

The many dimensions underlying perceived softness: How exploratory procedures are influenced by material and the perceptual task*

Müge Cavdan, Katja Doerschner, and Knut Drawing

Abstract— Haptic research has traditionally often equated softness with compliance. However, in a recent study we have suggested that compliance is not the only perceived object dimension underlying what is commonly called softness [1]. Here, we investigate how the different perceptual dimensions of softness affect how materials are haptically explored. Participants freely explored and rated 19 materials on 15 adjectives. The adjectives defined different perceptual tasks by being associated with different softness dimensions. Materials were chosen to represent extreme values separately for each dimension; some materials served as control. Hand movements were recorded on video and subsequently categorized into different exploratory procedures (EPs). A multivariate analysis of variance (MANOVA) yielded significant effects of material, of the perceptual task and of their interaction. Taken together, the results suggest that participants actively adapt their EPs to both the type of material being explored, and to the judged softness dimension, and thus support the notion of different dimensions of softness.

I. INTRODUCTION

The tactual properties of materials have been summarized by five main dimensions which are warmth (cold/warm), hardness (hard/ soft), micro and macro roughness, and friction (moistness/dryness, stickiness/slipperiness) [2]. Among these five, the most studied dimensions are roughness and hardness/softness. The studies that focus on haptic softness typically define compliance as a physical correlate of softness [3, 4], which is measured as an object's deformation in response to an applied force [5-8] (see [9] for an exception). In contrast, everyday experiences of soft materials seem to include a much broader range of physical correlates: from squeezing a playdough to stroking a rabbit's fur to digging your fingers into the warm sand on the beach. In previous work, we have investigated these different dimensions of perceived softness using a wide range of soft (and non-soft) materials and a Semantic Differential Method. In that study participants freely explored materials and rated them according to 31 different adjectives. The results suggested that perceived softness not only covaries with the compliance of the material but also its viscoelasticity, granularity, and furriness [1]. When actively exploring objects and materials, humans use a set of stereotypical

movement patterns to perceive different dimensions [10-12]. For instance, in order to perceive texture, a repetitive lateral motion is typically generated, or for temperature, stationary contact is used in order to maximize the contact area between object and skin. Individual exploratory procedures are associated with the perception of specific dimensions. During softness (compliance) judgements, *pressure*, is stereotypically used, which involves squeezing an object between index finger and thumb or pressing the object with a single finger [11]. Such EPs have been shown to be optimized for the specific task, e.g. roughness or softness judgments [10]. While this earlier work showed that the EP *pressure* is optimal for exploring softness when its physical correlate is object compliance [10], we have subsequently found that humans use several additional exploratory movements [13-15], when exploring materials. For example, participants tend to *rub* "furry" textiles (e.g. velvet), *pull* elastic stuff (e.g. rubber), and *run through* granular materials (e.g. poppy seeds). Table 1 shows the exploratory procedures observed in [13-15] used for soft and non-soft materials.

In [13-15] it has been demonstrated that material properties and their association with different softness dimensions influence the usage of these EPs. Here we investigate whether the perceptual task, in particular, which softness dimension participants aim to perceive, affects the usage of these EPs as well, and how task and material interact. To this end participants freely explored and rated a set of 19 soft and non-soft materials on 15 sensory adjectives which were associated with different softness dimensions. Materials were chosen such that they would be extreme values on the various softness dimensions. We also included six control materials. Hand movements of participants were recorded, and manually labelled by raters on individual EPs based on the definitions in the Tab. 1. Factor analyses was used to replicate the results of [1] and a two-way MANOVA was conducted to test how far task, material and their interaction affect EPs.

II. METHODS

A. Participants

30 students (aged 18-38 years; average 23.6 years, 21 women, all right handed) from Giessen University participated in the study and were compensated with 8 €/hour for their time. All participants were naïve to the purpose of the study and spoke German at a native-speaker level. None of them reported sensory, motor, or cutaneous impairments. The two-point discrimination threshold at

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M. Cavdan, K. Doerschner, and K. Drawing, are with the Department of General Psychology, Justus-Liebig University, Giessen. (e-mail corresponding author: Muege.Cavdan@psychol.uni-giessen.de).

the index finger of the right (dominant) hand of all participants was 3 mm or better.

