# The Effects of Hand Motion on Haptic Perception of Force Direction*

Xing-Dong Yang, Walter F. Bischof, and Pierre Boulanger

Department of Computing Science,
University of Alberta, Edmonton, T6G 2E8

**Abstract.** Most studies on the haptic perception of force direction have been conducted without hand movements, whereas hand movements are normally required in real-world applications. This paper reports a study on the perception of haptic force direction during hand movement. Discrimination thresholds for force direction were determined for two hand movement speeds, slow and fast, and for five reference force directions. The results show that the perception of force direction is not affected by hand movement speed. We also found that the perception of force direction was not impaired by the hand motion, nor by the direction of the reference force.

**Keywords:** Force direction, human perception, discrimination threshold, hand motion.

## 1 Introduction

The perception of haptic force has been widely studied, and research areas span from the perception of force magnitude to the perception of torque. However, very little is known about the perception of force direction.

Astrid et al. [2] demonstrated that humans have the ability to sense and reproduce haptic orientations. They found that the participants performed better at horizontal orientations (0° and 90° with respect to the sagital body plane) than at oblique orientations (45° and 135°). They called this the oblique effect. In addition, Toffin et al. [9]'s study showed that humans could discriminate different force directions. Note that differences between force directions can be too small to be detected. This may cause problems for some applications, for example for haptic motor skill training systems, which require users to be aware of the changes of the guiding force direction in order to keep their hands on the right path. If this is the case, additional feedback should be provided through other sensory channels. Therefore it is desirable to determine the smallest perceivable difference of force direction, which is also known as the discrimination threshold of force direction.

The discrimination threshold of force direction has only been studied in recent years. Barbagli et al. [1] reported a discrimination threshold of 25° obtained on

* This work was partially supported by the Natural Sciences and Engineering Research Council of Canada.

M. Ferre (Ed.): EuroHaptics 2008, LNCS 5024, pp. 355–360, 2008.

the participants' steady index finger. Tan et al. [8] found that the perception of force direction ranged from 25° to 33° and that it was not affected by reference force direction.

The reported thresholds were obtained without hand or finger motions. In real world applications, however, hand motions are necessary for performing many tasks. It is thus important to know if and how hand motion affects the discrimination of force direction. In our study, we asked participants to discriminate different force directions with their hands involved in a left-to-right motion, a fundamental component of most hand movements. It has been reported that hand movement speed can affect human perception of roughness [4] and the performance of certain tasks [10]. Therefore, we tested two different hand movement speeds, slow and fast, to investigate the velocity effect in the perception of force magnitude. We also investigated the direction effect when hand movement is involved. We measured discrimination threshold of force direction for five reference force directions, the same as those in [1] and [8].

## 2 Methods

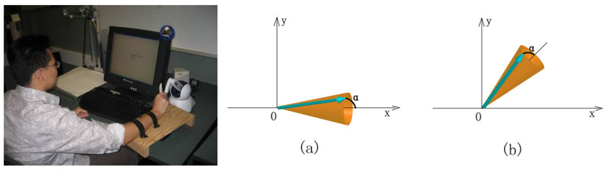
### 2.1 Participants

Twenty-five participants from the University of Alberta took part in this study. The experiment took about 45 minutes, and the participants received $10 for participation. Every participant signed a consent form prior to performing the experiment.

### 2.2 Apparatus and Stimuli

The participants held the stylus of a PHANToM Omni haptic device [7] like holding a pen. They placed their dominant arm on an armrest. Their arm movements were restrained by two velcro bands mounted on the armrest to minimize additional kinesthetic cues. A computer keyboard was placed next to the armrest for participants to give responses with the non-dominant hand. Visual feedback was displayed on a 17-inch LCD monitor (see Figure 1 left).

The participants were required to move the stylus at a constant speed from a start position on the left to an end position on the right. During the hand movement, a force was applied to the stylus, away from the movement direction, and the participants had to detect direction differences in these forces. Assuming the hand movement was along the $x$-$axis$, the reference force direction was $\beta$ degree away from the $x$-$axis$, where $\beta \in (0°, 45°, 90°, 135°, 180°)$. The reference force directions were same as those tested in [1] and [8], which allowed us to compare our findings with the thresholds reported in those papers. The test force deviated from the reference force by an angle $\alpha$. It could be in any direction, i.e. the phase angle of the test force was chosen randomly in every trial (see Figure 1 right). The force was ramped up from 0 to 1.5N within 1s of the trial start and ramped down to 0 within 1s of the trial end.




(Left) (Right)

**Fig. 1.** Left: Experimental setup for the study on the perception of force direction. Right: The test force vector could point in any direction, as long as the angle between which and the *x-axis* was equal to $\alpha$. For instance, if the reference force direction was $0°$ then the test force could lie anywhere on the cone in (a) and if the reference force direction was $45°$ then the test force could lie anywhere on the cone in (b).

