FORCE-DIRECTION DISCRIMINATION IS NOT INFLUENCED BY REFERENCE FORCE DIRECTION
(Short Paper)

Hong Z. Tan[1], Federico Barbagli[2], Ken Salisbury[2], Cristy Ho[3] and Charles Spence[3]

[1] Haptic Interface Research Laboratory
Purdue University, Indiana, USA
{hongtan@purdue.edu}

[2] Stanford Robotics Laboratory
Stanford University, California, USA
{barbagli,jks@robotics.stanford.edu}

[3] Department of Experimental Psychology
University of Oxford, UK
{cristy.ho,charles.spence}@psy.ox.ac.uk}

ABSTRACT

The authors report an experiment in which twenty-five participants discriminated force vectors presented along five directions (up, left, right, diagonally up left, diagonally up right). The force vectors were presented with a three degree-of-freedom force-feedback device. A three-interval one-up three-down adaptive procedure was used. The five reference force-direction conditions were presented in randomly interleaved order. The results show an average force-direction discrimination threshold of 33° regardless of the reference-force direction. Position data recorded at a nominal sampling rate of 200 Hz revealed a 10.1 mm average displacement of the fingertip between the start and end positions in a trial. The average maximum deviation from the starting position within a trial was 21.3 mm. We conclude that the resolution with which people can discriminate force direction is not dependent on the direction of the force per se. These results are useful for designers of haptic virtual environments.

1. INTRODUCTION

Force-feedback devices are now widely used in virtual environment and teleoperation systems. A typical haptic rendering algorithm uses both force magnitude and direction to convey the properties of virtual objects. While many studies have investigated the human perception of force (and weight), almost all are concerned with the magnitude, not the direction, of forces (e.g., [13][14][22][23]). Yet there is no doubt that force directions are important in describing the overall shape of an object (where resistive forces are usually rendered in the direction of the surface normals), or friction and viscosity (where force direction depends on the movement direction and velocity) (see, for example, [12][21][24]). It is within this context that we are investigating the resolution with which humans can discriminate force directions, and the factors that influence resolution.

In a recent study, participants judged force directions in an “odd-one-out” task using a force-feedback device [3]. The average force-direction discrimination threshold was found to be 25.6°. It was also found that the simultaneous display of visual vectors on a computer screen influenced haptic force-direction discrimination: congruent visual information reduced the force-direction discrimination threshold to 18.4°, whereas incongruent visual information increased it to 31.9°. These thresholds are quite poor considering that the average visual discrimination threshold for vector directions was only 3.25° [3]. The relatively poor discriminability of force-direction found in [3] explains why techniques such as “force-shading” (rendering force direction by averaging adjacent surface normals [20]) have succeeded in creating a smoother feel of polyhedral objects without introducing noticeable artifacts.

One issue that was not conclusive in [3] was whether force-direction discrimination depended on the reference force direction. Each participant in [3] was tested with only one of the five reference force directions under the three conditions of haptic cues only, haptic cues with congruent visual cues and haptic cues with incongruent visual cues. The results suggested that discrimination performance was not affected by the force direction, but a within-subject analysis could not be performed on the data due to the nature of the experimental design utilized. The issue, however, is of practical significance and warrants further investigation. In the present study, a new experiment was conducted in which each participant was tested with all five of the force directions. The methods used in the present study were similar to those used in [3]. The most pertinent details are repeated here for completeness.

2. METHODS

2.1 Participants

Twenty-five participants (S1-S25; mean age of 28 years, age range from 21-39 years; 15 males and 10 females) took part in this experiment. All of the participants had a normal sense of touch. Twenty-four of the participants were right-handed and one was ambidextrous by self-report. In terms of their prior experience with force-feedback devices, seven of the participants were “expert users” who use force displays regularly for their research, seven had “moderate” experience of being participants in previous haptics experiments, and the remaining eleven had never used any haptic device prior to the present study.

