Semantic Parameterization of Basic Surface Models Rendered with PHANToM Omni

Yugo Hayashi, Eric W. Cooper, Victor V. Kryssanov, and Hitoshi Ogawa

College of Information Science and Engineering
Ritsumeikan University
Kusatsu, Shiga, 525-8577 Japan
yhayashi@fc.ritsumei.ac.jp, {cooper, kvvictor, ogawa}@is.ritsumei.ac.jp

Abstract. This paper presents a study of subjective responses to haptic stimuli displayed as surfaces on a haptic force feedback device and a computer monitor and experienced through free kinesthetic exploration. The modified settings were stiffness, static friction, and dynamic friction as defined in the PHANToM Omni standard SDK. A sphere was used as the virtual shape for exploration. Subjects spoke freely about their subjective responses while session moderators recorded the comments as text. The responses were broken down and categorized by morphological analysis of haptic sensation primitives: hardness, softness, roughness, smoothness, and elasticity. Analysis of the resulting morphemes showed that eliciting specific subjective outcomes in kinesthetically experienced haptic space requires adjustment of multiple settings. Naïve understandings of haptic materials surface settings in such devices are likely to be insufficient. Open ended semantic studies such as the one described in this paper can result in a better understanding of this perceptual space and lead to better guidelines or supportive systems for haptic interface developers.

Keywords: subjective haptics, haptic materials settings, friction, stiffness

1 Background and Motivation

Designers of interfaces that employ haptic modalities require models of user subjective response for many purposes, including real-world fidelity, affective product design, and descriptive instruction. In the past decades, there have been many studies in physical surface texture sensations but the work was not followed up by studies on the haptic displays now commonly available, nor has there been a systematic study of the subjective responses to specific surface characteristic settings on these devices. Models of subjective response are necessary not only for systems designed to achieve specific subjective results but, more importantly, for the designers of various haptic interfaces who would then have a common reference layer of subjective interpretations for virtual surface characteristics.

There has been a considerable amount of research elucidating the physical and neurological basis of tactile and haptic sensations. Lederman and Klatsky gave a gentle introduction, including multimodal aspects of haptic interactions [1]. They also briefly outlined some work in affective responses, specifically emotions. However, such work does not provide interface designers with insight about the subjective response a user is likely to have for any specific device setting. After understanding the basic psychophysical processes of kinesthetically interactive haptics, and before moving on to higher cognitive aspects, such as affective response, designers of both experimental and applied interactions need a method for defining the qualitative dimensions of haptic sensation, their orientation, and, eventually, useful quantitative models relative to common software used to define interactions. In other words, when designers choose parameters for surface characteristics, they need a method to describe how it would feel to the users.

Another area that has received significant attention in research has been to match sensations experienced with haptic devices to those experienced with real-world objects. One complaint about this research from those needing to build applications has been that proposed models have been constructed from data or knowledge collected from expert users rather than from the psychophysical models, from real-life objects, or from groups of “ordinary” non-expert users [2]. The psychophysical background has extended into studies of subjective responses to interaction with actual objects. Especially, researchers have sought to model the perceptual dimensions and scaling relating to the sensations of roughness and hardness. Works [3], [4], and [5] describe studies on physical objects to model subjective response. There are, however, many objectives still not met in these models, including the clarification of other subjective aspects of perceptual spaces in sensations experienced with interfaces built around haptic force feedback displays. There is, therefore, a need for the development of new models that would be applicable to both virtual environments, intended to mimic real-world experiences, and more abstract applications of haptic sensation in design, as discussed in [6] and [7].

Because of the developmental and cognitive relationships between tactile sensations and emotive or affective responses, there have been studies of subjective responses in dimensions of emotional category models. Although a few have touched on the issue of quantifying the subjective haptic responses at various settings [8], [9], the proposed theories do not generally attempt to characterize the ordinary non-emotional sensations experienced as physical touch. In order to satisfactorily quantify subjective responses, first it must be established whether users, from a relatively homogeneous social group, respond similarly to similar stimuli rendered with a typical haptic force feedback interface. There are also two open questions about the range of user responses. Model developers and system designers need to know the overall range of subjective responses as a proxy for understanding the general range of subjective sensations the device could be used to communicate.

