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How Shape And Material Properties Affect Touch Patterns During Complex Shape Perception

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***Abstract*— Shape perception through touch allows object recognition without visual input. While humans can reliably perceive and discriminate geometric features like curvature, less is known about how perceivers explore and integrate these features to form coherent shape representations when perceiving complex shapes through touch. Here, we investigated whether individuals prioritise certain shape features when gathering information about complex shapes. We compared touch patterns for convex, concave and flat regions, when exploring shapes varying in material properties (rigid-plastic vs. deformable-silicone) and shape features (convex, concave and flat). Participants explored one reference and two test objects using a finger and selected the test object that was most similar in shape to the reference. We assessed dwell time, distance travelled, velocity, and force of touch. Across the two materials, exploration parameters were generally consistent, except that participants applied less force to deformable shapes. For both materials, participants showed a clear preference for exploring concave over convex or flat regions indicated by all parameters, suggesting that these regions were considered as more informative and formed an important basis of their shape judgments.**

Keywords— Haptic shape perception, shape features, material properties, exploration

I. INTRODUCTION

Shape perception through touch is an important aspect of how we interact with and interpret our surroundings. When reaching into a bag to find a phone or pen, we can identify objects by their shape using only touch without needing to look. Research showed that humans can identify and categorise not only familiar everyday items, but also complex and unfamiliar shapes by touch. Through deliberate explorations, they form mental representation of shape, integrating sensory information gathered through touch [1-5]. This process involves exploratory hand movements that are purposeful and finely tuned to the type of information sought and the material properties of the object [6-9]. For perceiving shape, observers typically employ two main exploratory strategies: enclosing or grasping the object to perceive overall shape and coarse features, and running one's fingertip along its edges or contours to discern finer details about its form [6, 7].

Research on haptic shape perception has demonstrated that people can reliably perceive and discriminate geometric elements, such as curvature, through touch. For instance, [10] found that curvature perception relies on the surface gradient of the stimulus and that people can detect curvatures with a base-to-peak height of less than 0.1 mm. [11] found that individuals are highly sensitive to subtle differences in surface curvature, effectively distinguishing between convex and concave surfaces. Using blocks with curvature magnitudes between 0.2 and 2.2 m^{-1}, participants achieved discrimination thresholds as low as 0.67 m^{-1} for younger adults using static touch. Similarly, [12] demonstrated that individuals could distinguish a flat surface from a convex curvature of 4.9 m^{-1} and from a concave curvature of 5.4 m^{-1} with a probability of 75%. Furthermore, [13-14] demonstrated that curvature matching performance is not affected by the tilt of stimuli, suggesting that curvature perception is robust regardless of object orientation. Taken together, these findings indicate that individuals possess remarkable ability to detect and perceive curvature, allowing them to reliably extract geometric elements of shapes through haptic exploration.

While much is known about how people extract shape information and discriminate curvature, investigations on how they organise and interpret this information to perceive the overall form of complex shapes remain scarce. Some evidence suggests that, in order perceive complex shape, individuals may simplify them by decomposing their structure into more familiar geometric elements. For example, [15] found that participants who haptically trace virtual shapes composed of a large ellipse with two small circles, often reproduced them with systematic biases, such as drawing ellipses as more circular, suggesting a tendency to simplify shapes into more familiar forms. Similarly, [16] demonstrated that when exploring contours made of semicircular arcs, quarter circles or ellipses, participants often misperceived complex shapes as simpler forms. Features like quarter circles were sometimes missed, with shapes interpreted as pairs of semicircles. These results suggest that the haptic system may go beyond local feature detection and actively simplify shape input to support recognition. One possibility is that such simplification arises from a tendency to prioritise certain types of features during exploration, allowing perceivers to focus on the most informative parts of the shape. This raises the question of whether certain geometric features are more likely to guide exploration, and whether this prioritisation support the construction of shape representations.

Insights from visual shape perception may offer a useful parallel for understanding which features are prioritised during haptic exploration. Studies suggest that areas of high curvature often contain the most information about a shape's structure and support the decomposition of shapes into local features. For instance, when individuals are asked to identify the most informative points along a shape's outline, they

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frequently select high curvature areas, as these regions are perceived to be important for shape recognition [17-18]. Within the visual domain, there's ongoing debate about the relative importance of different shape features. Some studies emphasise convexities as key for shape segmentation and recognition [19-22], while others highlight the role of concavities in defining part boundaries and aiding in the decomposition of complex shapes into components [23-25]. Some argue for the importance of both features, or the regions in-between curvatures, depending on the context and stimuli design [18,25-28]. It's plausible that individuals may find certain features more informative or focus more on specific aspects when perceiving shapes. These findings raise the question of whether similar feature-based priorities exist in haptic shape perception, specifically, whether concavities or convexities more likely to guide exploration and support shape decomposition.