B. Setup, materials, and adjectives

Active noise canceling headphones (Sennheiser HD 4.50 BTNC) were used to eliminate any sounds that might have been caused by the exploration of materials and to present be EPs to signal start and end of the exploration. The experiment was programmed in MATLAB 2017a (MathWorks Inc., 2007) using the Psychtoolbox routines [16, 17]. A standard laptop was placed to the left of the participants to run the experiment and collect responses. During the experiment hand movements were recorded via two identical Sony Digital 4K Video Camera Recorder that can record 28-bit videos at a spatial resolution of 1920 × 1080 pixels. Both cameras were placed on tripods to the left and right across the table from the observer.

TABLE I. EXPLORATORY PROCEDURES OBSERVED IN [13-15] (DEFINITIONS ADAPTED FROM [15])

EP	Definition of the EP
Pressure	Applying directional normal force to squeeze a material between palm and fingers or using one or more fingers to apply normal force (similar to pressure in [12]).
Stirring	Immersing one or more fingers into the material and moving them (this can be rotational).
Rubbing	Applying torque or lateral force with varied pressure levels, sometimes sweeping materials between index and thumb fingertips or forcefully stroking material with the thumb while poising the object with the other fingers.
Pulling	Stretching a part of the material by moving the fingers or separating them from each other.
Stroking	Moving the fingers or the whole hand laterally across the objects to get information about surface while applying only gentle force. It is considered as rubbing when the thumb was used or it is as strong as to deform the object (rubbing and stroking link to lateral motion in [12]).
Running through	Picking up some parts/portion of the material and letting them trickle through the fingers.
Rotating	Lifting parts of the material to move and turn its boundaries typically inside the finger(tip)s.
Tapping	Repeatedly and rapidly hitting a material with knuckles, fingertips [10], or nails

During the experiment, participants were seated in front of a table on which different materials were presented. A curtain was used to hide the materials from the participant's view. The experimenter sat behind the curtain and placed

flat plastic plates (diameter 21.5 cm; Fig. 1) with different materials on the table. The participants inserted their wrist to an armrest which was mounted in front of them and which could be rotated in the horizontal plane. The armrest ensured that all participants explored the materials from the same distance, for the same time, and also reduced potential discomfort with the arm posture during the experiment. We selected 19 materials for the present study (Tab. II). from [1]. In particular we choose materials that would yield extreme positive values on four softness-related dimensions (deformability, visco-elasticity, furriness, granularity), and on roughness (control dimension). Six more materials served as a control condition. Table II shows all materials used in this study, as well as the dimensions on which they had high scores in the present study. Materials that could be changed through exploration (e.g. hand cream) were

Deformability	Sponge, Stress balls, Playdough
Viscoelasticity	Hair gel, Hand cream, Cranberries, Stress balls
Furriness	Fur, Wool, Cotton balls
Granularity	Sand, Sugar
Roughness	Sandpaper, Felt, Wool, Cranberries
Control	Stones, Lentils, Paper balls, Linen, Velvet, Aluminum foil

renewed for each participant.

TABLE II. MATERIALS USED DURING THE EXPERIMENT AND THEIR ASSOCIATED DIMENSIONS

15 sensory adjectives were selected mainly from [1], and used according to factor loads on deformability, viscoelasticity, furriness, granularity as well as roughness (control condition). For each factor we choose the two adjectives with the highest positive-, and one with the highest negative load. In case adjectives with high loads were lacking, we used three positive adjectives (granularity: *sandy*, *powdery*, *granular*; fluidity: *moist*, *gooey*, *sticky*; hairiness: *velvety*, *hairy*, *fluffy* or one positive and one negative adjective (roughness: *rough*, *smooth*). Adjectives were translated from Turkish into German. We used the adjective *wobbly* instead of *gooey* because of its daily life usage in German. Both the German version and the English translation of all adjectives can be seen in Tab. III.



Figure 1. Experimental setup and material examples

B. Design and Procedure

Each participant rated 15 sensory adjectives for 19 different materials. The participants gave ratings for each adjective regarding to the extent they think it applies to the material. Adjectives were used as Likert

items being scored on a 5 point scale ranging from 1 (*not applicable*) to 5 (*strongly applies*).

In each trial, the participants first saw an adjective on the screen. To start the exploration of the material, they had to press the space button. Then, a beep sound was given to mark the start point of 4 seconds of exploration time. Participants explored materials using their right hand. There were no constraints on the exploration movements. After 4 seconds a second beep sound signaled the end of the exploration time for a given adjective. The participant removed his hand from the material by rotating it to the left side and rated the material according to the adjective by pressing the corresponding button (with the left hand) on the laptop. Each trial thus consisted of exploring a material and rating it.

