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Viscous Textures: Velocity Dependence in Fingertip-Surface Scanning Interaction

Daniel J. Brewer, David J. Meyer, Michael A. Peshkin, and J. Edward Colgate

***Abstract*— We explore the impact of fingertip velocity and material properties on the lateral force interaction between a fingertip and a texture. Three sinusoidal gratings of varying compliance were scanned by a finger at a variety of speeds while lateral force and fingertip position were measured. Two robust trends were noted: one, for more compliant textures, the DC component of lateral force was larger, and it increased with scanning speed (i.e., it had a viscous component); two, for all textures, but especially the more compliant ones, the $1/f$ background noise component of lateral force decreased with increased scanning speed. Focusing on the first of these trends, we used a TPad haptic device to implement virtual gratings with multiple levels of viscosity and DC friction, and we performed a multidimensional scaling analysis as well as comparisons to two of the physical gratings. The results demonstrate that both DC friction level and viscosity have significant perceptual consequences, but suggest that subjects may not be able to distinguish readily between friction and viscosity, at least at the levels implemented here.**

I. Introduction

Texture is a topic of growing interest to the haptics community, and questions about texture abound: what physical parameters (e.g., surface profile, skin vibration, lateral force, etc.) should be measured? What mathematical representation of texture data is most perceptually relevant, and most useful for processing the data (e.g., to make a virtual texture feel more or less rough)? What technologies (e.g., vibrotactile or variable friction) and what algorithms lead to the most flexible and realistic virtual textures? Our own work in this area has led to a healthy respect for the complexities of these problems; therefore, in the present study we have restricted our attention to one class of textures – sinusoidal gratings – and one display technology – variable friction via the TPad [1]. We focus on this combination because we have found that sinusoidal gratings displayed via the TPad can achieve a surprising degree of realism. We show, however, that the parameterization of even these simple textures can be surprisingly complex. We also show that gratings made of soft materials can yield a significant velocity dependence in addition to high levels of DC friction. This inspires a multidimensional scaling analysis of the effects of viscous friction and coulombic friction on the feel of a virtual sinusoidal grating.

II. Background

Minsky's Sandpaper system [2] is among the earliest and best known works on haptic texturing, but because it employed a force feedback manipulandum, it was also restricted to fairly coarse and low-frequency virtual textures. Most work in recent years has, in contrast, made use of vibrotactile devices that can produce AC forces from 10 Hz to 1000 Hz. For instance, Kuchenbecker and her colleagues have used a stylus incorporating a high bandwidth voicecoil to display vibrations when dragged across a flat surface [3]. A further challenge is to present virtual textures to the bare fingertip as it explores a surface. For example, piezo stacks mounted on a linear slide can create out-of-plane [4] or in-plane [5] vibrations that a finger experiences as it moves laterally. Surface friction-modulating devices [6] have also been shown to generate wide-bandwidth vibrations [7] and have been used to render texture [8].

Although various methods can produce wide-bandwidth vibrations at the fingertip, there is little guarantee that those vibrations will feel much like an actual texture. One issue is that the mechanics of skin-surface interaction is likely more complex than any existing technology can simulate. For instance, none of the techniques mentioned above can provide for spatial variation across the fingerpad, yet this may be quite important in perceiving natural textures. Aside from hardware limitations, there is the question of what physical variables should be measured, and the further question of how these variables should be represented mathematically in order to control the haptic device. In recent years, a wide variety of methods for characterizing texture mechanics have been investigated. For instance, surface height measurements have been correlated to texture perception [9], and several haptic interfaces have used surface-height analogies for rendering virtual texture [2]. Others have made measurements not on the surface itself, but on a probe dragged across the surface. For example, Culbertson et al. [10] used multi-axis acceleration of a probe coupled with velocity and normal force to populate a set of filter parameters. The filters could then be used to generate vibration signals in real-time [11]. Wiertlewski et al. measured lateral skin deformation as a function of space [12]. Bensmaia and colleagues have used laser doppler vibrometry to measure vibrations on the skin as textured surfaces are scanned across the fingertip [13].