The participants were recruited by word of mouth and received \$5-\$10 for their participation. The experiment was conducted in accordance with the Institutional Review Board ethical guidelines at both Stanford and Purdue University.

2.2 Apparatus and Materials

The participants were seated in front of a 19-inch computer monitor in a quiet experimental room. They were instructed to insert their right index finger into the thimble of a PHANToM force-feedback device (SensAble Technologies, Inc., Woburn, MA, USA), placed 30 cm away from the monitor in the direction of the participant's right hand, occluded from the direct view of the participants by a box cover (cf. Figure 2 in [3]). A computer keyboard was placed at a comfortable distance such that the participants could give their responses with their left hand. The participants were instructed to rest their right arm on the table, and to hold a deformable gel ball gently in their right hand with their index finger pointing outward (i.e., away from their body). The gel ball was used to prevent participants from making excessive hand or arm movements that might have given them additional kinesthetic cues. The experiment involved a force being applied to the participant's finger inserted in the thimble, subtly moving the finger in the direction of the applied force until the participant provided an opposing force to maintain the finger in a stable position.

2.3 Stimuli

The haptic stimuli were generated by the PHANToM force-feedback device. Five reference force vectors were used. They included the normal vectors corresponding to the left (L), top (U), and right (R) sides of a cube centered at the workspace of the device, and the normal vectors corresponding to the upper-front two faces (DL and DR) of an octahedron (see Figure 1). The magnitude of the force vectors were always presented in the same way throughout the experiment. The force magnitude was ramped up linearly from 0 to 2 N over 500 ms, and then ramped down linearly to 0 N over the next 200 ms (cf. Figure 3b in [3]). The maximum magnitude of 2 N was chosen so that the forces were clearly perceptible to all participants. The gradual increase in force gave the participants time to apply opposing forces in order to maintain the position of their finger inside the thimble. It also kept the haptic device stable and quiet throughout the experiment. No visual information was given concerning the nature of the stimuli.

2.4 Procedures

A three-interval one-up three-down adaptive procedure was used [17][18]. Five separate threads of the adaptive procedure were interleaved for the five reference-force direction conditions. On each trial, one reference force direction was chosen from the five references with equal *a priori* probabilities. The participant was presented with three stimuli (three intervals): two corresponding to the randomly chosen reference force direction (reference stimulus), and the other corresponding to a force direction that deviated from the reference by a certain amount (test stimulus). The interval during which the test stimulus was presented was randomly selected from the three intervals with equal *a priori* probabilities. The independent variable was the angle between the reference and test stimuli, denoted by α (see Figure 4 in [3]). Given a value of α, the test stimulus could lie anywhere on the cone with the reference-force vector as the axis and with an angle of α (in other words, the orientation of the plane formed by the reference- and test-force vectors was randomly selected with the constraint that the angle formed by the two vectors was exactly α).

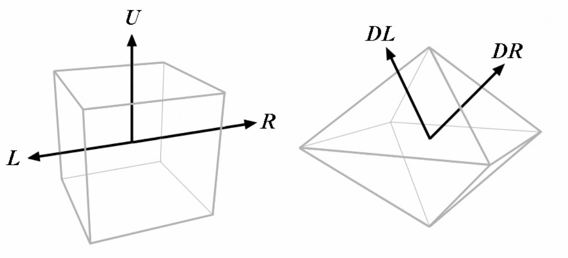

Figure 1. Illustration of the five force vectors used as the reference forces in the present study: left (L), up (U), right (R), diagonally left (DL), and diagonally right (DR).

Each trial began with the force-feedback device gently pulling the participant's right index finger to an initial starting position. The beginning and the end of the pulling were indicated by single and double audio beeps, respectively, presented at a clearly audible level from two computer loudspeakers, one placed on either side of the monitor. The three stimulus intervals followed immediately. The numbers “1”, “2”, or “3” were clearly displayed in large font on the computer screen to mark each of the three intervals. The participants’ task was to indicate the odd (i.e., test stimulus) interval by pressing “1,” “2,” or “3” on the keyboard (corresponding to interval one, two, or three, respectively). No trial-by-trial correct-answer feedback was provided.

