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Perceptual Thresholds for Haptic Texture Discrimination

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***Abstract*—The current study sheds light on the discrimination of haptic texture, of real life surfaces, to find out the thresholds beyond which two surfaces become perceptually different. For this purpose, a perceptual space using 84 real life textures was established by employing multi-dimensional scaling. Afterwards, a subset of 16 surfaces was experimentally selected for which the haptic texture thresholds were determined. Finally, these thresholds were deployed in the form of extended convex hulls. It was found out that surfaces appearing within the convex hull are perceptually similar.**

***Keywords*—Perceptual space. Haptic texture. Convex hull.**

1. Introduction

Haptic texture perception is similar to visual color perception in many ways. We interact with various textures in our daily life similar to the many colors we see. It can be a trivial task for us to distinguish among the various texture that we come across. However, in some cases where any two given textures exhibit a high degree of similarity in some aspects, distinguishing them apart can become a challenging task. This means that humans can only distinguish textures upto a certain extent beyond which all the textures appear to be perceptually similar, we can call this limit as the haptic texture discrimination threshold.

A lot of research has been done in trying to find out the human haptic sensitivity thresholds for textured surfaces of different kinds of roughnesses and various frequencies. But the shortcoming in these researches is that the textured surfaces used were either virtually constructed or physically controlled surfaces. In the virtually constructed surfaces friction, frequency and viscosity were varied and the thresholds were determined [1]. On the other hand, the surfaces used in the physically controlled surfaces were dot-patterns [2], [3], gratings [3], [4], [5] or sandpapers [6]. They provided accurate thresholds for these surfaces but the application of this information in real life scenarios is not possible. Since, in real life we dont often encounter such surfaces. Real life textured surfaces are a mix of complex attributes and physical dimensions. Therefore, a unified study addressing the classification of real life textures based on the perception thresholds is highly required.

In an effort to achieve this goal, this study focuses on finding out the threshold levels below which two real life textured surfaces are considered to be perceptually similar. This study is a continuation of our previous research [7], where we established a haptic perceptual space comprising of 84 real life surfaces located in relation to one another. The textured surfaces used in this study and the perceptual space can be seen in Fig. 1 and Fig. 2, respectively. Two surfaces located close to one another in the perceptual space are considered to be similar to one another. Despite this information, there appears to be no clear boundary beyond which two surfaces can be considered as perceptually different.

In order to find the perceptual threshold for different kinds of textures, we carried out another psychophysical experiment. In this experiment, a subset of the 84 surfaces, i.e. 16 surfaces, was used, and the perceptual thresholds were marked by enclosing the given surfaces in a convex hull. Subsequently, the standard convex hulls were extended, using a new method, to make them applicable to perceptual thresholds. It was considered that surfaces inside this perceptual convex hull are perceptually similar to the given surface.

The rest of this paper is structured as follows. The psychophysical experiment for gathering perceptual data is discussed in Sect. 2. In Sect. 3, we establish the thresholds in the form of convex and extended convex hulls. Furthermore, Sect. 4 provides inferences and insights gained from the study.

2. Psychophysical Experiment

In the previous experiment conducted in [7], we asked participants to classify 84 real life textures into various groups based on the similarities between them. There were five trials in that experiment and the total number of groups in the trials were 3, 6, 9, 12, 15, respectively.

In the current experiment we analyzed that grouping data for further processing. In order to find the best candidates for establishing a convex hull for a given surface, we calculated the grouping frequency of all the other surfaces with a particular surface. This calculation was done for all group sizes. Afterwards, scores were assigned to each surface based on this calculation. The scoring system is defined with the help of an example as follows; two given surfaces which were grouped together in group sizes of 3, 6, and 12 were assigned a score of 3+6+12 = 21. After calculating the scores for all the surfaces, the scores were normalized from 0 to 100. A score of zero means that the surfaces were never grouped together and a score of 100 means that the surfaces were grouped together across all the trials. In the current study, both the extremes appeared. This normalized score is called as the weighted sum of grouping frequency (WSGF). As an example, Fig. 3 shows the WSGF scores for surfaces 44 and 81.