One factor noted in both Culbertson et al. [11] and Manfredi et al. [13] is that the vibrations of texture are dependent on velocity. For instance, Manfredi et. al demonstrated that the frequency profile of fingertip vibrations varied significantly when scanning at different speeds (80 mm/s vs 120 mm/s). Intuitively, this dependency seems evident in, for example, the case of a finger scanning over a periodic sinusoidal grating. At lower velocities the skin is able to

The authors are with the Department of Mechanical Engineering, Northwestern University, 2145 N Sheridan Rd, Evanston, IL 60208, USA E-mail: brewer@u.northwestern.edu; meyerdj@u.northwestern.edu; peshkin@northwestern.edu; colgate@northwestern.edu

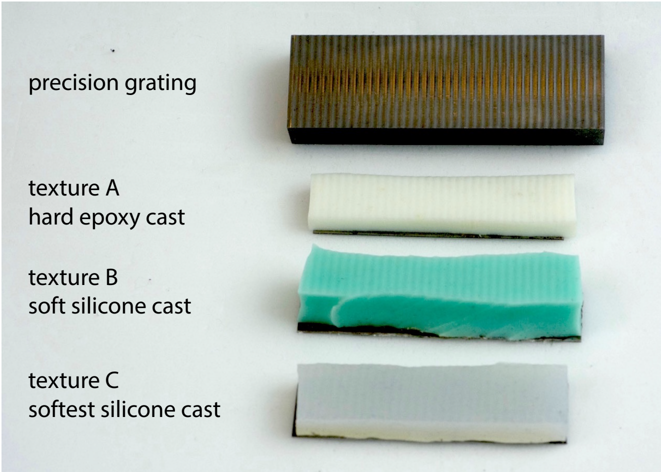


Fig. 1: Precision grating and three casts used for texture measurement

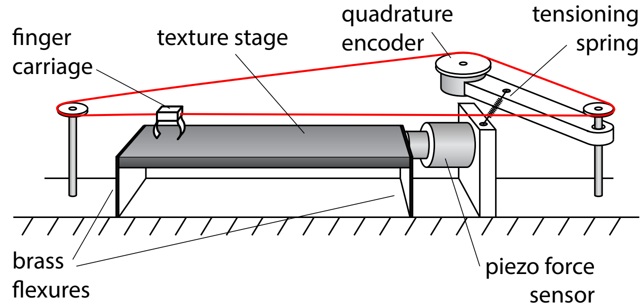


Fig. 2: Experimental apparatus

contour to the surface. As the speed increases, however, the skin is no longer able to sink into the troughs, but instead skims along the peaks. This velocity dependence has not been quantitatively modeled nor has it been implemented in a friction modulating haptic interface, such as the TPad.

Another factor noted in Manfredi et al. is that surface profile alone is a poor predictor of texture perception. The vibrations elicited by finger-surface interaction depend on material properties of the surface as well. Among the relevant properties are coefficient of friction and compliance.

In the present work, we aimed to measure perceptually relevant texture variables for a finger stroked across a sinusoidal grating. While the nominal shape of the grating was held constant, material parameters were varied. We then attempted to represent the texture data in a low-dimensional parameter space including velocity-dependent parameters. Finally, we explored the range of textures that could be created by varying friction and damping characteristics of a virtual grating, including comparisons to physical standards.

III. Experiment 1: Texture Measurement and Parameterization

In an initial set of experiments, the lateral forces exerted on various real textures as a fingertip was stroked laterally across them were analyzed. Three textures were used, all of which were cast from the same initial precision sinusoidal grating, shown in Figure 1, which had a spatial period of 2.5 mm and a height of 50 microns. Texture A was a hard epoxy cast, Texture B was a softer silicone cast with a higher coefficient of friction and Texture C was an even more compliant and sticky silicone cast.