In order to assess the amount of kinesthetic information available to the participants, the position of the thimble was recorded at a nominal sampling rate of 200 Hz in a WindowsXP operating system during the entire experiment.

The initial value of α was set at 40° for all five conditions. The value of α was increased after each incorrect response, and decreased after three consecutive correct responses. Initially, the magnitude of α changed by increments (or decrements) of 8° (for faster convergence), and then by 2° (for better resolution) after the first five reversals. A reversal occurred when α changed from increasing to decreasing, or vice versa. The value of α was calculated independently for each thread of the five adaptive procedures based on the participant's response history under that condition. Each thread of the adaptive procedure would terminate after twelve reversals at the 2° step size. Each condition typically contained about 60-90 trials. The experiment terminated after all five threads were completed.

Each participant was tested with all five reference force directions. The experimental session consisted of one practice block and one experimental block of trials. The practice block consisted of around ten trials. The experimental block consisted of trials from the five interleaved threads of adaptive procedure corresponding to the five reference force directions. A complete run lasted for approximately 60-75 min for each participant. To prevent fatigue, the participants were allowed to take a short break after the initial 45 min.

2.5 Data Analysis

For each participant, the mean threshold for each thread of the adaptive procedure was estimated by first calculating the six averages from the six pairs of peaks and valleys of the α values from the last twelve reversals. The mean threshold and its standard error were then derived from the six averages (cf. [5]).

Position data from 23 of the 25 subjects were analyzed.[1] For each trial, we computed (1) the Euclidean distance between the start and end positions (ignoring all intermediate recorded positions), and (2) the maximum Euclidean distance from the starting position at any point during that trial. Because the nominal sampling rate of 200 Hz could not be guaranteed in a WindowsXP environment, no temporal analysis was performed on the position data.

3. RESULTS

The force-direction thresholds for all participants are shown in a scatter plot (Figure 2). The thresholds covered a wide range, from 16.7° (S1, DR) to 68.3° (S5, L). An analysis of variance (ANOVA) with the factor of reference force direction (L, DL, U, DR, R) showed no main effect (F = 1.185, p =.322; Cohen's f effect size = 0.22, i.e., a small to medium effect). A comparison of the DL/DR group and the L/U/R group was performed because the latter corresponds to the cardinal directions. The result showed no significant difference between the two groups (t = -1.509, p =.144; Cohen's d = 0.22, i.e., a small effect).

A visual inspection of Figure 2 reveals large performance variations among the participants tested. When the data are grouped for the “expert”, “moderate” and “naive” participants, no significant effects were noted. However, when the data are divided into two groups corresponding to the “experts” and the “moderate” and “naive” participants combined, there was a borderline significant main effect of prior experience with the experimental apparatus (F = 3.381, p =.079; Cohen's f = 0.37, i.e., a medium to large effect size). Figure 3 shows a comparison of the mean threshold data for the three groups of participants. Despite the slight performance difference observed between the participant groups, the main effect of reference force direction remained insignificant (F = 1.034, p =.394; Cohen's f = 0.20, i.e., a small to medium effect size). There was no interaction between the two factors of prior experience with the apparatus and the reference force direction (F < 1). Therefore, we conclude that force-direction discrimination thresholds are not influenced by the direction of the reference force.