Here, we examined whether individuals prioritise certain shape features over others. In particular, we examine the roles of convex, concave, and flat regions in haptic shape similarity judgments by analysing various exploration parameters, such as dwell time, distance travelled, velocity, and force of touch. To test the generalisability of these priorities, we introduced material variation by comparing judgements and exploration behaviours between rigid and deformable shapes. Prior research has shown that an object's material properties can influence its perceived shape. For instance, [29] found that 3D shapes made of velvet were perceived as flatter than their matte counterparts, despite identical geometry. Similarly, [30] demonstrated that surface curvature of translucent objects tend to be underestimated compared to opaque ones. Building on these findings, our study aims to determine whether similar effects extend to haptic perception. By examining the consistency of exploratory strategies across materials, we seek to determine the extent to which they generalise and can be viewed as invariant strategies for gathering shape-related information.

II. METHODS

A. Participants

18 participants (4 males, aged 18-30, M_{age}= 22.9, SD_{age}= 3.1) were recruited from Giessen University. Three were left handed, all others were right-handed, and none reported motor or cutaneous impairments. All participants had a 2-point discrimination threshold of <4mm on their right index finger. All participants provided informed consent and received 8€/h for participation. One participant was excluded due to equipment issues, leaving a final sample of 17 participants. This study was approved by Giessen University's ethics committee (LEK FB06) in accordance with the 2013 declaration of Helsinki, except for preregistration.

B. Stimuli

Two sets of stimuli were used: silicone-deformable shapes and plastic-rigid shapes (Fig. 1). Silicone-deformable shapes were cast from 3D-printed moulds using a two-component silicone rubber solution (Alpa Sil EH A&B) mixed with silicone oil. The compliance level of the silicone-deformable shapes was 0.68 mm/N [31]. Plastic-rigid shapes were 3D-printed and were polished to minimise texture left by the printing process. Each set consisted of five shapes, varying in the number and prominence of curvature elements, with approximate dimensions of 60×60×20mm. Shapes were

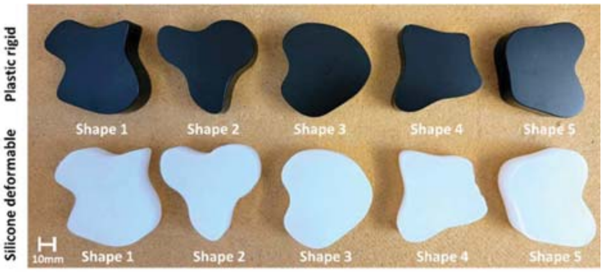

Fig.1. Stimuli used in the current experiment. Top row: Plastic-rigid shapes. Bottom row: Silicone-deformable shapes.

labelled numerically, however, these numbers bear no relation to the physical or shape characteristics of the objects.

C. Apparatus

The experiment took place at a visual-haptic workbench equipped with a PHANToM 1.5A haptic device (spatial resolution: 0.03mm; temporal resolution: 1000Hz) to track finger position. A force sensor (682Hz; 0.05N), was placed beneath the stimuli via a custom-made mount to record the force exerted during exploration. The visual scene was presented on a 24-inch computer screen (120Hz, 1600×900 pixels), displaying a scene that corresponded to the physical positions of the stimuli (Fig. 2A). In the visual scene, each stimulus was represented by a grey circular disc, and participants' finger position was represented by a green sphere. These visuals guided finger position before exploration and disappear upon contact with the stimulus. No visual feedback was provided during exploration.

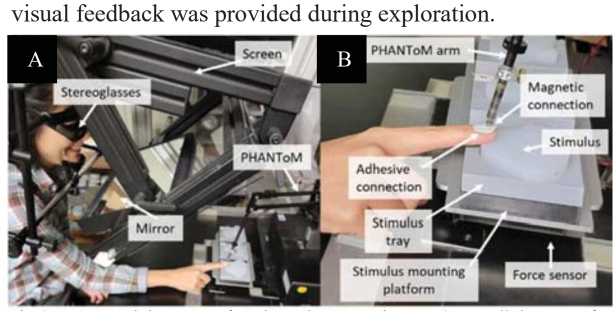

Fig.2. A) Participant performing the experiment (note: lights on for illustration; lights were off during actual trials). B) Close-up of the magnetic finger attachment to the PHANToM and the custom stimulus platform mounted on the force sensor.

