manipulating the haptic device with their right hand and positioned the pointer with the left hand to report estimated length. The participants' estimate was based on the visible scale of the report apparatus that they produced with the pointer, but it was not based on an extrinsic scale, such as inches or centimeters, as no such gradations were provided on the visible portion of the report apparatus [6–13]. Participants alternated between indicating length from the top and bottom of the report rail to avoid using reference points on the reporting apparatus as a bases for their judgments. This also eliminated over- and under- estimations by the participants that may be caused by any bias on the part of the subject to place the pointer towards the top or bottom of the rail. After the subject finished adjusting the pointer, the experimenter recorded the judged length using a ruler affixed to the rail (seen only on the experimenter's side) and then returned the pointer to its starting position for the next trial.

2.5 Modeling and force rendering of virtual rods

In order to simulate rods wielded with the haptic device, a dynamic model was derived with position and orientation of the haptic device-end effector as the input, and forces and torques exerted by the virtual rod as the output of the model. In the dynamic model, the wrist, which exerts and feels forces and torques, is treated as one joint. Also, motion of the rod within the hand is not considered in this model; it is assumed that the rod is held firmly within a closed fist. There has been some discussion regarding the proper frame of reference (origin at the center of wrist or endpoint of the rod) to use in modeling the dynamics of hand-held rods. Most researchers have assumed a rigidly coupled link between the wrist and the end of the wielded rod and have modeled the mechanical properties of the rod using a point of rotation located in the wrist [9,15,45]. More recently it has been shown that a more accurate assumption for understanding perception is to have a reference frame at the endpoint of the rod instead of the wrist [9,15,27]. Calculating forces and torques with respect to the end-point of the rod leads to accurate predictions of participants' judgments [8,19]. We derived the dynamics of a wielded rod with the reference frame attached to the endpoint of the rod as shown in Fig. 3. A step-by-step derivation of the virtual rod dynamic model is presented in Appendix A. To the best of our knowledge, such a detailed model is not available in current dynamic touch literature and may aid future research in virtual environments.

The mechanical properties of rendered rods, a subset of those used by Withagen et. al., are shown in Table 1.

2.6 Attunement feedback function

During the training phase, after users wielded the virtual rods and estimated their length, their "real" length was indicated on the report apparatus. Using this mechanism for multiple rods, it was hypothesized that users learned to interpret length based on its specifying invariants. This arbitrary feedback length, however, was not the actual length of the rod, rather the "inertial length" of the virtual rod, based on $\boldsymbol{I}$ of the rod alone, was given to the user as feedback. The feedback function relating length of the rod as a function of $\boldsymbol{I}$ alone was mathematically expressed as $l_f = f(I_1)$. To specify an appropriate function, $f(I_1)$, first consider the expression for $\boldsymbol{I}$ of a rod; $I_1 = ml^2/3$. Substituting the weight per length, ρ, of any rod into the inertia formula yields $I_1 = \frac{\rho l^3}{3}$.

