Human Perception of a Haptic Shape-changing Interface with Variable Rigidity and Size

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Abstract

This paper studies the characteristics of the human perception of a haptic shape-changing interface, capable of altering its size and rigidity simultaneously for presenting characteristics of virtual objects physically. The haptic interface is composed of an array of computer-controlled balloons, with two mechanisms, one for changing size and one for changing rigidity. We manufactured two balloons and conducted psychophysical experiments with twenty subjects to measure perceived sensory thresholds and haptic perception of the change of size and rigidity. The results show that subjects can correctly discriminate different conditions with an acceptable level of accuracy. Our results also suggest that the proposed system can present an ample range of rigidities and variations of the size in a way that is compatible with the human haptic perception of physical materials. Currently, shape-changing interfaces do not hold a defined position in the current VR / AR research. Our results provide basic knowledge for developing novel types of haptic interfaces that can enhance the haptic perception of virtual objects, allowing rich embodied interactions, and synchronize the virtual and the physical world through computationally-controlled materiality.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction devices—Haptic devicesTreemaps; Human-centered computing—Human computer interaction (HCI)—Empirical studies in HCI

1 Introduction

Shape-changing interfaces use changes in physical properties to provide input and output as a new means of interaction with digital processes. Despite such possibilities, there are still three main issues that prevent a successful integration of shape-changing interfaces with virtual environments. First, such interfaces are currently limited to their materiality which is usually static; second, most of the existing examples are 2.5D pin displays. Therefore they are not suitable for presenting volumetric objects; third, even if some of these interfaces can partially alter their rigidity and size, they cannot perform these changes simultaneously. Such aspects are critical since the haptic interface must be able to present arbitrary virtual shapes and their characteristics like size and rigidity. On top of that, the current research on shape-changing interfaces lacks an understanding of human factors such as haptics, and how different changes are perceived by users [1].

This paper expands on previous development of a system composed of an array of computer-controlled balloons for presenting virtual surfaces [5]. The system is composed of two independent mechanisms. The change of rigidity is defined by Hooke's law. Here, a linear actuator and an air-pressure sensor are used to control the internal pressure of each balloon through a piston and an air cylinder. To change the size, another linear actuator is employed to slide the balloon through a trumpet-shaped tube (Fig. 1). We hypothesize that the proposed interface can present material properties in the range of soft and stiff, and sizes from small to large. To test such hypothesis, we conducted a study using psychophysics to measure the human tactile perception of these changes. We provide three psychophysical metrics, such as the Point of Subjective Equality (PSE), the Just-Noticeable Difference (JND), and Weber Fraction (WF). Our results can contribute to the understanding of the perception of variable physical cues oriented to the design of shape-changing interfaces for AR and VR.

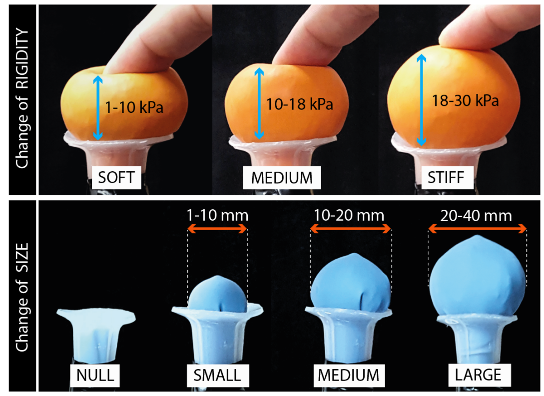

Figure 1: A single computer-controlled balloon presenting different types of rigidities (top) and sizes (bottom).

2 Phsycophysical Experiment

The experiment consisted of two sessions, one dedicated to studying the human haptic perception of changes of rigidity, and a second for the changes of size. To avoid possible order effects, the order of how these sessions were presented to subjects has been counterbalanced for each subject. These two sessions were divided into three parts, corresponding to three conditions. They consisted of a two-alternative force-choice discrimination task. In each task, subjects were with a reference stimulus of fixed rigidity or size, and a test stimulus with variable characteristics. For rigidity, three standard stimuli were chosen to cover the spectrum of the possible rigidities that our system can present, expressed with their respective internal pressure: *soft* (7 kPa), *medium* (15 kPa), *stiff* (22 kPa). For size, the three conditions correspond to three ranges, such as: *small* (10 mm), *medium* (20 mm), and *large* (30 mm). To avoid possible errors of anticipation and habituation the sequence of how the three conditions were presented was randomized between each subject. A one-up-one-down staircase procedure was used to estimate the thresholds [2]. Whenever a subject chose the reference stimulus as larger or stiffer, the test stimulus in the next trial was a presented one step down.