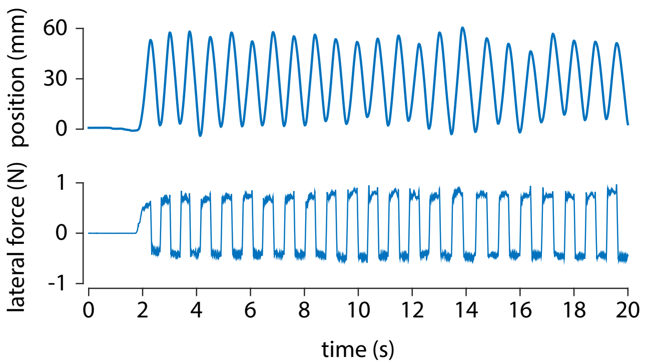
Data were collected using the setup seen in Figure 2. Finger position was measured with a quadrature encoder having a resolution of 3.8 microns and sampling at 125 kHz. A steel wire was wrapped around the encoder and attached to a plastic carriage that clipped securely to the finger. A high bandwidth piezoelectric force sensor which resolves mN forces was used to measure the lateral force exerted on the texture by the finger. The texture samples were attached to a magnetic stand, and were roughly 7 cm in length. The overall resonance of the device was around 1000 Hz. The quadrature encoder and force sensor data were imported into Matlab for data analysis. Data were collected in 20 second trials, during which the lead author's finger scanned back and forth along the length of the texture for 20 seconds. An example result is shown in Figure 3a. The lateral force signal was then low pass filtered at 1000 Hz with a 1st order Butterworth filter to avoid interference from the device's overall resonance. The normal force exerted by the finger was considered constant for all trials.

The lateral force signal was divided into sections of constant velocity, with only the sections falling within 2.5% of the desired velocity being saved. Since no apparatus aided in maintaining proper finger velocity, this tolerance (coupled with a lot of practice) allowed for a reasonably high fraction of finger-swipes to be saved rather than discarded. Non-steady-state sections (such as the ends of travel) were removed. One example constant velocity section is shown in Figure 3b. The saved sections were resampled in the spatial domain and interpolated linearly, the result shown in Figure 3c. A spatial (rather than temporal) FFT of each section was taken. This approach was chosen because the rendering method used in the second experiment controlled TPad friction level (and therefore, lateral force) as a function of fingertip position and velocity, not as a function of time. This procedure was repeated for all three textures at five different speeds: 50, 80, 120, 180, and 270 mm/s.

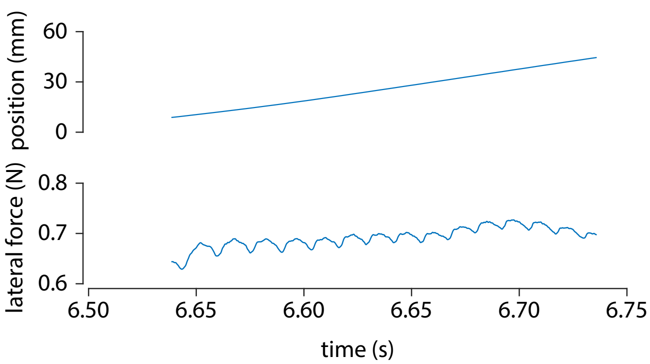
To interpret the large amount of data gathered, the FFTs were considered to consist of three components: DC friction, AC friction harmonics, and background $1/f$ noise[14]. The components were each modeled with a power fit to simplify the FFTs into five parameters: f_{DC}, α_b, β_b, α_h, and β_h. According to this parameterization, the lateral force can be described by equation 1. The fit of the average frequency spectrum is shown in Figure 4.

$$
\begin{gathered}
f(x) = f_{DC} + A_k \sin(2\pi f_k) + B(x) \\
A_k = \beta_h f_k^{-\alpha_h} \qquad B(x) = \beta_b f^{-\alpha_b} \text{ noise}
\end{gathered}
\tag{1}
$$

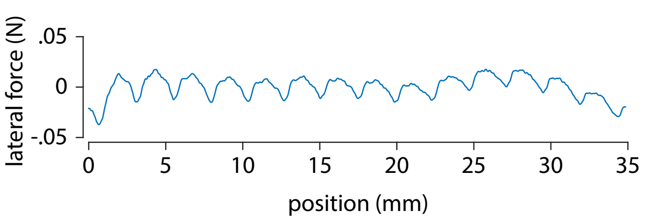
For the background noise component, the α_b, β_b values were determined for a given texture and speed by running a best fit power model through the non-harmonic sections of all of the FFTs for the given texture and speed. For the harmonic