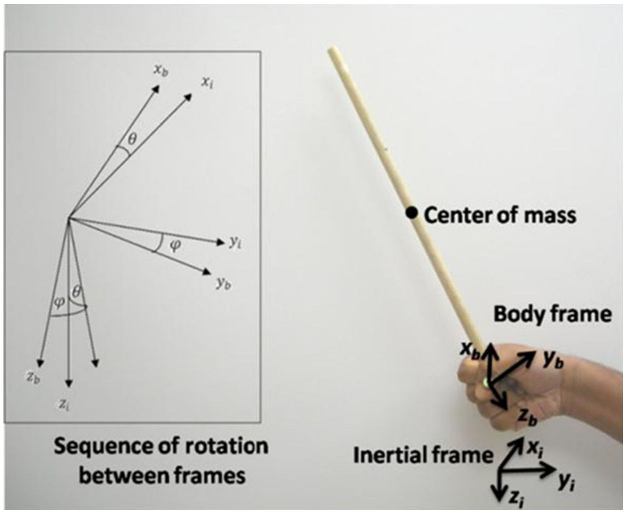

Fig. 3 Inertial and body frames for rod design

This can be rearranged as $l \propto \sqrt[3]{I_1}$. A constant of proportionality of 3 (for lightweight material) yields the mapping: $l_f = f(I_1) = 3\sqrt[3]{I_1}$. Note that this equation defines a new (false) length, the *inertial length*, that is a function of the rod's $\boldsymbol{I}$. The scale factor was chosen to make the inertial length range close to its real length. The constant of proportionality assumes a constant, density. Since users were trained using a metric based on $\boldsymbol{I}$ alone (inertial length), it was expected that they would become sensitive to I_1, felt inertia, after training. Since the feedback length was directly based on inertia, we hypothesized that after training the results would show a greater reliance on $\boldsymbol{I}$. The last column in Table 1 shows the inertial lengths for each of the training and test rods. The effect of the attunement process is studied during the post-test phase.

3 Results and discussion

Data analysis was performed to answer two primary research questions: first, can the haptic device render mechanical variables that have been shown to underlie and aid kinesthetic perception? Second, can this haptic device be used to train users to become attuned and calibrated to a mechanical variable, thereby improving kinesthetic perception? Two software packages were used for data analysis: Minitab (v. 15.1) for statistical analysis and MATLAB (v. 2007a) for graphing. To enable data analysis using correlations and regression models, the relationship between the mechanical variables had to be analyzed using log transforms since the relationship between length and $\boldsymbol{I}$ of the rods was non-linear. Thus, following standard practice in the dynamic touch literature, all data was computed using logarithms of the recorded data [7,8,20].

3.1 Overall analysis

The primary objective of the study was to test the attunement to mechanical variables after feedback. To test for this, a regression model was computed with the logarithm of perceived length (l_e) as the dependent variable and logarithm of principal major inertia (I_1) as independent variable (see Fig. 4). The regression model from pre-test data of all ten participants was calculated to be

$$\log(\textit{reported length}) = 2.75^* + 0.552^* \log(\textit{inertia}).$$

The *R-squared* statistic showing "goodness of fit" was .216 (p value <0.001). This indicates that about 22 % of the variance in the length estimations was accounted for by $\boldsymbol{I}$.

For post test data, the regression model was similarly calculated as

$$\log(\textit{reported length}) = 2.57^* + 0.398^* \log(\textit{inertia}).$$

The *R-squared* value, however, nearly doubled to 42.2 % (p value <0.001). The post-test data shows that reported length after training was more heavily based on $\boldsymbol{I}$ than in the pre-test. These results indicate that the device rendered $\boldsymbol{I}$ in a way that could be apprehended by the participants and the haptic training with the inertia-based feedback function increased the reliance on this mechanical quantity. That is, after training, participants were more attuned to $\boldsymbol{I}$. The haptic device was thus able to render $\boldsymbol{I}$ of wielded virtual rods in a way that enabled haptic perception and training based on it.

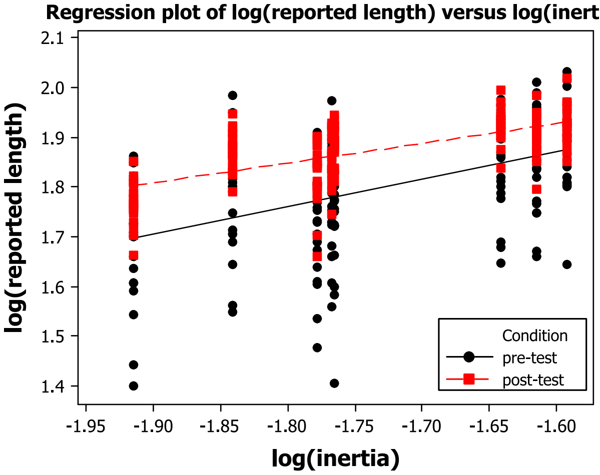

Fig. 4 Regression plot for user attunement to inertia in pre-test and post-test (*dots* show individual user data and *lines* denote regression models)