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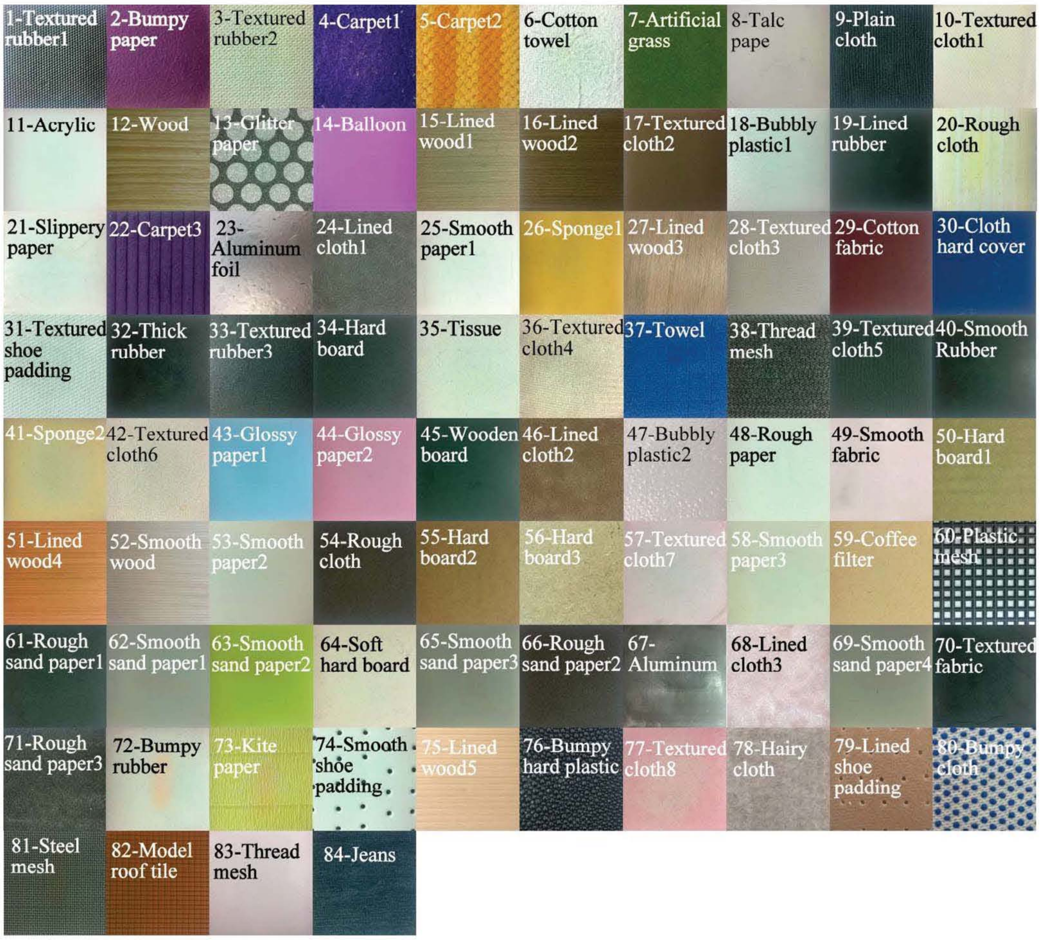


Fig. 1. Texture samples used in this study.