Participants wore stereo-glasses (CrystallEyesTM) and viewed the screen via a mirror, with head position stabilised by a chin rest. The right index finger was connected to the PHANToM via a magnetic attachment secured to the fingernail (Fig. 2B), allowing six degrees of freedom in finger movement while keeping the fingertip pad free for tactile exploration. The devices were connected to a PC that controlled the experiment and record finger positions and applied force at a temporal resolution of 3ms. Noise-cancelling headphones (Sennheiser HD 280 Pro) played white noise to mask background sounds and delivered beeps to signal the start and end of each exploration period.

Each stimulus was placed in a shape-specified tray (80×63.3×15mm) with a 1mm clearance, allowing it to protrude by 10mm above the surface to minimise displacement during exploration. For each trial, three trays were mounted side-by-side on a 3D-printed platform (80×240×15mm) with a metal base attached to the force sensor: standard object on the left, first comparison in the centre, and second comparison on the right, spaced ≈3cm apart. Stimuli were presented in a fixed orientation,

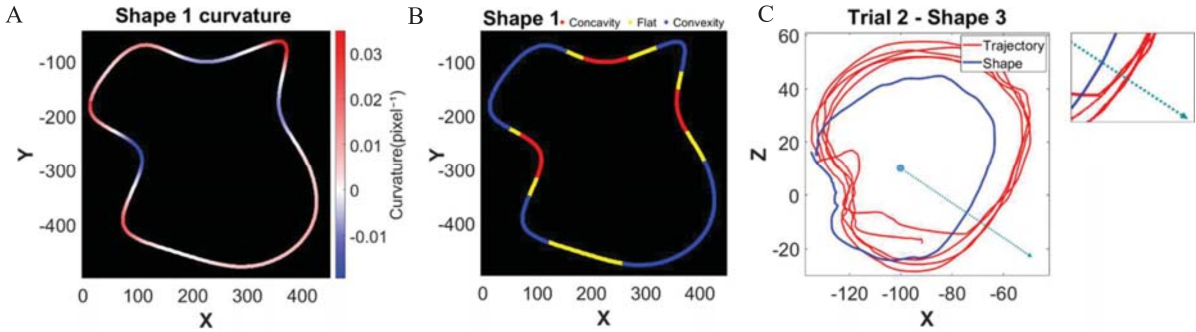

Fig. 3. Curvature analysis and data alignment. A) Shape analysed based on curvature values: positive(red), negative(blue) and near-zero curvature (white), with darker shades indicating greater magnitude. B) Shape segmented into convex (blue), concave (red), and flat (yellow) regions based on the defined curvature thresholds. C) Data alignment schematic: red lines represent trajectory data, blue line shows the shape outline in PHANToM's spatial coordinates.Each trajectory point was mapped to the closest point on the outline via a centroid-projected line.

determined by the shape-specific trays used to stabilise placement. This ensured consistent positioning but did not allow for testing the effects of orientation variability.

D. Design and Procedure

Participants completed two conditions in one session: plastic rigid shapes and silicone deformable shapes, with order counterbalanced across participants. Each stimuli set consisted of five shapes, and 20 distinct standard × comparison objects combination were generated and used for both conditions. Each shape served as the standard object four times, with the others as comparison objects twice. In each trial, participants used their right index finger to explore a standard object and two comparison objects sequentially (15s each), then selected the comparison object they perceived as most similar to the standard object's shape. The 20 standard-comparison combinations were presented once per condition in randomised order. Participants completed 20 trials per condition, resulting in a total of 40 trials, lasting about 1-1.5hrs. The experimental session began with participants providing informed consent and demographic information, followed by measuring the two-point discrimination threshold on their right index finger using a two-point discriminator.

In the visual scene, stimuli were represented by a grey circular disc that turned red to cue finger placement. At the start of each trial, the left disc (standard object) turned red and disappeared immediately upon contact, before any haptic exploration began. The disc served only as a generic positional cue and was not visually informative about the stimulus shape. Participants then explored the object until an auditory beep signalled the end of the exploration period. The same procedure followed for the centre (first comparison) and right (second comparison) objects. After exploring all three objects, a decision screen appeared and participants selected the comparison object they perceived as most similar to the standard object's shape by pressing a virtual button.