Before the experiments, participants gave written informed consent to participate. Then, they were given a questionnaire to assess any potential sensory, motor, or cutaneous impairments, and we measure the two-point discrimination threshold at the dominant hand's index finger. Just before the experiment, three practice trials were run in order to familiarize the participants with the setup and the experiment. The presentation order of the materials and adjectives was randomized for each participant. For each single material all 15 adjectives were rated one after another. The experimenter changed the material after the end of an adjective list. If needed the participants' hand was cleaned and dried when the material was changed (e.g. after hand cream). The experiment lasted about one and a half hours.

III. RESULTS

A. PCA on adjectives

We analyzed the adjective ratings of the materials using a principal component analysis (PCA) in order to verify our assumptions on the different perceived dimensions. First, we analyzed the consistency between participants' ratings based on pair-wise correlations across all adjectives, separately for each adjective. To do so we calculated standardized Cronbach's α per adjective. Cronbach's α values range from 0 to 1; values larger than or equal to 0.7 have been considered as acceptable, 0.8 good, and 0.9 excellent [18]. Standardized Cronbach's α results revealed an excellent consistency between participants for each adjective (each $\alpha \geq .95$).

Hence, we averaged responses over participants, separately for each remaining adjective and material. Averages were submitted to a covariance based PCA. We checked whether data are suitable for PCA using Bartlett's test of sphericity and the Keyser-Meyer-Olkin (KMO) criterion. The KMO criterion of sampling adequacy indicated the score of .48 which is a borderline value. However, Bartlett's test of sphericity was significant, $\chi^2(105) = 415.79$, $p < .001$ which suggests that observed correlations are meaningful. Principal components were extracted according to the Kaiser-criterion and rotated using the varimax method. Five principal components were extracted, explaining 94.3% of the variance (see Fig. 2 for Scree plot).

Table III shows the varimax-rotated factor loadings per adjective in the five-factor solution. The first rotated factor was strong with a high explained variance of 25.89%. Adjectives fluffy, velvety, hairy, and soft load on this factor. Therefore, this factor seems to be related with the material's furriness or fibrousness. The second factor accounted for 20.60% of the variance in the data. We labeled this factor viscoelasticity because high loading adjectives are sticky, moist, and wobbly. Factor three explains 20.58% of the variance. High loading adjectives are powdery, sandy, and granular, and we labeled the factor granularity.

TABLE III. ROTATED FACTOR LOADINGS OF ADJECTIVES

Adjective (English/ German)	Factors I-V : Loadings				
	I. Furriness	II. Visco-elasticity	III. Granularity	IV. Deformability	V. Roughness
Fluffy / flauschig	1,324	-0,407	-0,268	-0,283	0,164
Hairy / haarig	1,051	-0,248	-0,389	0,057	0,481
Soft / weich	0,895	0,360	-0,082	-0,677	-0,131
Velvety / samtig	0,800	-0,179	0,013	-0,318	-0,147
Moist / feucht	-0,119	1,137	-0,025	0,048	-0,249
Sticky / klebrig	-0,260	1,106	0,038	-0,150	-0,085
Wobbly / wabbelig	-0,025	0,947	-0,221	-0,387	-0,050
Sandy / sandig	-0,153	-0,119	1,136	0,288	0,255
Granular / körnig	-0,417	-0,025	1,082	0,692	0,236
Powdery / pulverig	-0,051	-0,052	0,973	0,170	0,098
Hard / hart	-0,613	-0,407	0,159	-0,901	0,101
Inflexible / unbiegsam	-0,234	0,067	0,422	-0,865	-0,054
Elastic / elastisch	0,114	0,273	-0,313	0,780	0,081
Smooth / glatt	-0,271	0,114	-0,202	0,110	-0,949
Rough / rau	-0,383	-0,333	0,373	0,132	0,704

a. A few materials load in two factors.

The fourth factor explains 17.79% of the variance. With high loads of the adjectives inflexible (- = negative load), elastic, and hard (-) this factor can be linked to and labelled deformability. Finally, the last factor explains 9.45% of the variance. The adjectives smooth (-) and rough load on this factor, and we labelled it roughness. To sum up, 5 different factors were obtained (4 dimensions of softness and one control dimension) as a result of PCA. These results confirm that the adjectives represented the five predicted dimensions and further results on the materials' factor scores confirm that also the selected materials represent these dimensions as we had intended (Tab. II).