The goal of the presented work is to lay a foundation for a quantitative model of semantic responses to haptic sensations experienced for a three-dimensional surface form expressed in interactions with a popular force feedback display and graphic user interface, specifically the semantic characterization of the PHANToM Omni parameter space, as defined with the standard SDK [10]. The model is to connect settings related to modeling surface stiffness and friction to possible subjective responses.

This paper thus describes experiments in which subjects experience the kinesthetic haptic sensation of touching a 3D object displayed in a graphic interface and rendered on a PHANToM Omni force feedback device. Each time, the surface characteristics for stiffness, static friction, and dynamic friction are randomized and recorded. The subject speaks freely about the sensation and these semantic phrases are recorded as text. The resulting text data is morphologically analyzed and keywords are extracted to form a basic model of semantic responses to the interactive experience. Section 2 describes the experiments. Section 3 gives the experimental results. Section 4 proposes a model of subjective semantic response of young Japanese subjects to the given kinesthetic haptic interaction with the PHANToM Omni display. This section also discusses the conclusions drawn from the study's results and outlines directions for future work.

2 Methods

The experiments described in this paper collected subjects' open-ended, subjective responses to a typical interaction with a PHANToM Omni haptic device. The interaction is touching a virtual sphere displayed both on an ordinary computer monitor and in a 3D haptic space by the Omni device. The standard SDK (OpenHaptics Toolkit [10]) was used to create the software used in the experiment. For each experimental session, settings were randomized for surface parameters of stiffness, dynamic friction, and static friction. Subjects were instructed to comment on their impressions during the interactive sessions and their comments were recorded as text.

These experiments were intended to explore as much of the perceptual space as practically possible in one study while still gaining applicable data. Each of the randomized settings was normalized and split into three ranges: low, medium, and high, as shown in Table 1. All of the permutations of these sets were tested and each specific setting within a given range was randomized to produce the parameters used in one session. The three ranges for each of the three modified parameters gave a total of 27 basic experimental setting types and every subject completed all the 27 range combinations.

Table 1. Settings were randomized within the given ranges, all bounding values inclusive.

Setting range	Minimum	Maximum	Label
Low	0.03	0.15	L
Medium	0.3	0.6	M
High	0.85	1.0	H

Preliminary experiments with various shapes showed that subjects experienced different shapes differently, even for the same settings. Responses of hardness were stronger in shapes with edges or discontinuities (e.g. as in the case of modeling a plane spanning all virtual space rendered). With the objective of this study being to examine the settings for surfaces rather than edges, a sphere was used for the shape. The subject was instructed to observe a sphere displayed on a computer monitor. The sphere's gray, non-reflective surface was illuminated with ambient light, as shown in Fig. 1. The subject was then instructed to hold the haptic device and touch the sphere's surface by moving the PHANToM's stylus and viewing the haptic interface pointer (HIP) as it "touched" the surface on the visual display. The subjects were free to move the stylus in any way they felt would be the best to experience the surface quality of the virtual object.

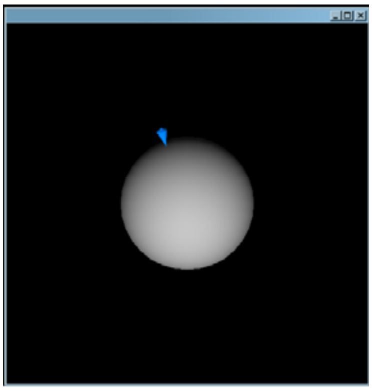

Fig. 1. The graphic interface of the experimental setup.

For each specific stimulus setting, after viewing the 3D shape on the monitor and experiencing the shape using the stylus, the subjects were instructed to report any physical sensations or impressions for the given setting. A second participant, the moderator, coordinated the experiment procedure and recorded the subject's spoken verbal responses as text. Neither the subject nor the moderator knew any details of the virtual surface models used. The subjects and moderators were discouraged from recording metaphors, such as similes, and only to record descriptive terms. The moderator recorded all relevant monologues, in text form on a separate computer. All of the experiments were completed in Japanese. 35 undergraduate and graduate students (25 male and 10 female, average age 21.3 years old) participated in the experiments for a total of 945 recorded sessions and more than 5,000 semantic phrases, of which about 3,300 were extracted as adjective or noun phrases in the subsequent morphological analysis, described in the following section. All the subjects and moderators were native Japanese speakers with no prior experience of haptic interface and were not compensated for their participation. As no specific time limits were set, it took from 24 to 47 minutes (average time = 31 min.) per subject to complete all 27 sessions.