E. Analysis

1) Curvature Analyses: To examine whether touch patterns varied by shape features, we categorised object boundaries into concave, convex and flat regions using a curvature visualisation tool ('CurvatureVisualize'[32-33]). Positive values indicated convexity, negative values indicated concavity, and near-zero values represented flat regions (Fig.3A). Curvature thresholds were defined emprically from the full range of curvature values observed across all shapes ($-2.35E^{-2}$ to $5.05E^{-2}$pixel^{-1}, $\approx -8.88E^{-2}$ to $1.91E^{-1}$mm^{-1}), with flat regions defined as $\pm 4.2E^{-3}$pixel^{-1}($\approx \pm 1.59E^{-2}$mm^{-1}). Remaining values were assigned to convex ($>+4.3E^{-3}$, $\approx$ $1.62E^{-2}$mm^{-1}) or concave regions ($<-4.3E^{-3}$pixel^{-1}, $\approx -1.62E^{-2}$mm^{-1}). These threshold reflect the distribution of curvature across the stimuli and allowed us to segmented shape features in a way that preserved geometric distinctions. They were not arbitrarily selected, but derived from the observed curvature range across all stimuli. To further quantify the curvature composition of each shape, we calculated the proportion of the ouline corresponding to convex, concave and flat regions. These values are summarised in Fig.4.

Shape					
Convex	53.52%	62.21%	62.69%	43.67%	54.47%
Concave	19.14%	20.38%	6.72%	11.35%	6.38%
Flat	27.34%	17.41%	30.59%	44.98%	39.15%

Fig. 4 Curvature composition of each shape. Shapes are segmented into different shape feature categories based on curvature thresholds. Percentages indicate the proportion of each shape's contour classified as each feature type.

The slightly asymmetric range boundaries accounted for skew in the curvature distribution, ensuring that flat regions were tightly defined and that positive and negative curvature were separated appropriately. This categorisation was necessary to enable analysis of exploratory behaviour relative to shape features, which would not be feasible with continuous curvature values alone. Segmented features were mapped to PHANToM-derived spatial coordinates, with shape outlines recorded at each experimental locations (left, centre, right) and aligned with the curvature-based segmentation to identify feature boundary coordinates for each shape (Fig. 3B).

2) Data filtering: The PHANToM recorded timestamp, finger position coordinates and the applied normal force (N) measured at each timestamp. Each trial involved three stimuli, each placed in its own tray on a platform on top of a force sensor. To isolate participant-applied force, baseline forces (reflecting object weight) were measured and subtracted from recorded data. Force values at baseline indicated no finger contact, while values above the baseline reflected active interaction. Occasional values below the baseline, likely due to improper stimulus placement or sideways force destabilising the object, were treated as artefacts and excluded to ensure only genuine instances of active exploration were analysed.

3) Mapping trajectory data to shape feature categories: Trajectory data points were aligned with the shape's spatial coordinates to determine which parts of the shape each trajectory point corresponded to. While the raw data included timestamped finger position and force measurements, it did not directly indicate which part of the shape was in contact. Misalignments occurred to due natural variations in finger use, participants sometimes made contact with areas beyond the tracked fingertip (e.g. near the second joint), resulting in small spatial offsets between the recorded trajectories and the actual shape outline (Fig. 3A).

Despite these offsets, the recorded trajectories still closely followed the overall shape contours. To approximate the corresponding location on the shape outline, we used a centroid-based projection method (Fig. 3C dotted line): for each trajectory point, a line was projected from the shape's centroid through the point to identify the closest point on the shape outline along the same radial direction. This process mapped each trajectory point ($X_{trajectory}$, $Z_{trajectory}$) to a corresponding point (X_{shape}, Z_{shape}) on the shape's outline. While this method does not capture the exact contact point, it provides a consistent and geometry-based approximation sufficient for feature-level analysis. Using the curvature-based segmentation described earlier, the mapped points were assigned to their respective shape feature category (convex, concave, or flat), enabling analysis of exploration relative to specific shape features.