B. Hand movements

We analyzed the participants' hand movements during exploration based on the video recordings. Exploratory procedures were classified according to the list of eight EPs observed in [14-15] (see Tab. 1 for detailed description) plus

an additionally observed hand movement of “flat-handed pick up” (trying to lift up a portion of the material by maximizing the contact surface with the flat hand). For each 4-second exploration per individual, material and adjective we coded for each of the 9 EPs whether they had occurred or not regardless of their duration. Then the data were normalized to a “percentage value” by dividing 100% by the number of EPs observed in that trial (e.g. if 3 EPs were coded in a trial, each of the three EPs obtained a value of 33.3%).

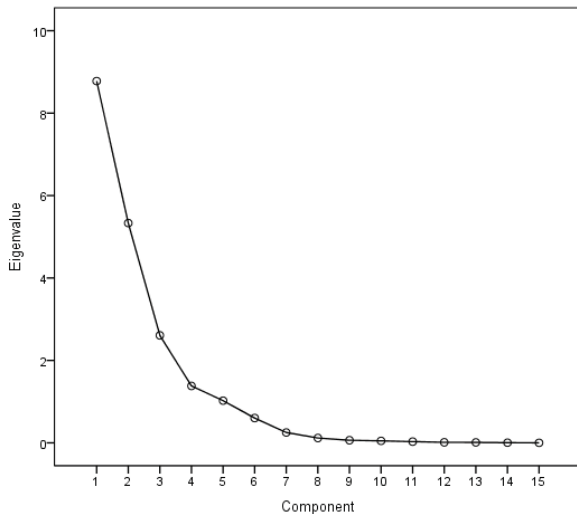


Figure 2. Scree plot for PCA of sensory adjectives

Due to the enormous effort needed to manually video coding we chose a random subsample of 15 participants, the EPs of which were coded by the first author. Additionally, two raters coded 20% of the same videos (corresponding to 3 participants) for testing inter-rater reliability [19, 20]. The inter-rater reliability was high (Cronbach’s $\alpha = .89$, $p < .001$) which confirmed very good reliability in judgments of the three raters to the different types of EPs.

C. The Effects of Material and Task on EPs

A two-way MANOVA was conducted in order to test material and task effects on the patterns of exploratory procedures. The individual percentages of all EPs were collapsed across the adjectives that load highest on each of the four different perceptual dimensions and roughness (control) separately for each material. These values were submitted to a two-way MANOVA with the independent variables of perceptual dimension (5 levels of task: *furriness*, *viscoelasticity*, *granularity*, *deformability*, and *roughness* [control]) and material (19 levels), and the dependent variables being the percentages of the nine EPs (9 levels: *flat handed pick up*, *pressure*, *pull*, *rotate*, *rub*, *run through*, *stir*, *stroke*, *tapping*). In the MANOVA we used Pillai’s trace and all effects were significant: the main effects of material, $V = 1.9$, $F(162, 11970) = 19.97$, $p < .01$, partial $\eta^2 = .21$ and task, $V = .45$, $F(36, 5300) = 18.73$, $p < .01$ partial $\eta^2 = .08$ (Fig. 3 and Fig. 4).

Separate univariate ANOVAs for task effect indicated significant differences in flat handed-pickup, pressure, pull, rotate, rub, run through, stroke, and tapping at $p < .01$ level, $F(4, 1330) = 24.89$, partial $\eta^2 = .07$, $F(4, 1330) = 126.89$, partial $\eta^2 = .28$, $F(4, 1330) = 21.02$, partial $\eta^2 = .059$, $F(4, 1330) = 4.26$, partial $\eta^2 = .013$, $F(4, 1330) = 107.36$, partial $\eta^2 = .24$, $F(4, 1330) = 5.85$, partial $\eta^2 = .017$, $F(4, 1330) = 4$, partial $\eta^2 = .012$, $F(4, 1330) = 5.37$, partial $\eta^2 = .16$ respectively. Only stir was not statistically significant, $F(4, 1330) = 1.42$, $p = .23$, partial $\eta^2 = .004$.