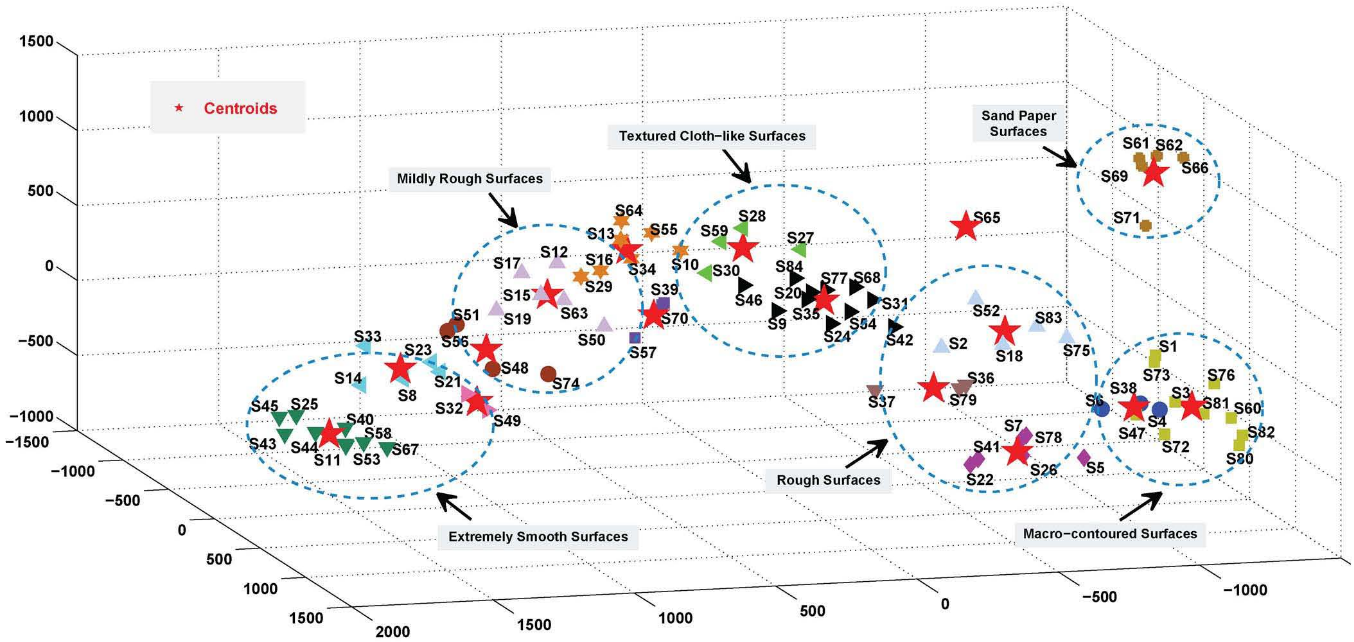


Fig. 2. Three dimensional MDS of perceptual space. Different colors show the individual groups after K-means grouping. The red stars show the centroids of the groups.

2.1. Experimental Procedure

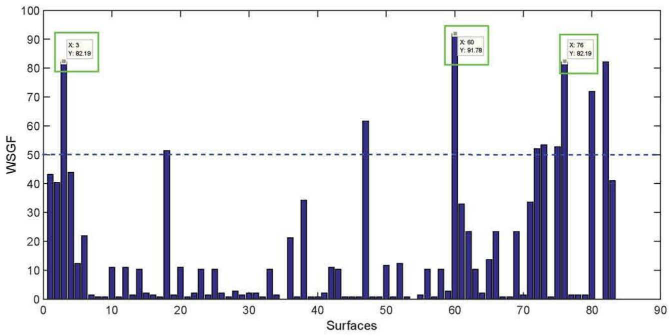
A total of six participants took part in this experiment. The first step was to select a subset of surfaces from the total of 84 surfaces for which thresholds were to be calculated. For this purpose, the perceptual space was divided into various number of groups using K-means algorithm. It was empirically found out that 16 groups sufficiently represented the perceptual space. Increasing the groups beyond 16 would cause unnecessary division of groups, while less than 16 groups would leave some groups to be very large. The perceptual space after K-means grouping is shown in Fig. 2. Afterwards, the surfaces nearest to the centroid of each group was selected for the experiment. Thus, a total of 16 surfaces were selected from the perceptual space for which perceptual thresholds were to be calculated inside the perceptual space.

The second step for the experiment was selecting candidate surfaces for comparison with the above 16 surfaces. For this purpose, a baseline criterion was defined. The surfaces having a WSGF score of 50% or higher with a given surface were used as candidates for comparison.

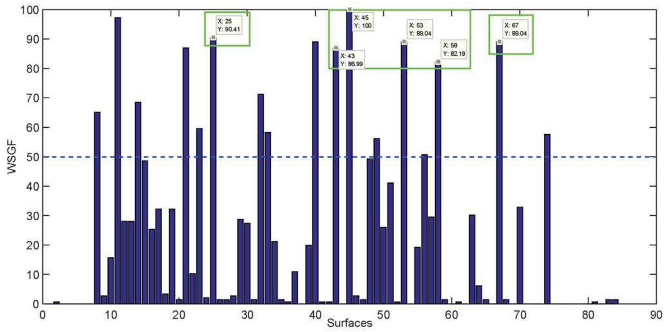
The participants were provided with the baseline surface with which all other candidate surfaces were to be compared. If the candidate surface was perceptually same, it was considered as lying inside the perceptual threshold for the given surface. This procedure was repeated for all the 16 selected surfaces.