4) Data analysis: We extracted exploration parameters - dwell time, cumulative distance, force and velocity for each trial, shape and location. Parameters were computed by shape feature category (concave, convex, flat) based on the segmentation described above.

a) Dwell time (ms): Total time spent on each feature, calculated by multiplying the number of trajectory samples at each XZ coordinate by the 3ms sampling interval and summing across each feature region.

b) Cumulative Distance (mm): Total distance travelled across each feature. Computed by summing the Euclidean distances between each consecutive trajectory points:

$$Distance = \sqrt{(x_2 - x_1)^2 + (z_2 - z_1)^2} \quad (1)$$

c) Velocity(mm/ms): Speed of touch across shape features, computed by diving the Euclidean distance between each pair of consecutive trajectory points by the time interval to obtain the instantaneous velocity. These values were then aggregated by shape feature category and averaged to calculate the mean velocity for each feature type.

d) Force: Mean normal force during contact, calculated by averaging force readings from trajectory points mapped to that feature.

5) Data normalisation: To account for differences in shape feature proportions and to ensure our data reflected exploration behaviour relative to the size of each shape feature, we normalised dwell time and cumulative distance by dividing the values for each feature by its percentage within the shape.

6) Similarity judgements: We computed Cronbach's α across participants for each standard object x comparison object combination to assess the interobserver consistency of their perceptual judgements in each condition. We also examined how often an object was judged to be most similar to a given standard object by examining the instances in which an object was judged as more similar when compared to another, to do this we counted the number of such occurences and divided it by the total number of comparisons.

III. RESULTS

A. Exploration parameters

Our findings indicated that touch patterns were primarily influenced by shape features, with concave regions being explored longer and more extensively than convex and flat regions across most shapes (see Fig.5). Exploration parameters, except for force, remained consistent across material conditions. Repeated-measure ANOVAs with Bonferroni post-hoc pairwise comparisons assessed the effects and interactions of materials and shape features effects, Greenhouse-Geisser corrections were applied when needed. Shape-specific effects across parameters were reported after the main repeated-measures ANOVA results on exploration parameters.

1) Relative Dwell time: The repeated-measures 3-way ANOVA revealed significant main effects for shape feature, $F(1.105, 17.677) = 131.96$, $p < .001$, $\eta_p^2 = .89$. Participants

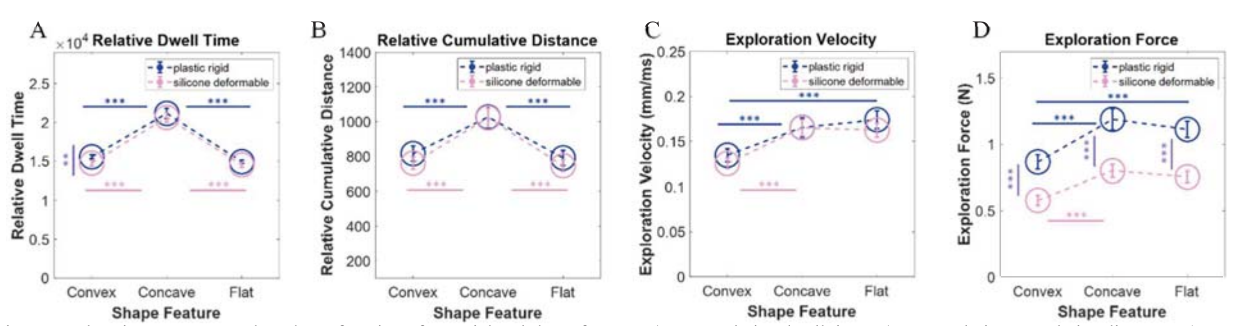

Fig. 5 . Exploration parameters plotted as a function of material and shape feature. A) Mean relative dwell time, B) Mean relative cumulative distance, C) Mean exploration velocity, and D) Mean exploration force. For force, there was further a significant interaction of material x shape across all shapes, with participants applying more force to plastic rigid shapes (Shape1 : *M*= .87, *SE*= .06; Shape2 : *M*= .95, *SE*= .06; Shape3 : *M*= 1.11, *SE*= .07; Shape4 : *M*= .95, *SE*= .05; Shape5 : *M*= 1.41, *SE*= .09) than silicone deformable shapes (Shape1 : *M*= .58, *SE*= .03; Shape2 : *M*= .62, *SE*= .04; Shape3 : *M*= .75, *SE*= .05; Shape4 : *M*= .64, *SE*= .04; Shape5 : *M*= .96, *SE*= .06; *ps*< .001 for all comparisons). Blue lines represent plastic rigid shapes and pink lines represent silicone deformable shapes, error bars represent 1± SE.