3.2 Individual subject analysis

In the post-test all ten participants showed a significant relationship between perceived length and $\boldsymbol{I}$, while only seven showed a significant relationship in the pre-test (see Table 2). Overall, eight of the ten participants showed a greater reliance on $\boldsymbol{I}$ after training, as indicated by an increase in the *R-squared* statistic. The two exceptions were Subject 5 and Subject 8. Subject 8 showed a significant dependence on $\boldsymbol{I}$ during pre-test with an *R-squared* value of 73.3 %. After feedback, the reliance on $\boldsymbol{I}$ dropped to an *R-squared* value of 54.2 %, which remained significant. Subject 5 showed almost no improvement in *R-squared* value although in both pre-test and post-test their dependence on $\boldsymbol{I}$ was significant. The greater reliance on $\boldsymbol{I}$ after training is an indication of

Table 2 Regression models for individual participants

Subject	R^2	Intercept	Log$\boldsymbol{I}$
Pre-test			
1	.159	2.21†	.219
2	.106	2.49†	.455
3	.370†	2.51†	.385†
4	.545†	2.87†	.633†
5	.467†	2.39†	.294†
6	.248†	2.42†	.389†
7	.138	2.53†	.433
8	.733†	3.49†	.937†
9	.326†	3.01†	.667†
10	.489†	3.60†	1.07†
Post-test			
1	.625†	2.39†	.322†
2	.522†	3.11†	.710†
3	.550†	2.64†	.433†
4	.602†	2.27†	.211†
5	.472†	2.24†	.325†
6	.431†	2.51†	.357†
7	.701†	2.46†	.341†
8	.542†	2.63†	.416†
9	.493†	2.83†	.562†
10	.541†	2.38†	.292†

† p value ≤ 0.05

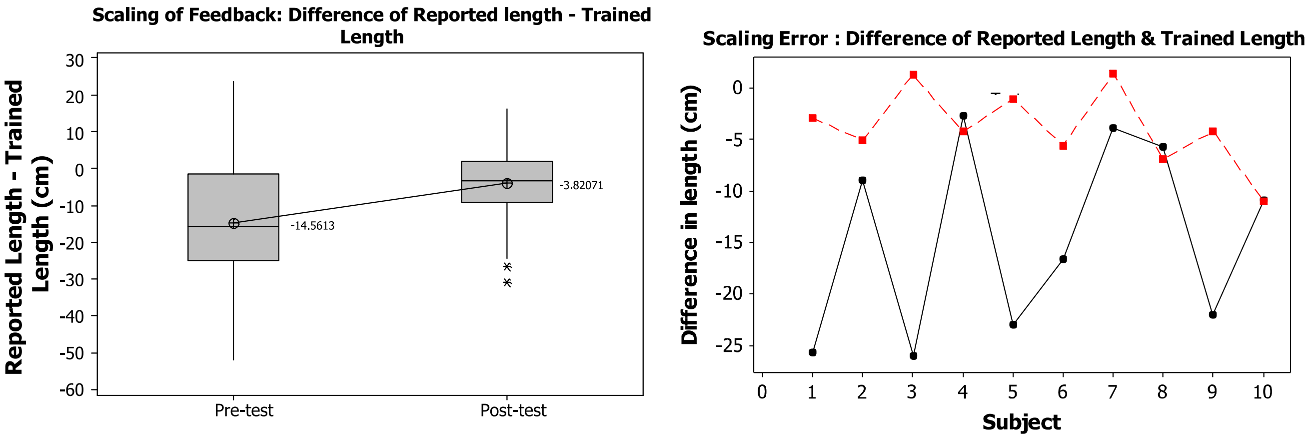

Fig. 5 Scaling information during pre-test and post-test; (*right*) *black lines* indicate pre-test and *red lines* indicate post-test

attunement, and the increase in the *R-squared* statistic was confirmed with a paired *t*-test utilizing the data from all ten Subjects ($t = -2.59$, $p < 0.05$).

3.3 Scaling analysis

Previous studies investigating haptic attunement to specific mechanical variables have also found evidence of the complimentary process of calibration [22,23]. In attunement, the correlation between perceptual judgment and variable(s) specifying perception is tested. However, to correctly identify an object property users not only need to base their judgments on the specifying variable(s) but they must also do so with an accurate scaling. Analysis of our data showed a significant improvement in calibration after feedback. A measure used to test scaling or calibration is the mean difference between inertial length corresponding to the feedback function, $l_f = f(I_1)$, and the participants' perceived length (l_e) values. For the pretest data this mean difference had a mean value of -14.6 cm while in the post test it was reduced to -3.8 cm. A paired t-test between the data confirmed that this difference was statistically significant ($t = -7.56$, $p < 0.001$). This result indicates that not only were users able to attune to $\boldsymbol{I}$ as depicted by the haptic device, but they were also able to use feedback to calibrate the scale of their perceptual judgments (see Fig. 5).