2.2. Results

The list of all the 16 surfaces used in the experiment along with the selected candidate surfaces is given in Table 1. Figure 3 shows the result of this experiment for two baseline surfaces i.e., S44, and S81. The surfaces above the 50% line were used in the experiment as candidates. The surfaces enclosed in a green outline are the ones positively identified by participants as perceptually the same.



(a) Weighted sum of grouping frequency for surface 81



(b) Weighted sum of grouping frequency for surface 44

Fig. 3. The surfaces having WSGF higher than 50 were used as candidate surfaces for comparison with baseline surfaces. The green boxes highlight the surfaces selected as perceptually similar by participants.

3. Convex Hulls as Perceptual Thresholds

Based on the psychophysical experiment, we found out the perceptual boundaries for surfaces in the perceptual space. These boundaries were in the form of nearby surfaces which were perceived as same by participants. A convex hull was drawn for each of the 16 mentioned surfaces based on its perceptually similar neighbors. The 16 surfaces along with the perceptually similar neighbors are given in Table 1. As a result of this exercise, the perceptual space was converted into a cluster of convex hulls. Figure 4 shows the perceptual space with the convex hulls for 16 surfaces.

3.1. Analysis of Convex Hulls

From Fig. 4, we can see that most of the selected textured surfaces are bounded by convex hulls which show the perceptual threshold for a given textured surface.

However, as we know that a convex hull requires at least four non-coplanar points in space. But from Table 1 we can see that some of the selected surfaces had two or less perceptually similar textured surfaces. As a result of this, it was impossible to form a threshold in the form of a convex hull. From Fig. 4 it is visible that some of the selected surfaces are not bound by convex hulls. The fact that some surfaces had very few other perceptually similar surfaces can be attributed to the method of collecting the surfaces for making the perceptual space. While establishing the perceptual space, a conscious effort was being made to include as many diverse surfaces as possible, therefore, some of the surfaces were perceptually very different from all or most other surfaces.

Thus it was concluded that the current approach of making convex hulls exhibited two major drawbacks:

- It used the perceptually similar surfaces, for a given selected surface, as the vertices of the convex polyhedrons for forming the convex hulls. In most cases such a bounding box would suffice. But since we are dealing with perceptual thresholds, it can be argued that the threshold level for a certain texture cannot be limited to the farthest perceptually similar textured surface. Since, the vertices of the convex hulls are deemed as perceptually similar, it would be fair to assume that the perceptual threshold lies somewhere beyond that vertex.
- The textured surfaces with two or less perceptually similar surfaces also needed to be bounded by a threshold. Since, the current implementation of convex hulls could not find a solution for this, a new method was formulated for finding the thresholds for them.