spent the most time exploring concave regions compared to convex ($p < .001$) and flat ($p < .001$) regions, no significant difference was found between convex and flat regions ($p = .07$), see Fig.5A. A weak main effect of material was also observed, $F(1,16) = 4.641$, $p = .047$, $\eta_p^2 = .23$, with participants spending slightly more time exploring during the plastic rigid condition ($M = 17198.24$, $SE = 308.82$) than the silicone deformable condition ($M = 16621.02$, $SE = 346.84$, $p = .047$). No other significant main effects or interactions were found related to material ($ps = .08 - .65$).

2) Relative Cumulative Distance: The repeated-measures 3-way ANOVA revealed a significant main effect of shape feature, $F(1.131, 18.102) = 92.99$, $p < .001$, $\eta_p^2 = .85$, with concave regions being explored more extensively than convex($p < .001$) and flat ($p < .001$) regions, no significant difference was found between convex and flat regions ($p = .06$), see Fig.5B. A significant interaction of material × shape feature was observed, $F(1.271, 20.342) = 4.53$, $p = .038$, $\eta_p^2 = .22$. For rigid plastic shapes, concave regions were explored more than convex ($p < .001$) and flat regions ($p < .001$), with convex regions explored more than flat regions ($p = .002$). For silicone deformable shapes, concave regions were explored more than convex ($p < .001$) and flat regions ($p < .001$), with no significant difference between convex and flat ($p = .62$). There were no other significant main effects or interactions in relation to materials ($ps = .29–.34$).

3) Velocity: The repeated-measures 3-way ANOVA revealed a significant main effect of shape feature $F(1.408, 22.527) = 77.57$, $p < .001$, $\eta_p^2 = .83$. Exploration was slowest at convex regions compared to concave ($p < .001$) and flat ($p < .001$) regions, with no significant difference between concave and flat regions ($p = .93$), see Fig.5C. An interaction between material and shape feature was also observed, $F(2, 32) = 6.73$, $p = .004$, $\eta_p^2 = .30$, in which for rigid plastic shapes, velocity was slowest at convex regions compared to concave ($p < .001$) and flat regions ($p < .001$), with no significant difference between concave and flat regions ($p = .07$). For silicone deformable shapes, velocity was also slowest at convex regions compared to concave ($p < .001$) and flat regions ($p < .001$), there was no difference between concave and flat regions ($p = 1.00$). No other significant main effects or interactions related to material were found ($ps = .14 – .27$).

4) Force: The repeated-measures 3-way ANOVA showed a significant main effect of shape feature $F(1.211, 19.372) = 51.79$, $p < .001$, $\eta_p^2 = .76$. In which convex regions received less force than concave ($p < .001$) and flat ($p < .001$) regions, with no significant difference between concave and flat regions ($p = .25$, see Fig.5D). There was also a significant main effect of material, $F(1, 16) = 36.34$, $p < .001$, $\eta_p^2 = .70$, with participants applying more force to plastic rigid shapes ($M = 1.06$, $SE = .06$) than silicone deformable shapes ($M = .71$, $SE = .04$, $p < .001$). Additionally, a significant interaction of material × shape was found, $F(2.034, 32.539) = 3.65$, $p = .04$, $\eta_p^2 = .19$. Across all shapes, participants applied more force to plastic rigid shapes compared to silicone deformable shapes (see Fig.5 caption for details). There were no other significant main effects or interactions ($ps = .13 - .18$)

5) Shape-Specific Effects on Exploration Parameters: Exploration parameters showed consistent main effects of shape and significant shape × shape feature interactions, suggesting distinct exploration patterns for specific shapes. Across all parameters, Shape 5 consistently elicited the highest values (dwell time, cumulative distance, velocity, and force), indicating that it may required or encouraged more extensive exploration compared to the other shapes. Conversely, Shape 3 exhibited a distinct pattern, where flat regions were explored more extensively than concave and convex regions, deviatng from the general trend observed for other shapes. Notably, both shape 5 and 3 had the lowest proportion of concave regions (<7%), yet they differed in how these features were explored, suggesting that curvature composition along may not fully explain shape-specific behaviours. Detailed statistical results and pairwise comparisons are reported and visualised in Fig. 6.