4 Conclusions

This study demonstrates that virtual environments can be designed to incorporate kinesthetic interaction using intentional haptic feedback via force-based interface devices. Using the framework of attuning users to specific rendered variables (in this case $\boldsymbol{I}$), participants can learned to base their estimates of a property of virtual objects (here, length) on rendered inertia. That is, we found that users can attune to the inertia of virtual objects after training with inertia-based feedback and their judgments can become appropriately scaled.

Rendering the dynamics of objects enables perceptual learning. As a result, users will be more adept at skillful haptic manipulations. In surgical simulators, for example, rendering the moment and $\boldsymbol{I}$ of surgical tools may allow for quicker perception and more intuitive learning of tool functionality [46]. The transfer of training from virtual simulations to performance in the real world has also been an area of recent interest [37]. Depicting mechanical properties of manipulated objects may enable smoother transfer of training to the real world as these variables are used for haptic perception.

High fidelity systems strive to render the virtual (training) environment to exactly match the real world. In most cases, given current technological limitations, this is impossible. A more reasonable goal is to design medium and low fidelity simulators using a subset of parameters available in the real world that are needed for training specific skills. For example, in a simulator training pilots to control a plane, the graphic rendering of the scenery has been shown to not be critical [37]. Analogously, for haptic surgical training for laparoscopy, for instance, it is important to determine which parameters are critical for training. With tool use and object manipulation, the apprehension of mechanical properties by kinesthetic touch may be critically important as they have been shown to underlie real-world object perception. In some cases (or for low fidelity simulators), rendering the inertia or first moment alone could suffice in training the users in the skilled use of the virtual tools or objects. In short, training for attunement and calibration can serve as an important methodological tool during the development and testing of haptic devices.

Additional work may lie in the efficient rendering of stiffness or other properties of non-rigid materials. The effectiveness of many virtual skills training environments, particularly in the area of medical and surgical simulation, is a function of perceptually optimal rendering. Further work needs to investigate the attunement-based haptic rendering framework for non-rigid objects, like tissues, which can be deformed, torn, cut, or otherwise altered by the user. It is important to note that such properties may still be appropriately quantified by mechanical invariants, such as the stiffness, to which users may potentially become attuned.

In the present study the participants were asked to perceive a property of objects while simply holding and wielding them. The property to be perceived was length, though the procedure did not rule out the possibility that the subjects learned to use the length reports to give estimates of perceived inertia. This possibility does not reduce the value of the present work in demonstrating the ability of subjects to attune and calibrate to a mechanical variable through feedback. Nonetheless, future work should investigate protocols where participants are asked to judge the usefulness of objects for specific purposes or where they are engaged in meaningful tasks, such judging if an object is long enough to reach a target or narrow enough to fit through restricted space, or where subjects are otherwise manipulating objects in some purposeful way. The authors are currently developing a surgical simulator to test such questions within the context of training for laparoscopic surgery.

We have also shown here that the dynamic touch paradigm provides a simple psychophysical measure that can be used to compare the ability of haptic devices and simulations to render mechanical properties. In the present experiment the resulting *R-squared* values predicting subject judgments from simulated mass moments were found to be much lower than what has been observed in past experiments involving real objects [8–11]. There are at least two reasons for this; first, the device is limited in the ranges of forces and torques it can render. In our study, for the heaviest rods, the rendering limit of the device was approached (as a function of user motion). Another factor is the device's own inertia and associated backlash, which interferes with the haptic rendering. Second, users were confined to a relatively small workspace in which to wield the rods. While this reveals limitations in the ability of our device to render mass moments, the protocol presented can be successfully employed to benchmark haptic rendering platforms in skills simulators by comparing them with real objects. Future work should investigate the range of mechanical properties that various haptic devices can render. These studies should lead to recommendations concerning which devices are best for rendering specific object properties, specific skill learning or during specific classes of manipulations. The protocol could also be employed to test improvements during the development of hardware and software systems for haptic rendering.