### 2.3 Procedure and Experimental Design

To prevent participants from moving off the straight left-to-right trajectory, we put a tangible virtual cylinder between the start point and the end point. To facilitate velocity control, we asked the participants to follow a horizontal progress bar, which had the same hight as the virtual cylinder. A detailed description of the control mechanisms can be found in [11].

Participants were given warm-up trials to ensure that they mastered the moving task so that they could attend to the task of discriminating force magnitudes during the experiment. The participants were asked to practice as much as they wanted until they could master the task. The warm-up sessions took between 5 and 20 minutes.

An experiment consisted of a number of blocks, and each block consisted of three trials, two with the reference force direction ($\beta$) and one with the test force ($\beta + \alpha$). In each trial, the current stimulus number (1, 2, or 3) and the desired hand movement speed were displayed on the computer monitor. The three trials within a block were randomly ordered, and the participants had to indicate which of the three trials had a different force direction by entering 1, 2, or 3 on the keyboard. Responses were recorded and used to determine the value of $\alpha$ in the next block. For each trial, the hand movement was analyzed, and if the speed bar had been followed at least 90% of the movement duration then the trial was accepted, and the next trial was presented. If not, the whole block was restarted.

The discrimination threshold of haptic force direction was found using a one-up-two-down adaptive staircase method [5]. The test force deviation $\delta\alpha$ was set to $9°$, the step size $\alpha$ was initially set to $9°$, $\alpha$ was increased by $\delta\alpha$ after each incorrect response, and decreased by $\delta\alpha$ after 2 consecutive correct responses. After 5 staircase reversals, $\delta\alpha$ was set to $2°$. A staircase run was terminated after 10 reversals with $\delta\alpha = 2°$. The experiment finished after two staircase runs were completed. The hand movement speed was the same for each staircase run.

Participants were divided into five groups. Each group tested one of the force directions at two levels of hand movement speed, slow (14mm/s) and fast

(28mm/s). The force directions were randomly assigned to the groups, and the speed levels were fully counter-balanced.

## 3 Results

Means of the last 10 staircase reversals were calculated for each participant. Individual discrimination thresholds were then calculated by averaging these means. The estimated discrimination threshold of haptic force direction was computed by averaging the thresholds of the corresponding group (Figure 2), for each force direction. The estimated thresholds were analyzed using a two-way mixed analysis of variance (ANOVA) with force direction as a between-subjects factor and (hand-movement) speed as a within-subjects factor.

The ANOVA yielded no significant effect of reference direction, $F(4,40) = 1.13,\ p > 0.05$. There was also no significant effect of hand-movement speed, $F(1,40) = 0.23,\ p > 0.05$, and no interaction between force direction and hand movement speed, $F(4,40) = 0.47,\ p > 0.05$.

To investigate the motion effect, we compared our finding (32°) with the reported range of threshold (25° to 33°) obtained on the participants' steady index fingers [8]. A one-sample $t-test$ was conducted to compare our result against the lower and upper bound of the reported threshold range. The results show that 32° is significantly higher than the lower bound 25°, $t(49) = 3.2437,\ p < 0.001$, and statistically similar to the upper bound 33°, $t(49) = -0.7193,\ p > 0.05$.

## 4 Discussion

Our study revealed a mean difference threshold of force direction of 32°, which suggests that, in situations where the change of force direction is less than 32°, additional visual cues may be needed to facilitate awareness. For instance, assume a

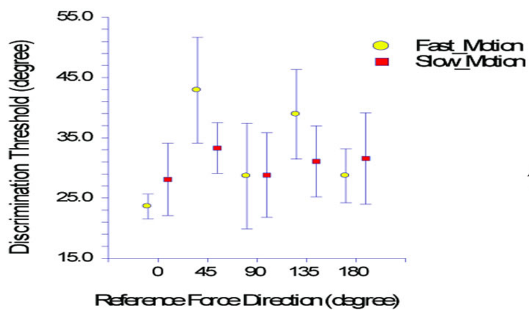



**Fig. 2.** Discrimination thresholds of force direction for five reference force directions at two speed levels. Means and standard errors are shown.

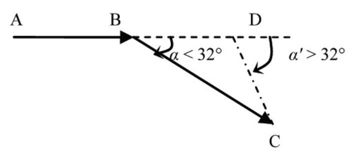



**Fig. 3.** If the change of haptic force direction is less than 32°, the user will not be able to follow the ideal trajectory of ABC. Instead, the user will likely follow a wrong trajectory of ABD.

motor skill training system leads a user's hand through a trajectory from position A to position C (see Figure 3). The trajectory turns about $\alpha$ degree at position B. Based on the threshold we have found, if $\alpha$ is less than $32°$, the user will not be aware of the direction change and will likely continue moving towards position D. Therefore, visual clues should be provided in this case.