B. Similarity judgements

We assessed how consistent participants were with their shape similarity judgements across material conditions. The Cronbach's α values were .96 for shape judgments of plastic rigid objects and .97 for silicone deformable objects, indicating high level of consistency. In Fig.7 we showed a

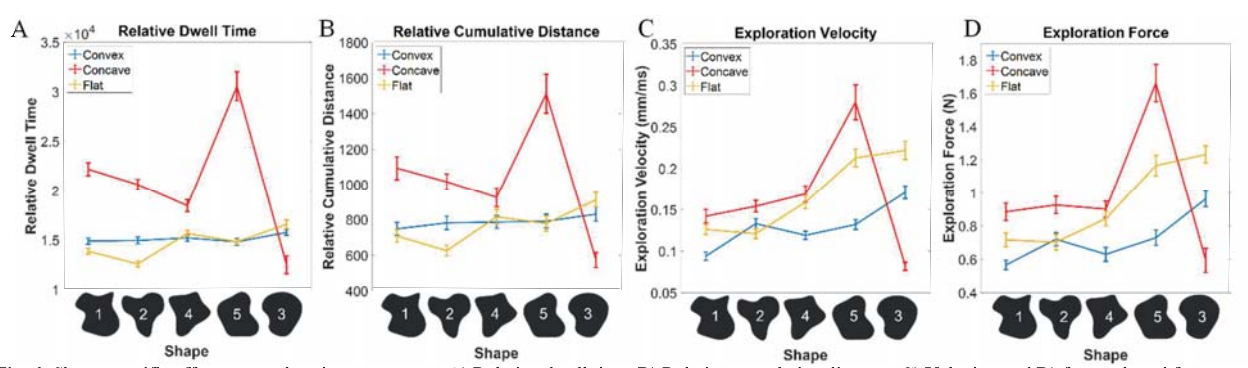

Fig. 6. Shape-specific effects on exploration parameters. A) Relative dwell time, B) Relative cumulative distance, C) Velocity, and D) force, plotted for convex, concave, and flat regions across shapes. Significant main effects of shape were observed across all parameters, with Shape 5 consistently showed the highest overall values across parameters, and significantly exceeding shape 1-4 ($ps < .001$ for all comparisons). Relative dwell time: $F(1.568, 25.087) = 61.38$, $p < .001$, $\eta_p^2 = .79$; relative cumulative distance: $F(1.380, 22.082) = 54.90$, $p < .001$, $\eta_p^2 = .77$; velocity: $F(1.468, 23.490) = 144.50$, $p < .001$, $\eta_p^2 = .90$; Force: $F(2.065, 33.037) = 75.01$, $p < .001$, $\eta p^2 = .82$). Shape × shape feature interactions were also significant for all parameters (i.e., relative dwell time: $F(1.920, 30.727) = 64.01$, $p < .001$, $\eta_p^2 = .80$; Relative Cumulative Distance: $F(1.459, 23.339) = 73.49$, $p < .001$, $\eta_p^2 = .82$; Velocity: , $F(1.556, 24.897) = 94.89$, $p < .001$, $\eta_p^2 = .86$; Force: $F(2.302, 36.825) = 59.53$, $p < .001$, $\eta_p^2 = .79$). Pairwise comparisons revealed that concave regions were generally explored longer (dwell time), more extensively (distance), faster (velocity), and with greater force, except for Shape 3, where flat regions dominated across all measures ($ps < .001$). Error bars represent 1± SE.

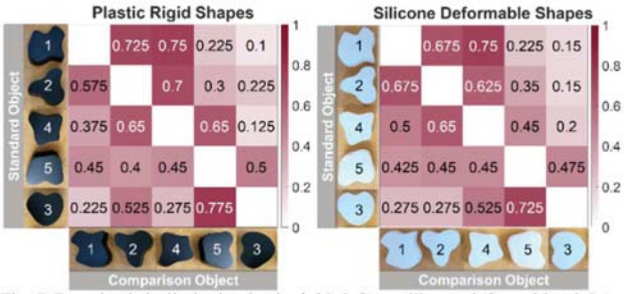

Fig. 7. Perceived similarity in plastic rigid (left) or silicone deformable (right) shape judgments.These similarity matrices illustrate how often an object was rated as most similar to a given standard object, with light colours indicating lower values and darker colours indicating higher values.

visualisation of the perceived similarity in participants' perceptual judgements across material conditions. The correlation between similarity matrices of silicone deformable and plastic rigid shapes were also strong (r^2 = .87, p< .001), suggesting that participants were not only consistent with their exploration behaviours, but they also perceived the shapes consistently in both material conditions.