(a) Twenty seconds of lateral force data from a single trial



(b) A section of the lateral force signal in steady-state behavior



(c) Steady-state lateral force resampled in the spatial domain

Fig. 3: Data slicing and resampling steps

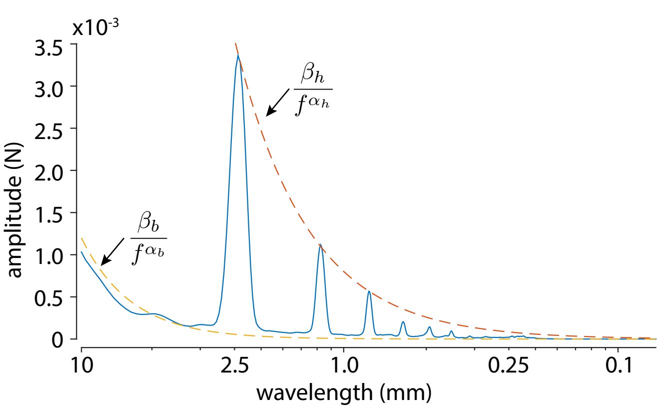


Fig. 4: Parameterization of lateral force spectra

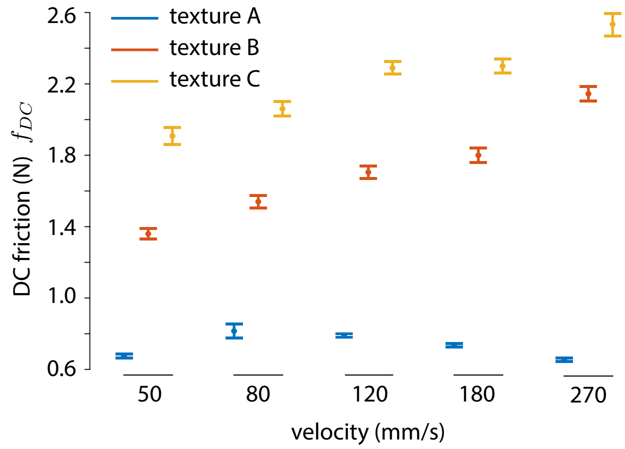


Fig. 5: Average magnitude of DC friction versus scanning velocity for all three textures

component, the parameters were found by running a best fit power model through the first three harmonic peaks of all FFTs for a given texture and speed. At higher speeds, the fourth harmonic peak begins to be affected by the 1000 hz low pass filter.

We calculated these five parameters for all three textures for each scanning velocity. The resulting data is summarized in Figures 5 and 6. The data indicate that as scanning speed increases, background noise decays at a greater rate and the overall magnitude of background noise decreases. For Textures B and C, all parameters increase compared to Texture A. No significant velocity dependence was identified for the harmonic components for all three textures. Most notably, however, is a trend seen in Figure 5. For Textures B and C, lateral force increases linearly with scanning speed. However, for Texture A, this dependence is absent.

IV. Experiment 2: Perceptual Effects of Viscous Damping and Friction

In a second set of experiments, the perceptual significance of these findings was explored. Virtual textures were implemented on a TPad: a haptic interface that can control lateral forces on the fingertip by varying friction levels on its surface.

The TPad was constructed as follows. Two piezoelectric actuators were glued to a 104mm x 22mm x 3mm glass plate and used to excite a flexural mode resonance at approximately 32 kHz. These vibrations set up a squeeze film of air in the gap between the fingertip and the glass surface, decreasing the frictional force on the finger[1]. Modulating the amplitudes at which the piezoelectric actuators vibrate allowed for control of the relative surface friction of the haptic display. The total friction range was resolved with 16 bits, yielding very fine open-loop control over the friction level. Finger position was measured using a special-purpose infrared light sensor. Position data was sampled and the friction level updated at 8.3 kHz with a 5.3 micron resolution. The virtual textures were one-dimensional and each was approximately 100mm wide. The 8.3 kHz sampling rate and 16 bit friction range resolution allowed the TPad to display a wide range of textures with very low latency.

The five-parameter model described previously was simplified to generate virtual textures. Because there is no explicit function for generating $1/f$ noise, we did not implement the background noise in our hardware. Moreover, because the signal is dominated by the fundamental period, and because there is evidence that phase information at high spatial frequency does not play a substantial role in perception[15], we did not include the relative phase of the harmonics as a parameter in the reconstruction. The friction commanded to the TPad is given by equation 2. The main parameters of interest for this study were viscosity and DC friction, as their relationship to increasing compliance and stickiness was perhaps the most evident out of all the parameters: more compliant textures are more viscous and have higher DC friction levels.

$$f(x,v) = f_{DC} + v f_{vis} + (\beta_h + v\beta_{vis}) \sum_{i=1}^{4} i^{-(\alpha_h + v\alpha_{vis})} \sin\left(\frac{2\pi x}{\lambda} i\right) \tag{2}$$