3 Results and Analysis

The recorded texts were broken down into morphemes with the Japanese morphological analysis tool MeCab (Java Sen port) [11], [12]. This linguistic analysis software is commonly used for extracting Japanese keywords indicating specific affective response in interactions [13]. The objective of the first stage of the analysis was to simply extract the keywords indicating semantic response labels.

MeCab software is capable of performing complete morphological analysis of Japanese natural language [12]. In the presented study, this tool was used to extract and label the verbal responses to the experiment described in the previous section. MeCab was first used to give a frequency count of all expressions recorded, over 5000 terms. Of these, MeCab then categorized about 3,000 responses as adjective, verb, noun, and adverb terms, 246 different terms total.

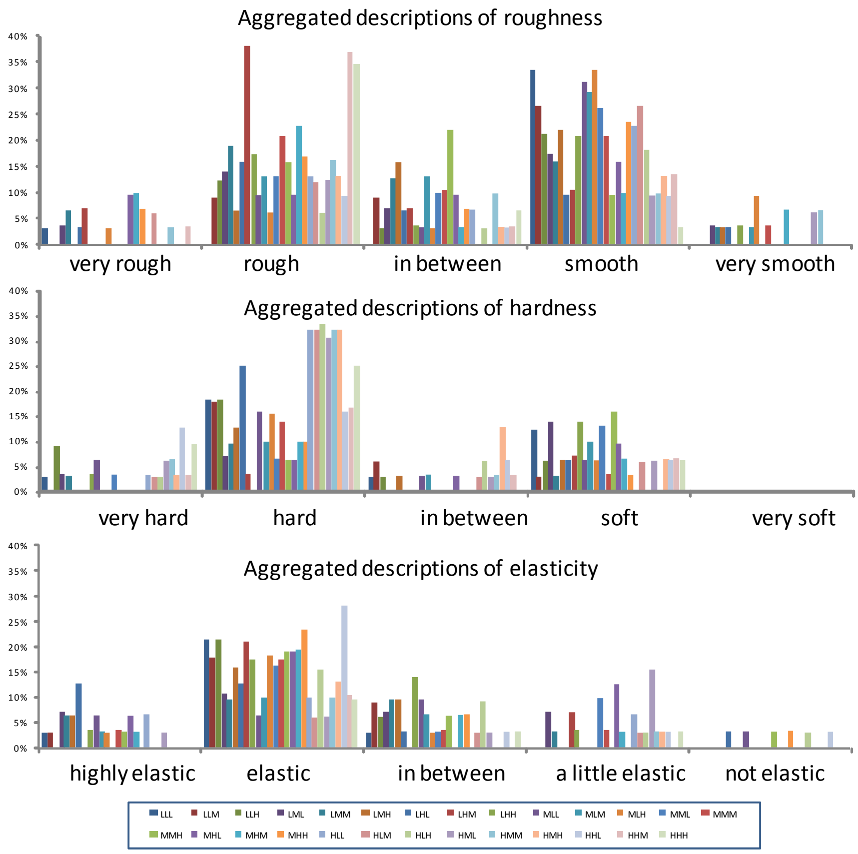

Fig. 2. Classification of reported perceptions by morphological analysis shows that all sets evoked strong response and that the responses were spread throughout the selected classes. The labels (LLL, LLM, etc.) give the settings for the stiffness, static friction, and dynamic friction parameters, respectively, as specified in Table 1. Values shown are percentage points of all categorized responses recorded for a given setting combination.

The next step was to label each of the terms as a haptic response keyword or as an adverb related to a haptic response term. The majority of the terms were haptic response keywords and were readily identified as belonging to three basic surface sensation types: hard to soft, smooth to rough, and high elasticity to low elasticity. A few terms were not classified on these axes, most notably those that were related to (or might be categorized as belonging to) a heavy to light axis. (All terms are given here as English translations for reference only, as such brief translations between different languages may not necessarily be accurate.) The adverb terms were nearly all readily classified along a single axis, indicating strength or intensity of the haptic response. These terms were used to weight the haptic responses positively or negatively and included phrases corresponding approximately to English terms such as very, a lot, a little, slightly, not so, etc. The procedures described in this section categorized, classified, and labeled 851 of the original 945 experiment sessions completed by the 35 subjects, successfully including more than 90% of the data recorded.