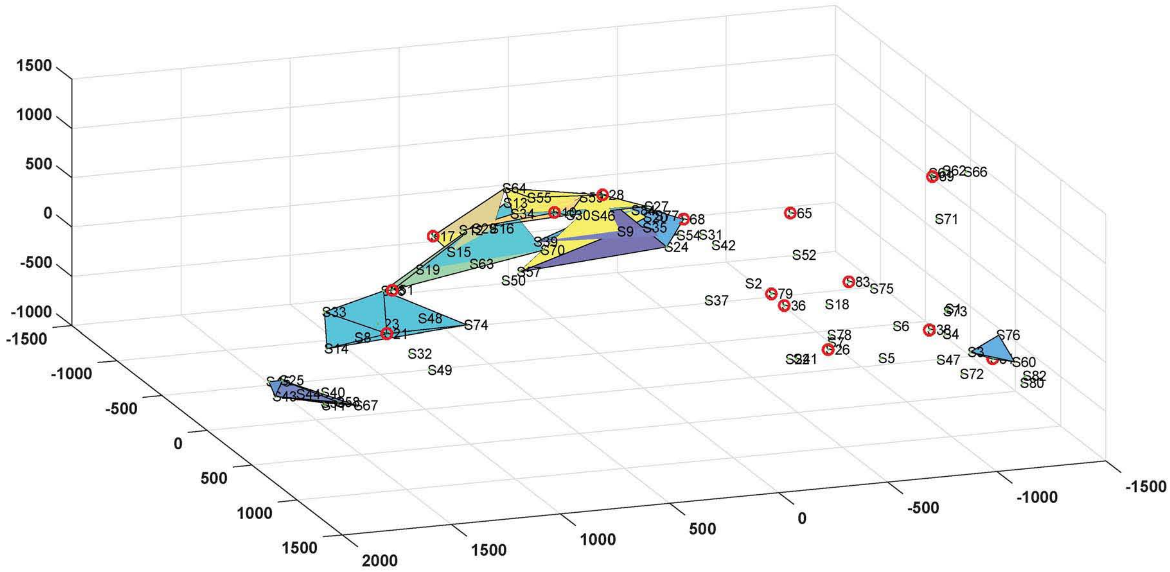


Fig. 4. Normal convex hulls for the 16 selected surfaces. The red circles show the selected 16 surfaces. It can be seen that some of the selected surfaces are not bounded by convex hulls due to lack of perceptually similar textures.

TABLE 1
BASELINE SURFACES ALONG WITH SELECTED CANDIDATE SURFACES

S. No	Baseline Surface	Perceptually Similar Candidates
1	81	76, 60, 3
2	44	58, 53, 67, 43, 45, 25
3	28	59, 64, 55, 30, 34, 27
4	17	64, 15, 16
5	36	6
6	65	-
7	51	56, 70
8	68	24, 28
9	83	73
10	26	41
11	69	69, 62, 61
12	10	39, 34, 59
13	21	74, 56, 48, 33, 14, 8
14	84	54, 46, 39, 35
15	79	26, 22
16	38	6, 73

3.2. Extended Convex Hulls

A new approach for forming convex hulls was applied in order to incorporate the two major drawbacks of the standard approach. Both the drawbacks were countered with just a single tweak in the standard algorithm for making a convex hull. The details of the modified algorithm are given as follows.

Each vertex of the standard convex hull was extended into three vertices. To achieve this, the three nearest neighbors for every surface in the convex hull, for a given selected surface, were identified. Afterwards, the center point from each neighbor to a given point in the convex hull was selected as the perceptual boundary between the two points. Thus, as a result of this exercise, the boundaries of the standard convex hulls were extended to incorporate the first drawback discussed in the previous section.

The second drawback was countered automatically using the above approach. After extending each point into three new points, the problem of having four or more points no longer remained. And thus the surfaces with two or lesser perceptually similar surfaces could also be bounded by a perceptual threshold in the form of a convex hull.

The extended convex hulls are shown in Fig. 6. It can be seen that all the convex hulls are larger than the normal convex hulls. Additionally, the surfaces with two or less perceptually similar surfaces also have convex hulls. Thus all the surfaces now exhibit a perceptual threshold.

3.3. Comparison Between Standard and Extended Convex Hulls

Figure 6 shows the comparison between the extended and standard convex hulls for one of the test cases (one selected surface). It can be seen that the vertices of extended convex hulls cover more area as compared to the standard ones. It is only logical that the perceptual boundary cannot lie on a perceptually similar textured surface. For instance, if we look at the standard convex hull for dimension 1, it shows four distinct vertices. All these four vertices are perceptually similar textured surfaces. While, in the extended convex hull, the above mentioned vertices are stretched further to extend the threshold and to incorporate some area beyond the perceptually similar surfaces. Same is the case for the other two dimensions also.