Furthermore, follow-up separate univariate ANOVAs were run to see material effects on the percentage of different EPs. They were statistically significant for each EP at $p < .01$ level, $F(18, 1330) = 4.05$, partial $\eta^2 = .05$, $F(18, 1330) = 44.65$, partial $\eta^2 = .37$, $F(18, 1330) = 79.62$, partial $\eta^2 = .52$, $F(18, 1330) = 75.96$, partial $\eta^2 = .51$, $F(18, 1330) = 84.18$, partial $\eta^2 = .53$, $F(18, 1330) = 106.32$, partial $\eta^2 = .59$, $F(18, 1330) = 12.71$, partial $\eta^2 = .15$, $F(18, 1330) = 5.75$, partial $\eta^2 = .07$, $F(18, 1330) = 4.28$, partial $\eta^2 = .05$ for flat handed pick up, pressure, pull, rotate, rub, run through, stir, stroke, and tapping sequentially. Finally, separate interaction effects of material and task on each EP was tested. Flat handed pick up, $F(72, 1330) = 1.62$, partial $\eta^2 = .08$, pressure, $F(72, 1330) = 4$, partial $\eta^2 = .18$, pull, $F(72, 1330) = 2.95$, partial $\eta^2 = .14$, rub $F(72, 1330) = 2.93$, partial $\eta^2 = .14$, and run through, $F(72, 1330) = 1.89$, partial $\eta^2 = .09$ were statistically significant (all $p < .01$). However, stir, $F(72, 1330) = .96$, partial $\eta^2 = .05$, rotate, $F(72, 1330) = 1.17$, partial $\eta^2 = .06$, stroke $F(72, 1330) = .89$, partial $\eta^2 = .04$, and tapping $F(72, 1330) = .49$, partial $\eta^2 = .02$ were not statistically significant (all $p > .05$).

Finally, in order to determine whether EPs can predict the perceived softness dimensions we conducted a classification analysis. Classification analysis was computed for EPs using a support vector machine (SVM) with Euclidian distance. The SVM received the first half of the data (152 observations) as a training set and it was two-fold cross validated. Then the trained algorithm was used to predict the perceived softness dimensions of the remaining data (133 observations). The prediction performance of the SVM was 57.14% (76 out of 133) and significantly above the chance level (chance level: 16.6% because of 6 categories).

IV. DISCUSSION

We investigated whether and how the perceptual task, i.e. which softness dimension participants aim to rate, and the properties of the explored material affects the usage of EPs. As a necessary precondition, we confirmed that indeed, our adjectives represent judgments on 5 different perceptual dimensions—Granularity, Deformability, Viscoelasticity, Furriness, and Roughness—, and the former four of these dimensions have been previously associated with aspects of softness [1]. Some might think that softness dimensions we found belong to another dimension that covaries with softness due to our stimuli selection. However, others [1, 8] also found dissociation. Moreover, we observed that participants use the stereotyped hand movements of pressure [11], tapping [10], stirring, rubbing, pulling, stroking [11], running through, or rotating [13-15] as well as flat-handed

picking up, mainly as expected for the used materials [13, 14]. Most importantly, the percentage occurrence of these EPs depended on the task, the material and their interaction. Furthermore, as can be well seen in Fig. 4 the differences in EP usage for different materials are shaped based on softness dimensions associated with these materials (Fig. 4). These results together further support our notion of existing different softness dimensions.

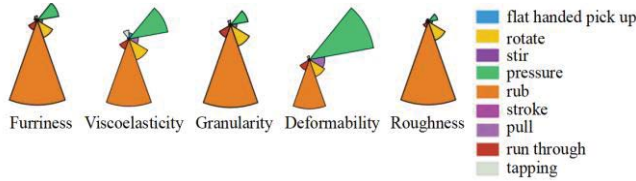


Figure 3. Mean percentage of occurrence of each EP as a function of rated perceptual dimension

As previously suggested for haptic softness and texture perception [13, 21], EPs were affected by the material properties. Considering the perceptually diverse dimensions of softness, we had expected to observe different EPs for materials that have high values on different softness dimensions just as different hand movements were observed for roughness and slipperiness in tactile texture perception [21]. Indeed, in Fig. 4 corresponding links can clearly be seen. For example, participants often applied *pressure* to a sponge or to playdough (which have high scores on deformability), they often used *rotate* and *run through* for sand and salt (scoring high on granularity), tended to *rub* and *pull* hair gel and hand cream (associated with viscoelasticity) and frequently used *rub* for fur or cotton balls (which have large values on the furriness dimension). It is also important to note that in our study, we obtain similar results for rough materials, namely a high percentage of *rub*, as were observed in [11] for judgments of roughness: in that study the roughness-associated EP was called *lateral motion*, while we differentiated this EP here into *stroke* and *rub*, based on the applied *pressure*. Note further that some materials (wool, stress balls) had high values on more than one dimension, so that results for these materials cannot be interpreted as straightforwardly as for the others.

