Exploratory movements in unconstrained tactile search with virtual surfaces

Theodore E. Milner, Roger Gassert
Rehabilitation Engineering Laboratory
HEST, ETH-Zurich
Zurich, Switzerland
tmilner@ethz.ch

Vincent Hayward
Sorbonne Universités, UPMC Univ Paris, 06,
UMR 7222, ISIR, F-75005, Paris, France

***Abstract*—The objective of this study was to determine how humans use tactile information to guide exploratory movement of the hand. A virtual environment made it possible to adjust the tactile input parameters online, based on subject behavior, something which is impossible with conventional techniques. We employed a haptic interface which applied distributed differential traction to the skin of the fingertip and investigated the effect of reducing tactile contrast on the ability to locate a virtually rendered ridge on a textured background. The difficulty of the task increased as the stimulus amplitude used to render the ridge decreased and the stimulus amplitude used to render the textured background increased. Difficulty depended more strongly on the amplitude of the textured background than on the amplitude of the ridge. The time taken to locate the ridge increased with difficulty. Most frequently, subjects crossed the ridge either once or twice before definitively establishing its location. The ability to locate the ridge did not appear to be sensitive to the velocity at which the ridge was crossed unless the difficulty was high. Our results suggest that haptic interfaces based on tactile stimulation to guide exploration could be used for both diagnostics and rehabilitation of sensorimotor hand function.**

Keywords—texture; finger; tactile discrimination; exploratory movement

I. INTRODUCTION

Most virtual reality environments that employ haptic interfaces combine haptic and visual feedback. However, when vision is not available we frequently perform actions using haptic feedback exclusively, e.g. retrieving an object from a pocket or skillfully typing on a keyboard. We used a novel haptic interface capable of rendering surface features through distributed differential lateral traction of the skin. This technique is based on the principle of contact mechanics that strain fields beneath the surface of a solid, such as a finger, depend on surface boundary conditions that include both pressure and traction distributions [1,2].

We examined how tactile feedback is used to detect and locate a virtually rendered feature present on a textured background in the absence of other sensory inputs. We applied a spatial traction wave in a small region to produce a sensation that was similar to moving over a ridge. Outside of this region we created a textured background by varying the traction amplitude in a disordered manner to investigate the effect of "tactile noise" on the ability to detect the ridge. The virtual environment enabled us to also conveniently study movement strategy.

Fine textures can only be perceived through relative sliding movement of a textured surface over the fingertip skin. Such sliding movements create time-varying patterns of surface boundary conditions that propagate as a time-varying strain fields beneath the skin surface where these fields are sampled by a dense population of cutaneous mechanoreceptors. The ability to render virtual textures by applying dynamic distributed strain patterns to the fingertip has been previously demonstrated in experiments conducted with the haptic device employed in the current study [3]. During sliding movement, even for typical tactile exploration speeds, the boundary condition can vary very rapidly owing to the presence of high spatial frequencies in a stimulus and/or owing to varying frictional interfacial forces [4-6], resulting in a rich source of information for the brain to perceive the underlying texture.

Whereas the perception and discrimination of textures have been extensively investigated using qualitative and quantitative methods, an extensive literature search identified only three previous studies in which quantitative methods were used to investigate how differences in texture guide exploratory hand movements in unconstrained tactile search [1,7, 8].

The motivation for this study was to determine how tactile feedback is used in exploratory movements to control motion of the hand when both sensation and brain function are normal. This behavioral study is a precursor to a study in which the same task will be used in conjunction with resting-state fMRI to determine which areas of the brain process tactile signals during transformation of tactile feedback to motor output. Once the normal sensorimotor transformation network has been identified the method will be applied to post-stroke patients to examine how the sensorimotor network involved in hand function is affected by stroke.

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II. METHODS

A. Haptic Interface

We used a 64-pin traction array to apply differential traction to the skin of the tip of the index finger [5]. The traction array was 8.4 mm square. A virtual ridge was created by displacing adjacent columns of the array in a linearly increasing and decreasing fashion as the fingertip passed over the location of the ridge. The haptic interface was attached to a three-link arm, allowing it to move freely in a horizontal plane. Encoders at each of the three joints permitted calculation of the position of the midpoint of the tactile array. The haptic interface moved on a Teflon surface, gliding with moderate friction. The ridge was rendered in a zone between two parallel lines separated by 8.4 mm. The target changed location between trials over a 150 mm range along the axis perpendicular to that of the parallel lines that delineated the ridge.

B. Protocol

Ten subjects between the ages of 21 and 30 participated in the study. Subjects were instructed and allowed to become familiar with the task for one minute with full vision prior to beginning the recording session. They placed the tip of the index finger of their dominant hand on the tactile array and moved the interface in any way they chose to locate the ridge. They were told that they would score points each time that they located the ridge and that more points could be scored by locating the ridge more quickly. They were also told that the ridge would be made more difficult to locate if they were successful but that the score would also increase with the level of difficulty. The training session was divided into three ten-minute intervals with an imposed break of approximately one minute between training intervals.