The threshold found in the present study can also be helpful for optimizing the communication channel of haptic collaborative systems [3,6]. In such systems, the haptic devices are physically connected by a network, and haptic signals are transferred over a band-limited channel. Our findings suggest that any force-direction changes less than $32°$ are normally undetectable. Therefore, such changes can be discarded from communication packages to save network bandwidth.

Given that the threshold that we found in this study fell into the reported range [8], where no hand motion was involved. we conclude that the perception of force direction is not affected by the left-to-right hand motion. Our conclusions cannot go beyond this because the direction of hand movement may possibly affect the perception of force direction.

The ANOVA revealed that the speed of hand movement did not affect the perception of force direction. Figure 2 shows that the threshold curves of were similar for fast and slow motion. People normally explore the virtual world within a range of hand-movement speeds. Within this range, people appear to be able to precisely perceive the virtual world haptically without being affected by hand movement speed. However, if hand movement speed exceeds the upper speed boundary, haptic perception should be impaired. This may be attributed to the velocity effect or due to reduced duration of haptic stimulation. To the best of our knowledge, such speed limit has not been reported. We chose the speed levels based on our observation of the speeds with which people usually move their hands to perceive the virtual world. Thus the tested speed levels were falling into a range of practical importance. Therefore, we suggest that hand movement speed does not affect human perception of force direction when it falls into this range. The velocity effect may appear when hand movement speed approach or exceed the speed limit.

Regarding the direction effect, the perception of force direction was found to be independent of reference force direction. This result is consistent with the finding reported in [8] and indicates that the perception of force direction is not impaired by the oblique effect [2]. However, as previously mentioned, the tested speed levels were falling into a range of practical importance. The direction effect and/or the oblique effect may appear to impair the perception of force direction if the speed of hand movement exceeds the upper bound of the range. Hence, we suggest that the reference force direction does not affect the perception of force direction when hand movement speed falls into this range.

## 5 Conclusion and Future Work

The findings of this paper show a preliminary picture of the relationship between perception of force direction and hand motion. We found the discrimination threshold of haptic force direction was $32°$. We also found that hand-movement speed and reference-force direction did not affect the perception of force direction. However, we do not yet know how fast humans can move their hands and still be able to perceive force direction precisely. The tested speed levels were assumed to be within the range of practical importance. A velocity effect or a direction effect may be found when the speed of hand movement approaches or exceeds these speed limits.

Future work will focus on confirming and identifying the speed range. Based on the findings, velocity effect and direction effect will be further investigated. We also plan to study if and how hand movement direction affects the perception of haptic force direction.

## References


1. Barbagli, F., Salisbury, K., Ho, C., Spence, C., Tan, H.Z.: Haptic discrimination of force direction and the influence of visual information. ACM Transactions on Applied Perception (TAP) 3(2), 125–135 (2006)
2. Kappers, A.M.L., Koenderink, J.J.: Haptic perception of spatial relations. Perception 28(6), 781–795 (1999)
3. Khademian, B., Hashtrudi-Zaad, K.: Performance issues in collaborative haptic training. In: Proceedings of IEEE International Conference on Robotics and Automation (ICRA), pp. 3257–3262 (2007)
4. Lederman, S.J., Klatzky, R.L., Hamilton, C.L., Ramsay, G.I.: Perceiving roughness via a rigid probe: Psychophysical effects of exploration speed and mode of touch. Haptics-e 1(1) (1999)
5. Levitt, H.: Transformed up-down methods in psychoacoustics. Acoustical Society of America 49, 467–476 (1971)
6. Oakley, I., Brewster, S.A., Gray, P.D.: Can you feel the force? An investigation of haptic collaboration in shared editors. In: Proceedings of Eurohaptics, pp. 54–59 (2001)
7. SensAble Technologies (1993), `http://www.sensable.com`
8. Tan, H.Z., Barbagli, F., Salisbury, K., Ho, C., Spence, C.: Force-direction discrimination is not influenced by reference force direction. Haptics-e 4(1) (2006)
9. Toffin, D., McIntyre, J., Droulez, J., Kemeny, A., Berthoz, A.: Perception and reproduction of force direction in the horizontal plane. Neurophysiology 90(5), 3040–3053 (2003)
10. Wu, M., Abbott, J.J., Okamura, A.M.: Effects of velocity on human force control. In: Proceedings of First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics 2005, pp. 73–79 (2005)
11. Yang, X.D., Bischof, W.F., Boulanger, P.: Perception of haptic force magnitude during hand movements. In: IEEE International Conference on Robotics and Automation (in press, 2008)