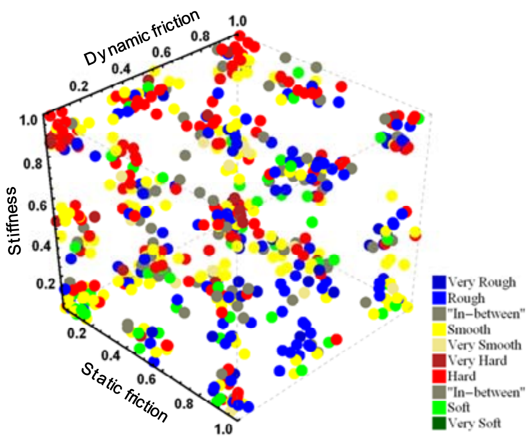

Fig. 3. Subjective semantic responses plotted in the PHANToM Omni standard parameter space show clusters for roughness and hardness, whereas perceptions of smoothness and softness appeared more evenly distributed.

Histograms of the categorized responses are shown in Fig. 2 in an aggregated form. Each vertical axis shows the ratio of terms in every combination used (LLL, LLM, etc). Each horizontal axis shows the coded terms with the labels indicating the combinations of the objective parameters used to render the stimuli. The expected responses were those hypothesized to be related to the stiffness setting and the two friction settings, namely responses of hard-soft and rough-smooth. There were also frequently reported terms related to elasticity, which was not one of the expected responses as no elasticity related parameters were explicitly used to render the surfaces. A Spearman's rank correlation analysis showed that the values of the stiffness coefficient and the values of the static friction coefficient were both weakly correlated with subjective response ($r=0.071$ and $r=-0.11$, respectively; $n=851$; $p<.01$). No correlation was detected between the dynamic friction coefficient values and the subjective responses obtained.

Shown in Fig. 3 are all but the elasticity-related responses plotted on the three dimensions of haptic materials settings. Several fuzzy clusters can be observed for each of the expected response categories (‘hard’, ‘soft’, ‘rough’, and ‘smooth’) that nevertheless have no clear boundaries.

Three ANOVA (analysis of variance) were performed between the haptic materials settings (stiffness, static friction, and dynamic friction coefficient values) and the three pairs of haptic sensations most reported: (1) ‘rough’ and ‘smooth’, (2) ‘hard’ and ‘soft’, and (3) ‘elastic’ and ‘inelastic’. On conducting the analysis, the reported sensations in each of the three groups were divided into two larger categories. The haptic sensations in (1) were categorized in the following way: ‘very rough’ and ‘rough’ as ‘rough’, and ‘smooth’ and ‘very smooth’ as ‘smooth,’ thus excluding the largely indeterminate responses of the in-between category. The haptic sensations in (2) and (3) were similarly categorized: ‘very hard’ and ‘hard’ as ‘hard’, ‘soft’ and ‘very soft’ as ‘soft’, ‘highly elastic’ and ‘elastic’ as ‘elastic’, and ‘not very elastic’ and ‘not elastic’ as ‘inelastic’.

In the first 2×2 ANOVA, the first factor was the haptic sensation pair ‘rough’ and ‘smooth’. The second factor was the haptic virtual materials settings (stiffness, static friction, and dynamic friction coefficients). The interaction between the two factors was found to be significant ($F(1,638)=7.5$, $p<.01$). Next, to investigate the differences of haptic sensations on each materials setting, an analysis of the simple main effect was conducted. Results indicate that the stiffness setting was higher when ‘rough’ was reported than when ‘smooth’ was ($F(1,957)=5.25$, $p<.05$). The static friction setting was also higher for ‘rough’ than for ‘smooth’ ($F(1,957)=35.947$, $p<.001$). No significant differences were found for the dynamic friction settings. These results indicate that parameters for ‘stiffness’ and ‘static friction’ would be useful for inducing in a virtual haptic space subjective perceptions related to roughness and smoothness.

The next ANOVA examined the ‘hard’ and ‘soft’ subjective reports against the haptic virtual materials settings. The interaction between the two factors was found to be significant ($F(1,452)=13.231$, $p<.001$). An analysis of the simple main effect was conducted in each level of the parameters. In the stiffness condition, adjusted parameters were higher on the ‘hard’ condition compared to the ‘soft’ condition ($F(1,678)=28.667$, $p<.001$). No difference was found for the static friction condition and dynamic friction condition versus perceived hardness or softness. These results indicate that parameters for ‘stiffness’ would be useful for inducing subjective perceptions related to hardness and softness.