IV. DISCUSSION

We investigated whether participants prioritise certain shape features and whether these priorities generalise across material properties. Our analysis of touch patterns and shape similarity judgements revealed three main insights: 1) a strong preference for exploring concave regions across all conditions and exploration parameters, 2) differences in applied force between material conditions, and 3) consistent shape perception across material conditions.

Participants exhibited a strong preference for concave regions, suggesting higher perceptual saliency and informativeness for shape perception. Across all exploration parameters, concave regions were explored more extensively than convex or flat regions, likely due to the distinct haptic cues they provide, like abrupt changes in contour direction, which could aid efficient shape perception. This aligns with visual research highlighting concavities in defining part boundaries and aiding in shape segmentation [23-24]. In the haptic domain, [34] employed a haptic search task to assess the saliency of 3D shape features, and found that edges and vertices, analogous to concavities, were particularly salient, and influence how individuals explore and recognise objects. Without visual input, concavities may act as perceptual anchors, guiding attention towards areas with reliable geometric cues. While this role parallels findings in vision, it may arise from different mechanisms in haptic perception. Concavities often provide more accessible contact point for the fingers, and their relative rarity in close contours may enhance their informativeness, in line with information-theoretic accounts suggesting that less frequent features carry more information/greater perceptual value [35].

Furthermore, biomechanical constraints may also modulate the tendency to prioritise concavities, as seen in the deviated touch pattern for shape 3. While both Shape 3 and 5 had similarly low proportion of concavity (6.72% and 6.38%, respectively), they differed in how those features were explored. Shape 5's was on the right- potentially more accessible for right-hand exploration, whereas Shape 3's was on the left. Supporting this, analysis of Shape 1, which had concavities on both sides, showed significantly greater exploration of the right concavity across all exploration parameters (p< .001). These results suggest that concavity salience is not solely determined by its geometric composition, but also by its spatial accessibility. Together, they highlight how concave regions can guide haptic exploration and shape perception, while showing the flexibility of exploration patterns in adapting to task demands and physical constraints.

While most exploration parameters were consistent across material conditions, participants applied significantly more force to rigid plastic shapes compared to deformable silicone shapes. This likely reflects a strategic response to material properties. For rigid shapes, increased force may enhance tactile resolution, allowing them to better detect fine geometric details. In contrast, for deformable shapes, participants may have moderated their force to avoid distorting the material, which could compromise shape perception. These findings demonstrated the haptic system's ability to dynamically adapt exploration strategies to optimise gathering of perceptual information and task performance under varying conditions [31].

The high agreement in perceived shape within each material condition, and the strong correlation between similarity judgments for rigid and deformable shapes, suggests that participants' shape perception was robust to variations in material properties. Despite differences in material properties, participants' shape judgements were guided by consistent geometric representations. These findings align with prior research showing that the haptic system is adept at isolating task-relevant dimensions while disregarding irrelevant ones [6, 34, 36]. This suggests that the cognitive mechanisms underlying shape perception are stable and primarily focus on geometric features, enabling consistent shape perception despite variable tactile feedback.

While our results indicate a strong focus on concavities, factors related to the experimental setup may have influenced this outcome. The PHANToM attachment and isolated finger exploration likely limited natural movements, making concavities more stable or accessible reference point. Additionally, all stimuli were presented in a fixed orientation using shape-specific trays, ensuring consistent positioning across trials but limiting assessment of orientation invariance. This constraint may have further biased exploration towards more accessible shape regions, including concavities. This aligns with previous research suggesting that feature saliency, such as edges and high-curvature points, depends on both task demands and exploratory context. For instance, [37] demonstrated that local features, such as points of high curvature, are prioritised during haptic explorations, especially under time constraints. Thus, the observed concavity saliency in this study may reflect an interaction between perceptual priorities, feature accessibility and exploration constraints.

Our findings demonstrated a balance between consistency and flexibility in haptic shape perception. Participants consistently prioritised concavities as stable focal points across material conditions, suggests that concavities provide invariant geometric cues important for exploration. While this priority generalised across materials, participants also adapted their exploration pattern, such as adjusting force, to optimise performance. These results demonstrated that while certain geometric features broadly guide exploration, exploration strategies remain responsive to contextual influences such as material variations.

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