The parameter values for our experiment were selected such that the highest levels produced textures with maximum lateral force outputs near the maximum coefficient of friction that TPad can simulate and the lowest levels generated textures with minimum lateral force outputs close to the minimum force that TPad can simulate. Each variable (except α_h and α_{vis}) is scaled such that 1 represents the maximum dynamic range capable in the hardware. For our experiment, four parameters were held constant, $\beta_h = 0.125$, $\beta_{vis} = 0$, $\alpha_h = 2.5$, and $\alpha_{vis} = 0$. The DC friction was tested at three values, $f_{DC} = [0.325, 0.500, 0.675]$, and viscosity was also tested at three values, $f_{vis} = [-0.2, 0.0, 0.2 \text{ per } 400 \text{ mm/s}]$. A negative viscosity was tested to offset the observed positive viscosity inherent on a glass surface, found both in our own measurements and in [16].

The perceptual experiments were composed of two sections: comparisons between different virtual textures, and comparisons of virtual textures to real textures. In the first section, participants were asked to rank the similarity of each pair of virtual textures. With nine virtual textures, a total of 36 comparisons were needed to complete a similarity matrix. Twelve warm-up comparisons were run prior to the 36 comparisons to provide context for participants to better determine similarity. In the second section, participants were asked to categorize each virtual texture as either closer to Texture A, or Texture B. Texture C was eliminated because the silicone itself was degrading rapidly. Each texture was presented in random order three times each for a total of 27 trials. In total, 75 trials were run on ten subjects. The protocol was approved by Northwestern University's Institutional Review Board, and all subjects gave informed consent.

The similarity data was inverted to create a 9x9 dissimilarity matrix. We performed a multidimensional scaling (MDS) analysis on this data, the results of which are shown in Figure 7. We plotted vectors representing the best fit lines for friction and viscosity parameters, as well as similarity to real textures through the MDS space using an optimization routine described in [9]. We scaled each of the parameter values to lie on vectors of length 1, centered at zero. For example low friction points correspond to -0.5 on the friction vector, high friction points correspond to 0.5. Similarly, we scaled the similarity to Textures A and B such that if a virtual texture always corresponded to B, it received a value of -0.5, whereas always corresponding to A was given a 0.5. Vectors were fit by a minimization equation which can be solved with equation 3, where q_i represents the parameter value of point i, and x_i represents the position of point i in MDS space.

$$\vec{p} = \frac{\sum q_i \vec{x}_i}{\sum q_i^2} \tag{3}$$

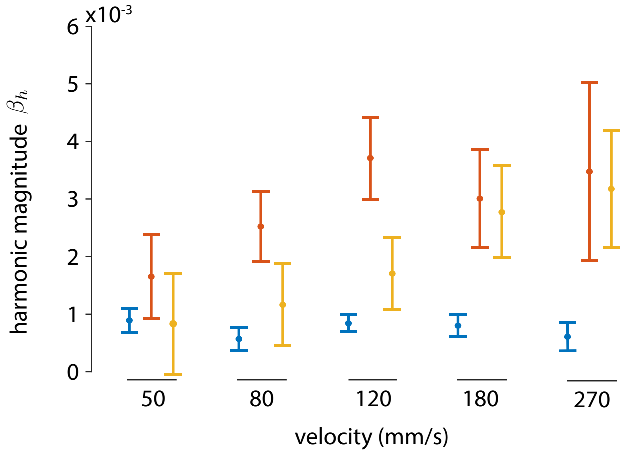
The resulting vectors are plotted in the same MDS space shown in Figure 7. The orientation of the vector indicates the general trend of the data, and the length of the vector indicates the relative strength of the parameter in MDS space.

In general, virtual textures having higher friction and viscosity were rated as feeling more like the Texture B than Texture A, whereas low friction and viscosity levels felt more like Texture A. In addition, the impact of friction and viscosity on likeness to either texture was roughly equivalent. It is also notable that when either friction or viscosity is fixed at one level, the lowest level of the variable parameter is closest to Texture A and the highest level is closest to Texture B. The virtual textures furthest on either ends of the spectrum still did not reach Textures A and B, indicating that the virtual textures were not able to replicate exactly the perceptual qualities of the real textures.