A third ANOVA was conducted to examine the reported sensations of ‘elasticity’ and ‘inelasticity’ with the haptic virtual materials setting. The interaction between the two factors was found to be significant, ($F(1,368)=5.24$, $p<.01$). Next, to investigate the differences of haptic sensations on each material setting, an analysis of the simple main effect was conducted. For the simple main effect, the settings were higher on the elastic condition compared to the inelastic condition in the stiffness condition ($F(1,552)=4.921$, $p<.05$). In the static friction condition, no difference was found. In the dynamic friction condition, adjusted parameters were higher on the elastic condition compared to the inelastic condition ($F(1,552)=5.251$, $p<.05$). These results indicate that parameters for ‘stiffness’ and ‘dynamic friction’ would affect subjective perceptions of elasticity. Although the exact causes of the elasticity-related reported sensations are not known, we speculate from these results that they are associated with the dynamic friction as it is experienced kinesthetically in the system of the arm and hand moving the stylus. Some of the elasticity may be from the actual physical properties of the joints and components and some may be from software idiosyncrasies. At the same time, much of this sensation of the elasticity is suspected to be an illusory, phantom sensation due to the conditions of the task and the visual perception of its virtual space. This sensation requires more and different experiments but, in keeping with the objective of this study, the responses associated with elasticity were not included in the data used in the following sections to model the perceptual space.

4 Discussion and Conclusions

The results described above generally corroborate those found in previous tactile studies of real-world objects, such as [3] and [5], which were, however, mainly focused on sensations from mechanoreceptors. Here, possible foundations for kinesthetic sensation models are proposed, based on the responses collected. Figure 4 shows clustering of hard and soft reports as plotted against the parameters used in the experiments. The asterisks in the legend indicate that these are aggregated hard and aggregated soft sets, formed by disregarding the “neither hard nor soft” responses and grouping all of each primitive together, ignoring modifiers (for example, Soft* includes “a little soft”). The figure demonstrates that sensations related to softness were less localized. It would be expected both intuitively and from the ANOVA results that stiffness coefficient plays a major role in hardness but the figure shows that the relationship is not straightforward. Figure 5, similarly, shows clusters of the combined rough and smooth reports. In this case, static friction coefficient would be expected to be the main parameter but the figure reveals, again, that simply increasing value of this coefficient will not necessarily result in a proportional increase in subjective sensations of roughness. These results demonstrate that more nuanced and nonlinear adjustments of multiple parameters are required to reliably communicate a specific sensation to the user.

Fig. 6 shows each of the four basic surface sensations as it would be perceived at the setting expected to elicit the response. Fig. 6(I) models hardness as it was reported at high values of stiffness coefficient (and at various values of the other two parameters), Fig. 6(II) models softness as it was reported in low stiffness, Fig. 6(III) models roughness at high values of static friction coefficient, and Fig. 6(IV) models smoothness at low values of static friction coefficient. The generalizations shown were obtained through polynomial interpolation (of the third order) of the corresponding empirical densities over the whole range of the parameters. These models again demonstrate that system interface designers cannot simply rely on the physical meaning of the virtual haptic parameters to get the expected result. They will instead need to use more precise support and, due to the nonlinear and irregular nature of the perceptual space vis-à-vis the haptic materials coefficients, this design support should be incorporated as part of the interface design tools.

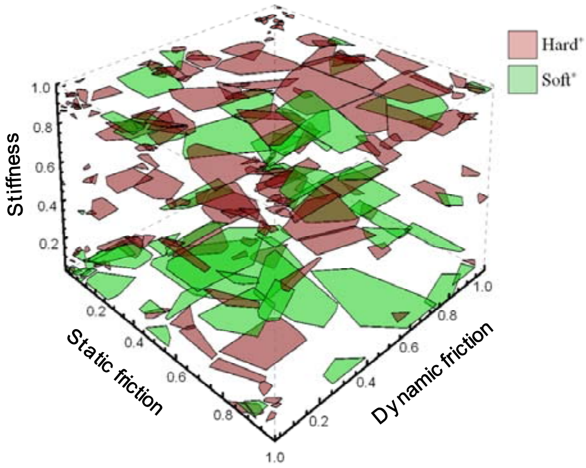

Fig. 4. Semantic characterization clusters plotted against haptic materials parameters shows that higher values of stiffness coefficient leading to perceived hardness (and, otherwise, lower stiffness to softness) is not rejected but also does not exhibit a straightforward, linear relationship.

