

under the LabVIEW™ environment on an ordinary computer equipped with the digital input-output board already mentioned.

3 Experimental Procedure for Perceptual Calibration

Having unambiguously converted a varying interaction force into a skin displacement during the scanning of a surface by means of an apparatus designed to establish robust causal relationships not achievable with conventional haptic devices, the question now arises of the value of the conversion factor that could elicit an equivalent sensation of roughness. Furthermore, if such a factor exists, does it vary from person to person? To address these questions, a calibration procedure was carried out with six participants in order to establish the point of subjective equivalent roughness between the natural texture and its simulated version. A 2-alternative forced choice, constant stimuli procedure was employed to find the gains \hat{G}_ψ that would elicit an equivalent sensation of roughness.

Stimuli. The standard stimulus was a triangular grooved grating of 1 mm spatial period with 0.1 mm of depth. Without relative motion, the roughness of this texture was not perceptible. The scanning force with this grating was measured using the sensor described earlier with the help of a “standard” participant. During recording, the speed v and the normal force F_n were held constant with a 10% tolerance. The signal was processed as described in Section 2.1, then normalized to ± 0.5 V. The filtered signal, expressed in Newton, and its Fourier transform are shown in Fig. 4b. The comparison stimulus was provided by the stimulator described in Section 2.2. Fig. 4a illustrates the precautions that were taken so that both stimuli were presented in exactly the same conditions: (a) The participants had their proximal phalanx resting in cradles connected to sliding guides so that the fingertip rested on the grooved texture or stimulator in same manner; (b) Both surfaces were made in polycarbonate; (c) The two sliders were mechanically connected so the same inertia and the same friction was felt for the standard and the comparison stimuli. The experimental setup was hidden by a curtain to avoid visual bias. Subjects wore sound isolation headphones (model K518, AKG Acoustics, Harman International Industries) playing white noise.

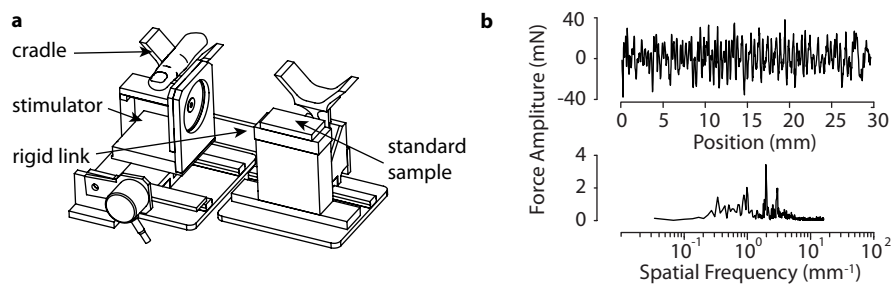


Fig. 4. a: Experimental setup. **b:** Stimulus and its spectrum. The scanning process transforms a simple surface waveform into a complex, broadband force signal.

Subjects and Procedure. Six volunteers participated in the experiment, two female and four male, all right-handed, aged from 24 to 31 years. They were from CEA LIST and two of them were familiar with haptic technology. Their hand was guided to explore the setup and after short instructions they were asked to judge whether the standard or the comparison stimulus was rougher and to give an answer via a keystroke. Like in [11], no definition of roughness was given except that “roughness is the opposite of smoothness”. Neither training nor feedback was provided during the tests. Gain G_Ψ was randomly chosen in a range of 1 to 10. Each value was tested at least 10 times.

4 Results

Subjects responded to gain changes following a typical psychometric curve, as shown in Fig. 5. The data were fitted with a cumulative Gaussian distribution $f(x) = 0.5 \left[1 + \operatorname{erf} \left(\frac{x - \mu}{\sqrt{2}\sigma} \right) \right]$ where x is the gain, μ the mean gain and σ^2 the variance. The data fitting was achieved using a nonlinear least-square fitting procedure.

The point of subjective equivalence (PSE) was extracted from the gain that corresponds to a 50% probability of judging the comparison rougher than the standard. Figure 6 shows the distribution of PSE's. The average across subjects is $\bar{G}_\Psi = 3.99$ with a standard deviation of 0.93.

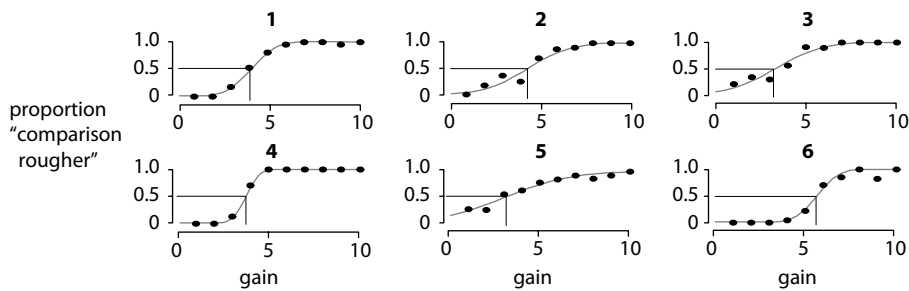


Fig. 5. Results of each participants and their sigmoid fitting

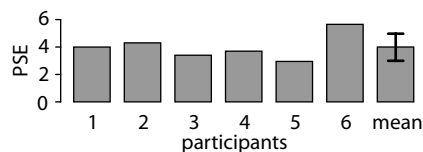


Fig. 6. Value of the Point of Subjective Equivalence of each subject

5 Discussion

The results indicate that the interaction force variation can be converted to skin displacement variations to elicit an equivalent sensation of roughness for a virtual surface compared to a real one. As a result, this particularly simple stimulation method is shown to

be effective at simulating the roughness of a surface. Moreover, participants frequently commented on the perceptual similarity of the sensations themselves between real and simulated surfaces.

These results support the idea that as far as fine textures are concerned, spatial information can be completely eliminated from the simulation, yet, the conscious experience can be that of a non-smooth surface. While similar observations have frequently been reported in the past, our experiments, given to the care that we put in controlling the causality as well as the quality of the transmitted signals, make it now possible to quantify the conditions under which such phenomenon occur. Another aspect of our results worthy of some comments is the relative constancy of the conversion factor among individuals. Of the six individuals who lent themselves to the experiment, five obtained very similar numbers. Only one required a significantly higher displacement stimulus to achieve an equivalent level of roughness. Our efforts will be directed in the future at understanding these individual differences.

6 Conclusion

With the help of a carefully engineered sensor, sliding frictional forces could be acquired within a very high dynamic range. The same device was turned in a stimulator having, by construction, a compatible dynamic range that could convert this frictional force into a displacement able to provide a simulated sensation.

This study has so far considered only one texture for perceptual calibration. We plan to investigate other aspects of texture signals, such as spectral content, in addition to amplitude, and to study the conditions under which perceptual equivalence can be achieved. The distribution of roughness perception across gain values was found to be a monotonic function. As a result, one could employ fast calibration procedures such as accelerated staircase methods as in [11].

A final implication of the present experiment is the possibility to replace force feedback stimulation by cutaneous displacement stimulators which may lend themselves to more favorable engineering tradeoffs, particularly with subminiature devices. Such miniature devices could for instance be embedded in the gripping surfaces of conventional force feedback devices.

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