Our finding that a haptic device can be employed for the attunement and calibration of kinesthetic perception points out a potential limitation inherent in many virtual environments and skills training simulators currently in use. Hidden or inappropriate training may result from unintended attunement that occurs when feedback is not controlled or is administered in an inconsistent manner. As a result, haptic training may not transfer to the real training environment, as can be noted from several virtual surgical simulator studies [47].

For the further study of attunement with haptic devices, hardware accommodations during device design should be made such that the motions, forces and torques of rendered virtual objects are as close as possible to real objects. In the haptic device used in this experiment, some "backlash" (energy losses among mechanical parts) was observed in the haptic device for heavier rods. This can result in poor haptic rendering and user perception, and may have contributed to the fact that the participants in our study did not perceive the inertial properties of virtual objects as accurately as participants in other studies have been shown to perceive those of real objects. Despite these limitations, we demonstrated that the haptic device can render mechanical variables and that this can be used for training users to become more perceptually attuned to mechanical quantities, improving their kinesthetic perception.

Appendix A: derivation of rod dynamics

The dynamical equations for the motion of a handheld rod were derived by defining two frames of reference; a static inertial (i) frame and a body (b) frame which moves with the moving rod. The rotation from i- to the b-frame is defined by the rotation angles θ and φ, with the sequence of rotation being rotation about the y_i-axis using the θ angle first, followed by rotation about the x_b-axis using the φ angle. The rotation matrix, C_i^b, from the inertial to the body frame is

$$C_i^b = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_\varphi & s_\varphi \\ 0 & -s_\varphi & c_\varphi \end{bmatrix} \begin{bmatrix} c_\theta & 0 & -s_\theta \\ 0 & 1 & 0 \\ s_\theta & 0 & c_\theta \end{bmatrix} = \begin{bmatrix} c_\theta & 0 & -s_\theta \\ s_\varphi s_\theta & c_\varphi & s_\varphi c_\theta \\ c_\varphi s_\theta & -s_\varphi & c_\varphi c_\theta \end{bmatrix},$$

where $c(\theta) = \cos(\theta)$ and $s(\theta) = \sin(\theta)$. Using Newton–Euler equations for dynamic equation formation, the total torque applied on the virtual rod is the sum of the gravitational torque and torque applied by the user; $M_{total} = M_{gravity} + M_{applied}$.

On the left hand side of the moments equation, the total torque consists of two sub moments; torque due to angular acceleration and torque due to translation of the bottom of the rod. The angular momentum, H^b, in the body frame is defined as $H^b = \boldsymbol{I} w_{ib}^b$, where $\boldsymbol{I}$ is the diagonalized inertia tensor,

$$\boldsymbol{I} = \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix},$$

with $I_{xx} = I_{yy}$ because the rods are cylindrical. w_{ib}^b is the angular velocity of the body with respect to the inertial frame, expressed in the body frame;

$$w_{ib}^b = \begin{bmatrix} p \\ q \\ r \end{bmatrix}.$$

Since the rod rotates only about the x_b*-and* y_b-axis, the z_b-component of w_{ib}^b is zero ($r = 0$). The moment due to angular acceleration M_{acc}^i in the inertial frame is obtained by differentiating the angular momentum

$$\begin{aligned} M_{acc}^i &= \frac{d}{dt} H^i = \frac{d}{dt}(C_b^i H^b) = \left(\frac{d}{dt} C_b^i\right) H^b \\ &\quad + C_b^i \left(\frac{d}{dt} H^b\right) = C_b^i \Omega_{ib}^b H^b + C_b^i \left(\frac{d}{dt} H^b\right), \end{aligned}$$

where Ω_{ib}^b is the skew symmetric matrix of the vector w_{ib}^b. Transforming the total moment with respect to the body frame yields

$$\begin{aligned} M_{acc}^b &= C_i^b M_{acc}^i = \frac{d}{dt} H^b + \Omega_{ib}^b H^b \\ M_{acc}^b &= \begin{bmatrix} I_{xx}\dot{p} \\ I_{yy}\dot{q} \\ I_{zz}\dot{r} \end{bmatrix} + \begin{bmatrix} -rqI_{yy} + qrI_{zz} \\ prI_{xx} - prI_{zz} \\ -pqI_{xx} + pqI_{yy} \end{bmatrix} \\ &= \begin{bmatrix} I_{xx}\dot{p} - qr(I_{yy} - I_{zz}) \\ I_{yy}\dot{q} - pr(I_{zz} - I_{xx}) \\ I_{zz}\dot{r} - pq(I_{xx} - I_{yy}) \end{bmatrix}. \end{aligned}$$