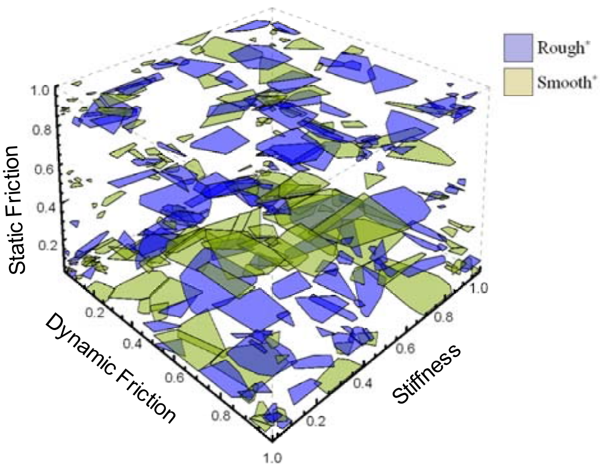

Fig. 5. Semantic characterization clusters plotted against haptic materials parameters shows higher static friction coefficient leading to perceived roughness (and lower static friction to softness) is not rejected but also does not exhibit a straightforward, linear relationship.

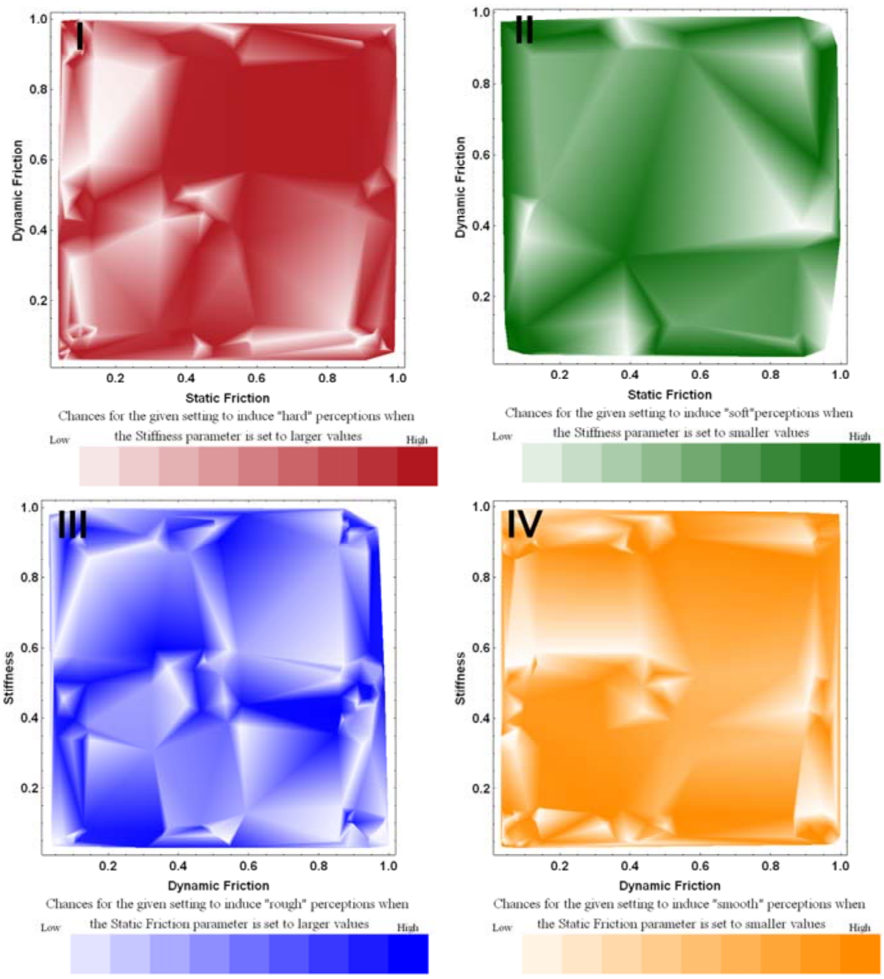

Fig. 6. Generalized modeling of the surface parameters against haptic perceptions suggests the space requires simultaneous and nonlinear manipulation of the given settings to possibly induce specific perceived haptic qualities in kinesthetically elicited haptic sensations (see text for details).