The ridge was oriented along an axis approximately parallel to the subject's sagittal plane. Subjects searched for the ridge by moving left and right. A trial ended whenever the subject located the ridge (stopped within the 8.4 mm zone for at least 0.5 s) or failed to locate the ridge within ten seconds. The ridge was then displaced in a random manner to a new location within the 150 mm workspace. If subjects succeeded in locating the ridge at least six times in an eight-trial block, the level of difficulty was increased by reducing the contrast between the ridge and the background texture. A somewhat disordered background texture was generated by displacing each pin in the traction array based on a sinusoidal function of the location of the interface and the matrix location of the pin in the tactile array. This created the perception of moving over a textured surface where the intensity of the sensation was increased by increasing the maximum pin displacement (lateral traction). The contrast between ridge and background was reduced either by reducing the displacement of the pins that rendered the ridge or increasing the displacement of the pins that rendered the background texture. If subjects succeeded on fewer than three attempts in an eight-trial block the contrast was increased. The contrast did not change when subjects were successful on three, four or five of the eight trials. Task difficulty was quantified on a nine-point scale according to the number of unsuccessful trials (0-8) in each block.

III. RESULTS

A. Task Difficulty

To assess the contribution of the intensity of the perception of the ridge and background texture to the task difficulty we performed multiple linear regression using ridge and background amplitudes as independent variables to predict task difficulty. The following expression provided a good fit to the mean data across trials and subjects: $D = 3.1 - 0.0058R + 0.087B$, where D is difficulty, R is ridge amplitude and B is background amplitude (r^2=0.81, p=0.016). This indicates that difficulty increased as ridge amplitude decreased and as background amplitude increased. However, the regression coefficient for background amplitude is more than an order of magnitude greater than for ridge amplitude, suggesting that the intensity of the perception of the background texture had a more profound effect on difficulty.

B. Trial Duration

The mean time taken to locate the ridge on successful trials increased in a relatively linear manner (r^2=0.67, p=0.013), from about 4.5 s to 6.6 s, as task difficulty increased from 0 to 7 (0 to 7 unsuccessful trials). Although the time increased incrementally from difficulty 1 to 7, there was a marked jump from 4.5 s to 5.9 s when difficulty increased from 0 to 1.

C. Number of Ridge Crossings

In an effort to better understand how subjects were able to locate the ridge, we examined features of their movements. One feature was the number of times they crossed over the ridge before stopping. If the ridge was difficult to detect one could expect that the subject would pass over the ridge multiple times to confirm its location. On almost all successful trials it was crossed either 1 (40%) or 2 (43%) times (Fig. 1). The mean number of ridge crossings remained in the range of 1.8 to 2.0 when difficulty was less than 6, but increased to 2.3 for difficulty 6 and 7 and 2.6 for difficulty 8.

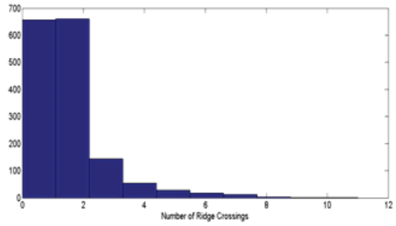

Figure 1 Distribution of the number of times the ridge was crossed before stopping.

D. Velocity of Ridge Crossings

We also determined the velocity at which the ridge was crossed on successful trials. The distribution of velocities for the final time that the ridge was crossed was similar whether it was crossed 1, 2, 3 or 4 times. It was generally greater than 10 mm/s but rarely exceeded 100 mm/s. Most frequently it was around 50 mm/s (Fig. 2). The mean ridge crossing velocity was a nonlinear function of the difficulty. It increased slightly from 57 mm/s to 61 mm/s for difficulty 0-2, decreased to 51 mm/s for difficulty 3-5, but increased sharply to 72 mm/s for difficulty 6 and to 86 mm/s for difficulty 7. This suggests that higher ridge crossing velocities provided greater sensitivity when the ridge was difficulty to detect. On average, subjects stopped near the center of the target, regardless of the difficulty. The average stopping position was between 4.85 mm and 5.45 mm from the edge of the target region across the range of difficulty.

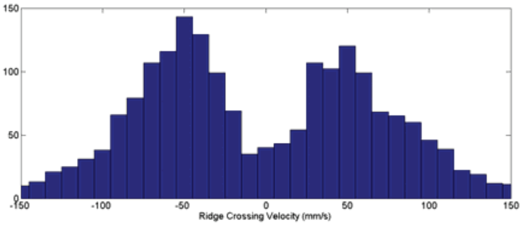

Figure 2 Distribution of the velocity at which the ridge was crossed just prior to stopping

IV. CONCLUSIONS

We have begun to investigate how tactile signals are processed to control movement of the hand during exploratory movements in tasks involving feature detection on a textured surface. Our results so far suggest that this ability degrades in a manner that depends much more strongly on the intensity of the background than the intensity of the feature. The results of this study provide a foundation for developing assessments of somatosensory impairment. Tactile displays similar to that used in this study can be used both as diagnostic tools and rehabilitation aids to train subjects in feature discrimination and localization. The ability to precisely control the characteristics of the tactile stimulus *and* to accurately quantify exploratory tactile behavior provides a dimension that has been so far largely unexplored in the field of sensorimotor function of the hand [9]. Further studies are planned to establish how the brain uses tactile information to guide hand movements in subjects with sensorimotor deficits.

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