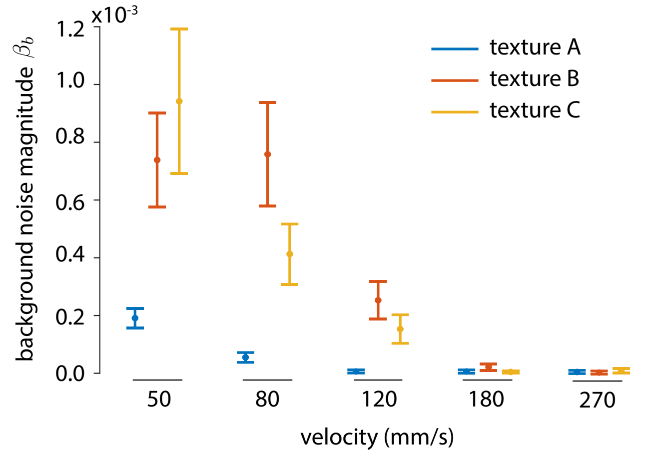
V. Discussion

Based on the results of the first experiment, as scanning speed increases, the background noise component of lateral force decreases in overall level and decays more rapidly. Interestingly, however, the harmonic component of lateral force is not affected by fingertip velocity. When scanning a periodic texture such as a grating at higher speeds, one would suspect that the fingertip would skip over some of the troughs of the grating and impact more forcefully against the peaks of the texture, increasing the harmonic component of the lateral force. Indeed, when scanning a texture such as a sinusoidal grating at higher speeds, it feels like the overall periodicity of the surface contributes more to the feel of the texture than other aspects like roughness. The data do not show this trend, instead they show the background noise component decreasing and the harmonic component remaining the same. Perhaps by decreasing the background noise, the harmonic component appears relatively stronger perceptually.

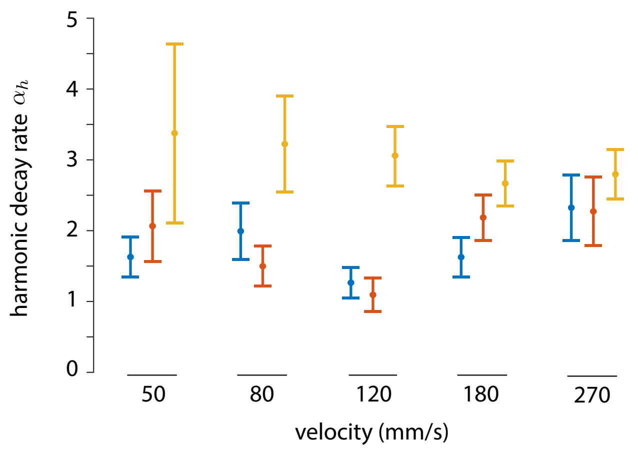
We also found that for Textures B and C, lateral force increased linearly with scanning speed. This suggests that compliant textures are more viscous than non-compliant textures. At similar speeds, more compliant textures produced a greater lateral force. This seems intuitively correct, as the more compliant gratings have higher coefficients of friction.



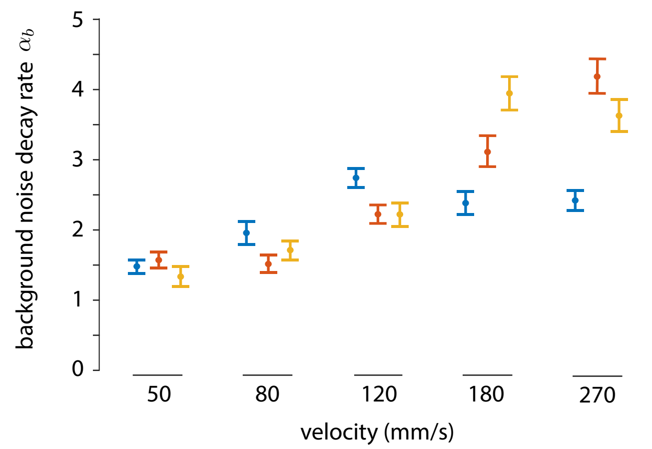
(a) Average magnitude of the lateral force harmonics versus scanning velocity



(b) Average magnitude of the background 1/f noise versus scanning velocity



(c) Average decay exponent of the lateral force harmonics versus scanning velocity



(d) Average decay exponent of the background 1/f noise versus scanning velocity

Fig. 6: Summary of results from experiment 1: plots of average parameter values obtained for each scanning velocity