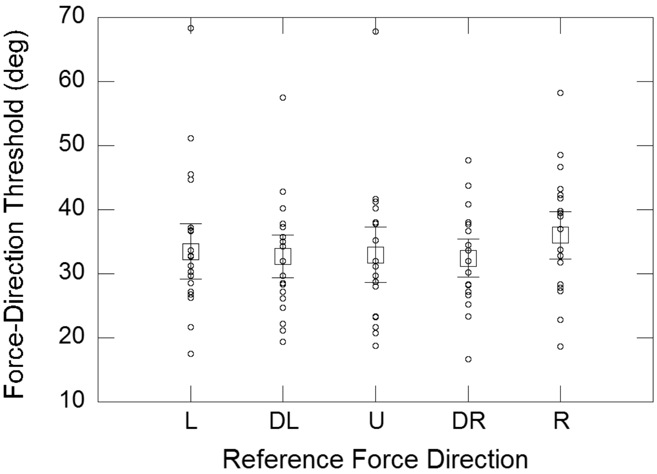

Figure 2. Scatter plot of all thresholds from the 25 participants (small circles). Also shown are the means (open squares) and the 95% confidence intervals (error bars), as a function of the reference force direction.

Finger-position data were analyzed to examine the extent of finger displacement during the experiment. The results are shown in Figure 4 in terms of (a) the average distance between the starting and ending positions, and (b) the average maximum deviation from the starting position. Averaged across the five reference force directions, the participant’s finger moved an average of 10.1 mm from the start of a trial to the end. The maximum deviation during the trials was on the order of 21.3 mm. An ANOVA revealed a significant effect of force direction (p = .045) for the start-to-end distances, although none of the pairwise comparisons was significant. There was also a significant effect of force direction (p = .050) for the maximum deviations as well as the standard deviations, indicating a high variability when participants tried to maintain the index finger positions by resisting the force applied to their fingers (in an extreme case, one participant’s finger moved by more than 60 mm in the DL and DR conditions, presumably due to the lower stiffness of the finger along these two directions). Finally, no significant correlation between the mean threshold and the average start-to-end distance was found.

---

[1] Data for the first two participants tested contained errors.

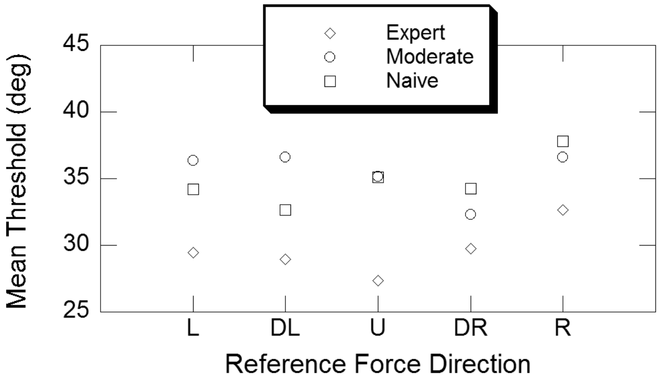

Figure 3. **Comparison of force-direction discrimination thresholds averaged over the participants within the groups of expert (lower thresholds), moderate and naive (higher thresholds) participants.**

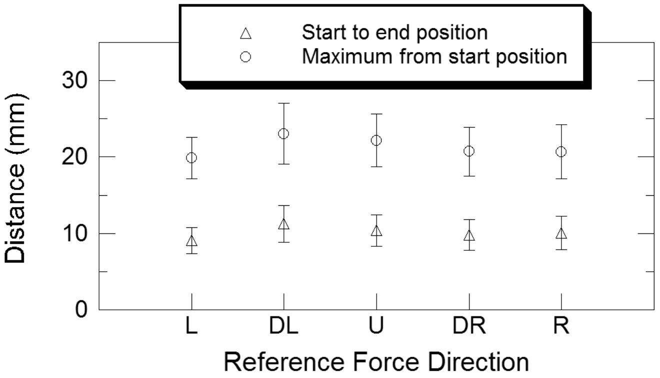

Figure 4. **Average start to end distance (triangles) and average maximum deviation from start position (circles) within a trial as a function of reference force direction. Also shown are the standard errors for the two measures.**

4. DISCUSSION

In the present study, we examined people's ability to discriminate force directions along five different directions using a force-feedback device. Earlier studies have shown that humans are quite adept at utilizing three-dimensional force information during typical object grasping and manipulation tasks. The cutaneous afferents in the fingerpad are credited for providing rich and precise information about both normal and tangential force [28]. Specifically, the SA-I afferent are biased towards responding to tangential force components in the distal direction, the SA-II in the proximal direction, and the FA-I type in the proximal and radial directions [4]. The anisotropic nature of the mechanical properties of the fingertip and the neural response of the underlying mechanoreceptors seem to suggest an anisotropic distribution of force-direction discrimination thresholds.