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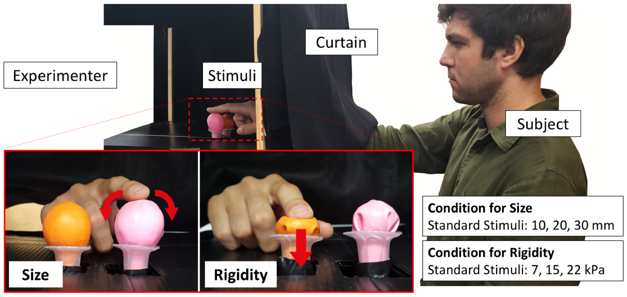

Figure 2: The apparatus used for the experiment, and the two types of actions that subjects had to perform for rigidity and size.

	RIGIDITY (kPa)			SIZE (mm)		
Standard Stimulus	7	15	22	10	20	30
PSE	7.5	14.6	21.9	10.06	19.9	30.4
JND	1.52	1.49	1.62	1.78	1.94	2.14
WF	0.21	0.07	0.07	0.17	0.09	0.07

Figure 3: The psychophysical metrics obtained from the experiment, reported with their total average values among all subjects.

Conversely, whenever the test stimulus was chosen as smaller or softer, the next trial was a small step up. When a subject reported a change, a reversal was recorded. One step corresponds to 1 kPa for rigidity, and 1 mm for size. Each task was composed of two staircases: one starting from the high end of the reference stimulus range, while the other started from the lower end. To prevent order errors, the staircase procedures were interleaved. To minimize errors of habituation and anticipation, the presentation order of the test and reference stimuli were also randomized for each trial. The number of trails varied since the procedure adapts to the performance of each subject. For all sequences, the experiment continued until 10 reversals were collected. In total, each subject had to perform 6 sequences (two for each condition), and 60 reversals were collected in total. Twenty healthy subjects participated in the experiment, eighteen males and two females, aged between 22 and 36. Three were left-handed, and seventeen were right-handed. Subjects were recruited using a mailing list, and they all agreed to volunteer for the experiment. In each session, subjects sat on a chair facing the apparatus, consisting of two stimuli placed side by side and surrounded by a curtain (Fig. 2). Therefore, subjects could only perceive them through tactile sense only. For each session, subjects were asked first to touch the standard stimuli, perform an action with the index finger of their dominant hand, then perform the same action on the variable stimuli, and finally, make a guess. For rigidity, the subjects were asked to press down the balloons with their index finger. For size, subjects had to trace the contour of the balloon with the same finger. The role of the experimenter was to guide the subjects, record their answers, and operate the system through a command line interface on a laptop computer running the control software.

3 Results and Discussion

We collected a total average of 125 trials per subject for rigidity, and 158 trials for size. We then plotted the collected data for both the ascending and descending sequences and the corresponding value of each reversal. Out of the ten reversals collected for each sequence, we excluded the first four reversals from the final analysis. The Upper and Lower Differential Limen were then computed to derive the corresponding PSE, JND, WF, which are provided in Fig. 3. On the PSE values, we performed an analysis of variance ANOVA (1 factor, 3 levels, within subjects) with post-analysis. The results of the Sphericity Test for both size and rigidity reported a $p < .001$, and the post-analysis reported $p < .05$ between each condition. Such results provide an essential ground for confirming our hypothesis. Therefore we can say that the interface can represent three different conditions (of both rigidity and size), which can be correctly distinguished by humans touch.

The JND values contribute to the understanding of how precise stimuli are perceived by subjects, which is close to the minimum step required by the system to perform a change. Finally, we computed the Weber Fraction, which provides additional information to clarify our results and claims better. For size, both the JND and WF are consistent with the ones found in the literature (i.e., [3]), where JND increases with the increment of the reference length, and WF for small stimuli are greater than the ones for large stimuli. For rigidity, the total average WF of all conditions is similar the values generated by previous work on haptic perception compliant objects, while the different fractions are in line with the ones found for soft and stiff materials [4].

4 Conclusion

The design of a haptic shape-changing interface for VR and AR requires the development of new mechanisms that can present characteristics of virtual surfaces physically. However, differently from other types of haptic interfaces where touch is mediated (through a tool or an exoskeleton), shape-changing interfaces aim to provide an experience similar to the one we have with ordinary objects, where volumetric surfaces can be explored directly by human's hands. Therefore, there is the need to develop an understanding of the human tactile perception of surfaces with variable physical properties. The psychophysical metrics reported in this study suggests that our haptic shape-changing interface has the potential to present a wide variety of sizes and rigidities that are distinguishable by touch. Our results also show that such cues might be perceived by human touch similarly to physical materials with similar characteristics. Nonetheless, this study is limited to the characterization of a specific type of technology that is still under development, and considers only haptic perception. For future works, we aim to expand the system by creating a larger array of balloons, develop methods for presenting arbitrary volumetric virtual objects. Also, we plan to expand this work by looking at the perception of visuo-haptic cues, since critical in the perception of both size and rigidity. By doing so, we might provide a better understanding on how to integrate haptic shape-changing interfaces with current VR and AR visual displays.

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