Since $r = 0, \dot{r} = 0$ and $I_{xx} = I_{yy}$, moment due to angular acceleration with respect to the body frame is given by

$$M_{acc}^b = \begin{bmatrix} I_{xx}\dot{p} \\ I_{yy}\dot{q} \\ 0 \end{bmatrix}.$$

Moment due to translation of the bottom of the rod causes the moments M_{tr}^b

$$\begin{aligned} M_{tr}^b &= -r_{AG}^b \times F_A^b = r_{GA}^b \times F_A^b \\ F_A^b &= m\left(C_i^b \begin{bmatrix} \ddot{x}^i \\ \ddot{y}^i \\ \ddot{z}^i \end{bmatrix} + \dot{\omega}_{ib}^b \times r_{AG}^b + \omega_{ib}^b \times (\omega_{ib}^b \times r_{AG}^b)\right) \\ M_{tr}^b &= m \begin{bmatrix} 0 & -\frac{l}{2} & 0 \\ \frac{l}{2} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \left(\left(\begin{bmatrix} c_\theta & 0 & -s_\theta \\ s_\varphi s_\theta & c_\varphi & s_\varphi c_\theta \\ c_\varphi s_\theta & -s_\varphi & c_\varphi c_\theta \end{bmatrix} \begin{bmatrix} \ddot{x}^i \\ \ddot{y}^i \\ \ddot{z}^i \end{bmatrix}\right.\right. \\ &\quad + \begin{bmatrix} 0 & -\dot{r} & \dot{q} \\ \dot{r} & 0 & -\dot{p} \\ -\dot{q} & \dot{p} & 0 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ -\frac{l}{2} \end{bmatrix} \\ &\quad \left.\left. + \begin{bmatrix} 0 & -r & q \\ r & 0 & -p \\ -q & p & 0 \end{bmatrix}^2 \begin{bmatrix} 0 \\ 0 \\ -\frac{l}{2} \end{bmatrix}\right)\right) \\ &= \frac{ml}{2} \begin{bmatrix} -s_\varphi s_\theta \ddot{x}^i - c_\varphi \ddot{y}^i - s_\varphi c_\theta \ddot{z}^i \\ c_\theta \ddot{x}^i - s_\theta \ddot{z}^i \\ 0 \end{bmatrix} + \frac{ml^2}{4} \begin{bmatrix} -\dot{p} \\ -\dot{q} \\ 0 \end{bmatrix}. \end{aligned}$$

The next moment to be considered is torque due to gravity. Assuming that the gravity is transmitted to the lower end of the rod along the z_b-axis in the body frame, the z_b-component of the gravity term causes a force F_g^b given by

$$F_g^b = C_i^b \begin{bmatrix} 0 \\ 0 \\ mg \end{bmatrix} = \begin{bmatrix} -s_\theta \\ s_\varphi c_\theta \\ c_\varphi c_\theta \end{bmatrix} mg,$$

where m is mass of the rod. The gravity term causes the moment, M_g^b, defined by $M_g^b = -r_{GA}^b \times F_g^b$. Using $r_{GA}^b = [0\ 0 \frac{l}{2}]^T$ (where l is the length of the rod) and F_g^b,

$$M_g^b = -\begin{bmatrix} 0 & -\frac{l}{2} & 0 \\ \frac{l}{2} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} -s_\theta \\ s_\varphi c_\theta \\ c_\varphi c_\theta \end{bmatrix} mg = \begin{bmatrix} s_\varphi c_\theta \\ s_\theta \\ 0 \end{bmatrix} \frac{lmg}{2}.$$