It is also well known that the spatial perception of *manipulatory* space (the space around the body within the reach of hands [16]) is anisotropic. For example, radial movements to and from the body are judged to be longer than tangential movements of the same linear extent [2]. Although we had restricted hand movements in the present study in order to minimize potentially confounding displacement cues on force-direction perception, typical use of force-feedback devices would result in users' hands and forearms move within the manipulatory space. It has been suggested that the overestimation of linear extent to and from the body may be due to an increase in the perceived effort in moving one's arm in this direction, thereby suggesting the possibility that force perception may depend on direction as well. In addition to distance estimation, numerous studies have also examined people's ability to reproduce or match angles in manipulatory space. Substantial errors were found when participants were asked to replicate the angle formed between two target locations (on a horizontal tablet placed on a table in front of the participant) that were felt by the left and right index fingers earlier through guided movements; the absolute angle-estimation errors ranged from 4.6° to 23.3° [15]. An attempt to model haptic perception in the context of motor control and planning using the Riemannian geometry as the metric structure found that haptic perception of rectangular lengths and triangular angles were both distorted, but the results were not consistent in that a single Riemannian metric could not simultaneously explain both the length and angle distortions [10]. Using a circle drawing task, it was also shown that the distortion of motor production was consistent with the distortion in length perception, thereby revealing a close link between perception and action in the somatosensory system [11].

In light of the overwhelming evidence in the literature that haptic perception is anisotropic, it seemed plausible that force-direction perception may be distorted as well. In the present study, we measured the force-direction discrimination thresholds along five different reference-force directions, three of which are along the cardinal directions of left, up and right. These five reference-force directions were chosen to cover the range of surface normals from the upper-frontal sides of virtual haptic objects as viewed by a user. Previous research has shown that the vertical and horizontal orientations are perceived more accurately than the oblique orientations by both vision and touch: the so-called oblique effect [1]. There was also evidence of a proximal-distal superiority in that sensitivity to gratings on the fingerpad was highest for gratings oriented proximally-distally, intermediate for oblique gratings, and lowest for medial-lateral gratings [9]. Our results showed, however, that the accuracy with which humans can discriminate force direction is not dependent on the reference-force direction.

The results of the present study should not be viewed as in direct conflict with the extensive literature on the anisotropic nature of our perception of manipulatory space. Unlike most studies on the anisotropic nature of haptic spatial representation that have measured the *distortion* in perception, our experiment examined the *accuracy* (or *variability, uncertainty, resolution*) of perception (see [8] for a discussion of the distinction between the two measures, and a new metric based on information theory for study of proprioception). Distortion is a systematic error in the perceived magnitude of a stimulus, or equivalently, an illusion, whereas variability can be measured in terms of discrimination threshold. It is therefore quite possible that users of a force-feedback device can perceive forces along the cardinal directions more accurately (something yet to be tested), but their ability to *discriminate* force directions is not dependent on the force direction. We hasten to point out that in the typical usage of a force-feedback device, the definition of cardinal directions may depend on the body orientation, hand/arm configuration, and even head tilt [19]. A calibration procedure to align the world coordinate frame of a force display with the sagittal and frontal axes of a user's body, however, is difficult if not impossible. For all practical purposes, however, our results provide a guideline for designers of virtual haptic environments in terms of an isotropic force-direction discrimination threshold on the order of 25-33° (from [3] and the present study).