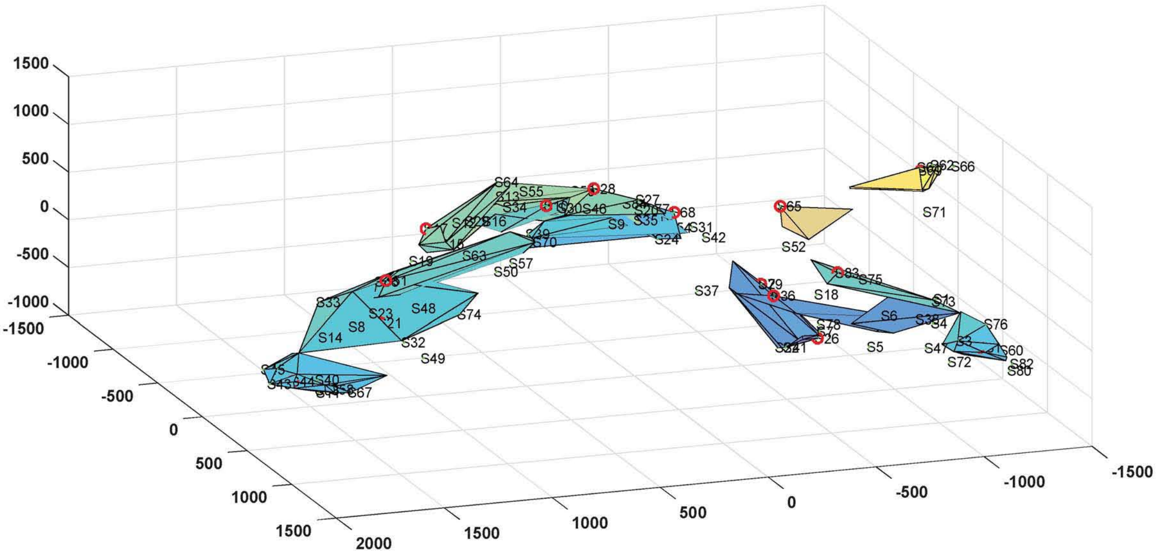


Fig. 5. Extended convex hulls for the 16 selected surfaces. The red circles show the selected 16 surfaces.

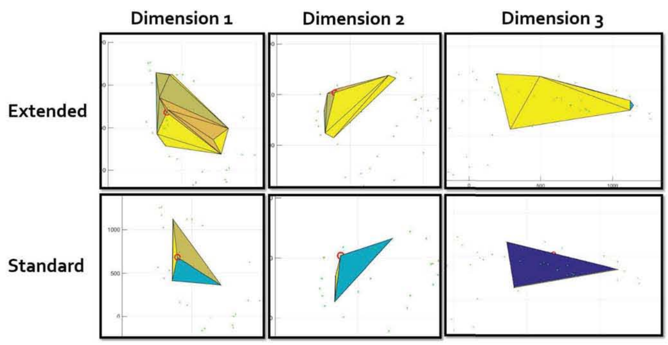


Fig. 6. Comparison between extended and standard convex hulls

As mentioned earlier, this approach was selected because the vertices of the given convex hull are perceptually similar textures. Now lets assume that another imaginary texture were to be inserted right next to a vertex but on the outside of the convex hull. In most likelihood, this new texture would be perceptually similar to the textures inside the convex hulls. But if we use normal convex hulls, this texture would be deemed as outside the convex hull and thus perceptually not similar. Therefore, the convex hulls were extended beyond the farthest perceptually similar textures.

4. Discussion

It can be seen from Fig. 5 that the convex hulls for very smooth (extreme left side) or very rough (extreme right side) textured surfaces were rather small. As it was very easy for participants to judge the differences for the two extremes. For example, a very smooth surface can be easily distinguished from a surface which is a little rougher. While, the convex hulls in the center of the perceptual space are rather inflated, meaning it was difficult for participants to clearly define perceptual boundaries in that region. As a consequence, a given texture surface was adjudged similar to more than one baseline textured surface and the respective convex hulls overlapped at certain regions. Another reason for this overlap could have originated from the nature of surfaces residing in the center of the perceptual space. Most of these surface are fabric based (which are soft) or have low stiffness. Therefore, even if the textures are different, it is being masked by the compliance of the material and thus the difference between the textures becomes perceptually less pronounced. This effect is called as pre-judgment, which is explained in greater detail in [8].

5. Conclusion

In the current study, we formulated perceptual thresholds for textured surfaces by performing a psychophysical experiment. As a result, we achieved accurate boundaries for haptic texture perceptual threshold for various pseudo-randomly selected textured surfaces. The perceptual thresholds were in the form of convex hulls. The convex hulls for the given surfaces covered almost all the perceptual space.

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