The external applied moment of the hand is defined as M_T^b. Using Newton–Euler balance equations, $M_{acc} = M_{gravity} + M_{tr} + M_{applied}$, the equilibrium of the body about the x_b- and y_b-axis results in the following equations

$$\begin{aligned} &\left(I_{xx} + m\frac{l^2}{4}\right)\dot{p} = s_\varphi c_\theta \frac{lmg}{2} \\ &\quad + (-s_\varphi s_\theta \ddot{x}^i - c_\varphi \ddot{y}^i - s_\varphi c_\theta \ddot{z}^i)\frac{ml}{2} + M_{T_x}^b \\ &\left(I_{yy} + m\frac{l^2}{4}\right)\dot{q} = s_\theta \frac{lmg}{2} \\ &\quad + (c_\theta \ddot{x}^i - s_\theta \ddot{z}^i)\frac{ml}{2} + M_{T_y}^b. \end{aligned}$$

Since the angular rates of the rod can be expressed as the time derivatives of Euler angles using

$$\begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} 1 & 0 & -s_\theta \\ 0 & c_\varphi & s_\varphi c_\theta \\ 0 & -s_\varphi & c_\varphi c_\theta \end{bmatrix} \begin{bmatrix} \dot{\varphi} \\ \dot{\theta} \\ \dot{\Psi} \end{bmatrix},$$

torque balance equations about the x and y axis are

$$\begin{aligned} &\left(l_{xx} + \frac{ml^2}{4}\right)\left(\ddot{\varphi} - \frac{s_\varphi}{c_\theta^2 c_\varphi}\dot{\theta}^2\right) \approx s_\varphi c_\theta \frac{lmg}{2} \\ &\quad + (-s_\varphi s_\theta \ddot{x}^i - c_\varphi \ddot{y}^i - s_\varphi c_\theta \ddot{z}^i)\frac{ml}{2} + M_{T_x}^b \\ &\left(l_{yy} + \frac{ml^2}{4}\right)\left(\frac{1}{c_\varphi}\ddot{\theta} + \frac{s_\varphi}{c_\varphi^2}\dot{\varphi}\dot{\theta}\right) \approx s_\theta \frac{lmg}{2} \\ &\quad + (c_\theta \ddot{x}^i - s_\theta \ddot{z}^i)\frac{ml}{2} + M_{T_y}^b. \end{aligned}$$

The vector $[-M^b_{T_x} \; - \; M^b_{T_y} \, 0]$ defines the output response torque and is applied to the 5 DOF haptic device.

Appendix B: table of terms related to the dynamic-touch approach to haptic perception

Dynamic touch	This term refers to perceiving properties of rigid objects by holding or wielding them
Kinesthetic	Typically, this form of haptic perception refers to motion-based touch interaction, in contrast with tactile (skin-based) feedback
Parameter	In this work, a parameter may mean a lower order (e.g., mass) or higher order (e.g., inertia/first moment) mechanical quantity
Inertia	Inertia is defined as the resistance of the object to angular acceleration. The inertia tensor, $\boldsymbol{I}$, describes the spatial distribution of the object's mass and its resistance to rotational accelerations in three dimensions. For a rigid object rotating about a fixed point of rotation, $\boldsymbol{I}$ is a constant and as a time-independent quantity, $\boldsymbol{I}$ is an "invariant" mechanical quantity describing the mass distribution of the rotated object. The eigenvalues of $\boldsymbol{I}$ (or principal moments of inertia, I_1, I_2, and I_3, where $I_1 \geq I_2 \geq I_3$) describe the resistances to rotations about the respective directions of the eigenvectors (or principal axes of inertia, e_1, e_2, and e_3, where e_1 is the axis of maximum resistance and e_3 is the axis of minimal resistance) [8]
Invariant	The mechanical quantity of an object that is not time varying or stimulus-dependent
Specifying variables	Those mechanical variables that are directly related to a particular object property
Attunement	The process of "honing in" on the specifying variable for a particular object property
Calibration	The process of scaling the specifying variable accurately based on visual or haptic feedback
Perceptual learning	In this work, we hypothesize that the dual processes of attunement and calibration are used in improving perception through feedback
Fidelity of rendering	The degree or quality of realism that the device or environment is capable of rendering

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