To what extent was force-direction discrimination facilitated by finger movements in the present study? To the best of our knowledge, we are not aware of any study on people's sensitivity to displacement at the fingertip, let alone how the sensitivity might depend on displacement directions. Instead, researchers have tended to examine joint-angle perception based on the widely-accepted view that proprioception encodes joint angle information from which position can be derived [7]. Using very different experimental methods, two studies found the joint angle resolution at the shoulder and elbow to be on the order of 0.6-2.0° with the shoulder exhibiting a higher precision [25] [27]. The precision at the wrist and the proximal interphalangeal (PIP) joint of the index finger, a quantity that is more relevant given the setup of the present experiment, is on the order of 2.0-2.5° [6][25]. More recently, a discrimination threshold of 2.5-2.7° was reported for the PIP joint of the index finger, and a threshold of 1.7-2.7° for the metacarpophalangeal joint, under a variety of finger-joint configurations [26]. Assuming a typical index finger length of 50 mm from the PIP joint to the tip of the finger, a 2.5° angle corresponds to a displacement of 2.2 mm at the fingertip. In the present study, we found that the participants' fingers moved an average of 10.1 mm from the starting to the ending positions of a trial during which the force exerted on the finger ramped up to 2 N and then down to 0 N, and the average maximum deviation from the starting position was 21.3 mm. The magnitude of the displacements were therefore clearly perceivable by the participants. Future studies on the human sensitivity to displacements in different directions will shed light on whether the finger displacements experienced by participants in the present study had inadvertently served to facilitate the discrimination of force directions.

ACKNOWLEDGMENTS

H.Z.T. and C.S. were supported by a Network Grant from the Oxford McDonnell-Pew Centre for Cognitive Neuroscience. H.Z.T. was also supported by a grant from the Ford Motor Company University Research Program, a NASA award under Grant No. NCC 2-1363, and funds from the Nissan Technical Center North America, Inc. F.B. and K.S. were supported by an NIH grant LM07295-01 "Collaborative, Simulation based, Surgical Training." C.H. was supported by scholarships from the Clarendon Fund, Oxford, and the Overseas Research Student Awards Scheme.

REFERENCES

[1] Appelle, S., "Perception and discrimination as a function of stimulus orientation: The 'oblique effect' in man and animals," *Psychological Bulletin*, 78, 266-278, 1972.

[2] Armstrong, L., & Marks, L. E., "Haptic perception of linear extent," *Perception & Psychophysics*, 61, 1211-1226, 1999.

[3] Barbagli, F., Salisbury, K., Ho, C., Spence, C., & Tan, H. Z., "Haptic discrimination of force direction and the influence of visual information," to appear in *ACM Transactions on Applied Perception*, 3, 2006.

[4] Birznieks, I., Jenmalm, P., Goodwin, A. W., & Johansson, R. S., "Encoding of direction of fingertip forces by human tactile afferents," *The Journal of Neuroscience*, 21, 8222-8237, 2001.

[5] Brisben, A. J., Hsiao, S. S., & Johnson, K. O., "Detection of vibration transmitted through an object grasped in the hand," *Journal of Neurophysiology*, 81, 1548-1558, 1999.

[6] Clark, F. J., Burgess, R. C., & Chapin, J. W., "Proprioception with the proximal interphalangeal joint of the index finger: Evidence for a movement sense without a static-position sense," *Brain*, 109, 1195-1208, 1986.

[7] Clark, F. J., & Horch, K. W., "Kinesthesia," In K. R. Boff & L. Kaufman & J. P. Thomas (Eds.), *Handbook of Perception and Human Performance: Sensory Processes and Perception (Vol. 1)*, pp. 13/11-13/62, 1986. New York: Wiley.

[8] Clark, F., Larwood, K., Davis, M., & Deffenbacher, K., "A metric for assessing acuity in positioning joints and limbs," *Experimental Brain Research*, 107, 73-79, 1995.

[9] Essock, E. A., Krebs, W. K., & Prather, J. R., "Superior sensitivity for tactile stimuli oriented proximally-distally on the finger: Implications for mixed Class 1 and Class 2 anisotropies," *Journal of Experimental Psychology: Human Perception and Performance*, 23, 515-527, 1997.