The study described created a collection of open-ended verbal responses to specific haptic stimulus settings on the PHANToM Omni device in controlled, interview-based experiments. Moderators recorded the verbal responses as complete text entries and those entries were deconstructed by the Japanese morphological analysis tool MeCab. The decomposition resulted in adjective, verb, noun, and adverb terms thought to be related to the haptic sensations of interest in the experiments. These resulting terms were weighted by adverbial phrases and linked to the settings at which they were recorded. A correlation was detected which suggests that similar settings elicit similar responses in users with a relatively homogeneous cultural and linguistic background and that the sensations causing those responses can be modeled for practical application.

The most important finding in the results, adding to previous studies, is that the subjective response to parameter settings is not obvious from the semantic labels of the settings. Interface designers may reasonably expect, for example, that increasing values of the parameter associated, based on the underlying physical model, with the virtual stiffness would result in a direct and proportional increase in perceived hardness, or that decreasing values of the parameter associated with the virtual friction would lead to a similarly increased subjective smoothness. This study demonstrated that, while some of those basic expectations are not completely misguided, the relationship is neither linear nor robust. This finding has consequences both for the descriptive terms given to the software settings and for development of haptic interfaces that are constructed with those terms as guidelines. The presented study focused on a morphological analysis of three major categories of haptic sensation, which was sufficient for categorizing nine-tenths of the sessions. Other responses were reported and more extensive experimentation would allow a more detailed modeling of the categories analyzed, as well as adding to the number of "objective" categories, e.g. related to elasticity and "springiness" (see [3] for a relevant study).

References

1. Lederman, S.J., Klatzky, R.L.: Haptic perception: A tutorial, Atten. Percept. Psychophys., 71 (7), 1439--1459 (2009)
2. Suga, Matsuda, Okamoto, Takizawa, Oshiro, Minato, Tsutsumi, Nagata, Sakai, Takahashi: Sensible human projects: haptic modeling and surgical simulation based on measurements of practical patients with MR elastography--measurement of elastic modulus, Stud. Health. Technol. Inform., Vol. 70, 334--340 (2000)
3. Hollins, M., Faldowski, R., Rao, S., Young, F.: Perceptual dimensions of tactile surface texture: a multidimensional scaling analysis, Percept. Psychophys. 54(6), 697--705 (1993)
4. Smith, A.M., Scott, S.H.: Subjective scaling of smooth surface friction, J. Neurophysiol. 75(5) 1957--1962 (1996)
5. Tiest, W., Kappers, A.: Analysis of haptic perception of materials by multidimensional scaling and physical measurements of roughness and compressibility, Acta Psychol., 121(1), 1--20 (2006)
6. MacLean, K., Enriquez, M.: Perceptual Design of Haptic Icons, Proc. of Eurohaptics, Dublin, Ireland (2003)
7. MacLean, K.: Haptic Interaction Design for Everyday Interfaces. E. Source: Reviews of Human Factors and Ergonomics, Vol. 4, 149--194 (2008)
8. Cooper, E.W., Kryssanov, V.V., Ogawa, H.: Building a Framework for Communication of Emotional State through Interaction with Haptic Devices. HAID 2010, 189--196 (2010)
9. Smith J., MacLean K.: Communicating Emotion Through a Haptic Link: Design Space and Methodology. J. of Human-Computer Studies, 65(4), 376--387 (2007)
10. OpenHaptics Toolkit, Sensable, http://www.sensable.com/products-openhaptics-toolkit.htm (accessed May 2011)
11. Kudo, T.: MeCab: Yet Another Part-of-speech and Morphological Analyzer, available at http://mecab.sourceforge.net (accessed May 2011)

12. Den, Y., Nakamura, J., Ogiso, T., and Ogura, H.: A proper approach to Japanese morphological analysis: Dictionary, model, and evaluation. Proc. LREC, 1019-1024 (2008)
13. Hasegawa, D., Rzepka, R., Araki, K.: Evaluation of Connectives Acquisition in a Humanoid Robot Using Direct Physical Feedback, LNAI Vol. 4830, 664--668 (2007)