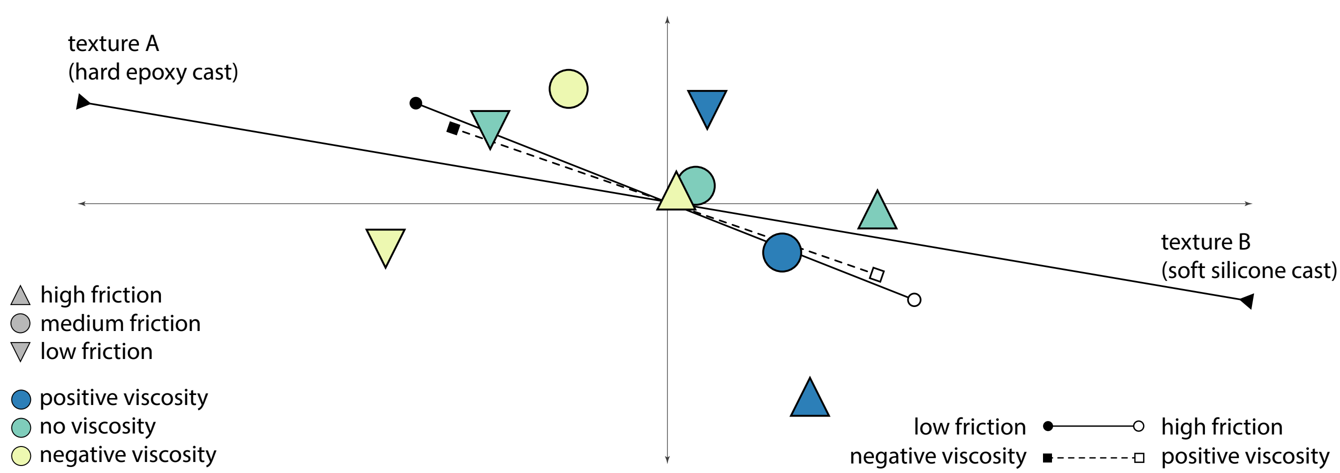


Fig. 7: Summary of results from experiment 2: multi-dimensional scaling of the resulting perceptual distances of the nine virtual textures. Shorter lines ends represent the projection of the friction and viscosity values into the MDS space. The long line represents the projection of the similarity to the real textures into the MDS space.

It's interesting to note that no viscosity was found for Texture A, despite a greater amount of energy being dissipated by the texture at higher scanning speeds. In addition to having a higher coefficient of friction, the softer grating peaks in Textures B and C may dissipate significantly more energy as they are deformed much more than Texture A whose peaks do not compress.

The results of the second experiment are in line with expectations based on our initial research. Virtual textures with higher viscosity and friction levels feel more similar to Texture B, whereas lower viscosity and friction levels feel more similar to Texture A. Viscosity and friction level are both perceptually important in simulating more compliant and sticky textures.

However, even with their implementation, the viscous and high friction virtual textures still did not feel equivalent to their real counterparts, as indicated by the magnitude of the real texture vector in Figure 7. One possible reason for this is TPad's inability to create friction levels as high as those experienced while scanning Texture A. Perhaps different viscosity relationships, such as a quadratic scaling of lateral force with velocity, would produce more realistic virtual textures. While the data from the first experiment indicate that lateral force scales linearly with velocity, its possible that a more exaggerated viscosity profile will have a greater perceptual impact.

The data also do not rule out the possibility that adding a viscosity relationship merely serves to further increase the overall friction output of TPad, and that the velocity dependence isn't perceptually significant, but rather the increased friction level resulting from it carries all the perceptual importance. We hope to further explore this in future work, and design an experiment that more clearly separates the impacts of DC friction and viscosity.

VI. Conclusion

We support the idea that surface height is not the only predictor of texture perception, rather other factors such as fingertip velocity must be taken into account. We parametrized lateral force in space in order to explicitly observe velocity dependence. We observed that while $1/f$ background noise decreases with increasing velocity, the harmonics of lateral force don't necessarily increase with increasing velocity. We observed differences in friction level and viscosity for different textures, and after testing the perception of these differences we found that the subjects classified the more viscous virtual textures as being closer to the more viscous real texture, and the higher friction level virtual textures as being closer to the higher friction real texture.

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