[10] Fasse, E. D., & Hogan, N., “Quantitative measurement of haptic perception,” *Proceedings of the 1994 IEEE International Conference on Robotics and Automation*, 4, 3199-3204, 1994.

[11] Fasse, E. D., Hogan, N., Kay, B. A., & Mussa-Ivaldi, F. A., “Haptic interaction with virtual objects: Spatial perception and motor control,” *Biological Cybernetics*, 82, 69-83, 2000.

[12] Ho, C., Basdogan, C., & Srinivasan, M. A., “Efficient point-based rendering techniques for haptic display of virtual objects,” *Presence*, 8, 477-491, 1999.

[13] Jones, L. A., “Perception of force and weight: Theory and research,” *Psychological Bulletin*, 100, 29-42, 1986.

[14] Jones, L. A., “Matching forces: Constant errors and differential thresholds,” *Perception*, 18, 681-687, 1989.

[15] Klatzky, R. L., & Lederman, S. J., “Representing spatial location and layout from sparse kinesthetic contacts,” *Journal of Experimental Psychology: Human Perception and Performance*, 29, 310-325, 2003.

[16] Lederman, S. J., Klatzky, R. L., Collins, A., & Wardell, J., “Exploring environments by hand or foot: Time-based heuristics for encoding distance in movement space,” *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 13, 606-614, 1987.

[17] Leek, M. R., “Adaptive procedures in psychophysical research,” *Perception & Psychophysics*, 63, 1279-1292, 2001.

[18] Levitt, H., “Transformed up-down methods in psychoacoustics,” *Journal of the Acoustical Society of America*, 49, 467-477, 1971.

[19] Luyat, M., Gentaz, E., Corte, T. R., & Guerraz, M., “Reference frames and haptic perception of orientation: Body and head tilt effects on the oblique effect,” *Perception & Psychophysics*, 63, 541-554, 2001.

[20] Morgenbesser, H. B., & Srinivasan, M. A., “Force shading for haptic shape perception,” *Proceedings of the International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, 58, 407-412, 1996.

[21] Pai, D. K., Doel, K., James, D. L., Lang, J., Lloyd, J. E., Richmond, J. L., & Yau, S. H., “Scanning physical interaction behavior of 3D objects,” *Computer Graphics (ACM SIGGRAPH 2001 Conference Proceedings)*, 2001.

[22] Pang, X. D., Tan, H. Z., & Durlach, N. I., “Manual discrimination of force using active finger motion,” *Perception & Psychophysics*, 49, 531-540, 1991.

[23] Paré, M., Carnahan, H., & Smith, A. M., “Magnitude estimation of tangential force applied to the fingerpad,” *Experimental Brain Research*, 142, 342-348, 2002.

[24] Srinivasan, M. A., & Basdogan, C., “Haptics in virtual environments: Taxonomy, research status, and challenges,” *Computer and Graphics*, 21, 393-404, 1997.

[25] Tan, H. Z., Srinivasan, M. A., Eberman, B., & Cheng, B., “Human factors for the design of force-reflecting haptic interfaces,” *Proceedings of the 3rd International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems,* 55, 353-359, 1994.

[26] Tan, H. Z., Srinivasan, M. A., Reed, C. M., & Durlach, N. I., “Discrimination and identification of finger joint-angle positions using active motion,” submitted to *ACM Transactions on Applied Perception*, 2006.

[27] van Beers, R. J., Sittig, A. C., & Denier van der Gon, J. J., “The precision of proprioceptive position sense,” *Experimental Brain Research*, 122, 367-377, 1998.

[28] Wheat, H. E., Salo, L. M., & Goodwin, A. W., “Human ability to scale and discriminate forces typical of those occurring during grasp and manipulation,” *The Journal of Neuroscience*, 24, 3394-3401, 2004.