Importantly, besides the material effects we also observed differences in the frequencies of EP usage as a function of task, i.e. of perceptual dimension (Fig. 4). Replicating previous results from [11] the task to judge roughness was dominantly associated with a kind of lateral motion (namely *rub*), whereas the task to judge deformability was most frequently associated with applying *pressure*. Further, in contrast to deformability, the other potential softness dimensions of furriness and granularity were mainly explored by *rub*. To rate viscoelasticity both *rub* and *pressure* were used, with frequencies in-between those for deformability on one side and furriness/granularity on the other side. This differentiation of the frequencies of EP

usage corroborates the notion that these perceptual tasks represent different (softness) dimensions. However, it is important to note that for each perceptual task not only one dominant, but a number of different EPs were occasionally used, e.g. *pressure*, *pull*, *rotate*, *rub* and *run through* for deformability.

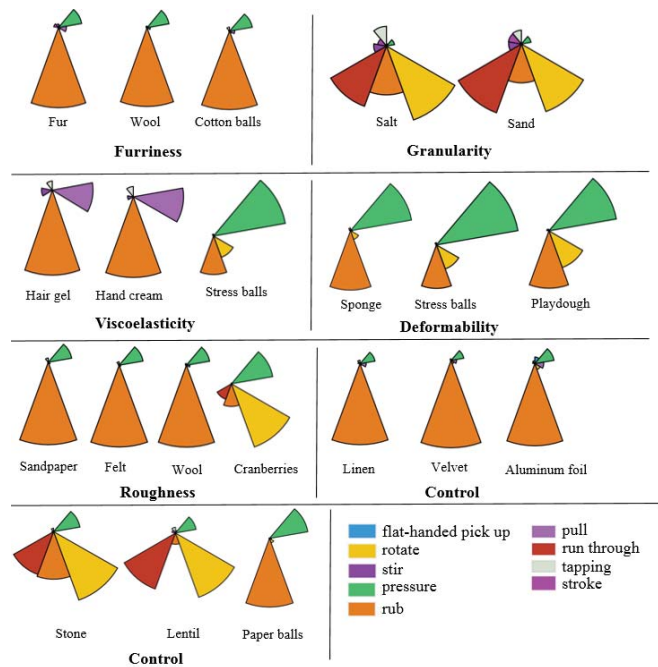


Figure 4. Mean percentage of occurrence of each EP as a function of material

Note also that material effects on the EPs tended to be stronger than task effects. However, we also found an interaction between task and material. That means, the combination of task and material together affects the EPs. This might mean that the same perceptual dimension is optimally judged with different EPs, depending on the material that is explored. In Fig. 5 we depicted as a showcase how EPs differ as a function of judged perceptual dimension for the highly granular materials sand and salt (for which overall *run through* and *rotate* dominate, see Fig. 4). When compared to Fig. 3, it can be seen how task effects differ for granular material as compared to all materials. That is, EPs are not determined by task or material in isolation.

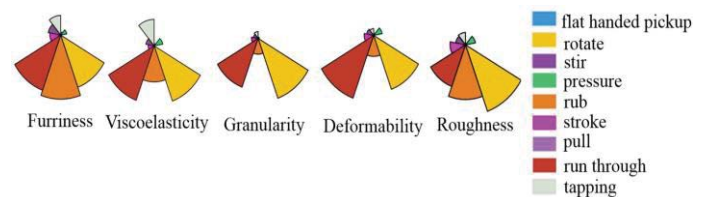


Figure 5. Mean percentage of occurrence of each EP as a function of perceptual dimension for highly granular materials

To conclude, our results support the idea of different softness dimensions by showing that the usage of EPs depends on the task, which softness dimension to rate, as well as on material properties linked to softness dimensions. Importantly, the results also demonstrate that it is the combination of task and dimension-related material properties, which is highly relevant for the usage of EPs.

However, there are still a number of questions that remain unanswered, and further studies are required to test the present conclusion from other viewpoints. Future studies might focus on the optimal EPs for different dimensions of softness by using an object recognition task as [11], and investigate how softness perception changes as a function of the body part used.

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