Exploring Squish: Understanding Dynamic Material Perception and Haptic Thresholds

A thesis submitted by

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Abstract

This research seeks to bridge the gap between neuroscience, psychology, engineering, and psychophysics by investigating the sensory perception of ‘squish’. Squish is defined in this research as the haptic feedback experienced when a person interacts with a material that deforms and rebounds. Gaps in current literature for perceptual thresholds (i.e., identification, detection and discrimination) of ‘squish’ interactions remain a barrier to harnessing it as a dynamic input/output device for human-machine interfaces. A pneumatic end-effector was designed to simulate varying levels of squish. Participant responses were documented to determine just noticeable differences (JNDs). The study findings can be used to inform the design of haptic feedback mechanisms that enhance user experience, and efficiency of human-machine systems. This research aims to lay the foundation for advancing haptic feedback systems by leveraging empirical data to explore how dynamic material properties, such as squish, can serve as a structured modality for tactile communication.

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Introduction

Squish, in this research, refers to the dynamic sensory experience that emerges while interacting with an object's surface compliance and material density. Tactile sensations, such as squish, engage cutaneous, proprioceptive, and kinesthetic inputs and are therefore essential for perceiving material properties and guiding physical interactions of everyday tasks. As a material property, squish can be quantified mechanically using measurements of stiffness, hardness, elasticity, viscosity, and compliance. A review of existing literature identified a few studies exploring how objects that ranged in durometer, a standardized measurement of mechanical deformation, given as a 'Shore value' impacted visual targeting tasks. Results from one study exploring force-based targeting indicates "participants found the *Soft* surfaces to be more *comfortable*, but perceived it as less accurate than the *Hard*" (Fruchard et al., 2021), based on post-task Likert-scale ratings. While the authors noted that the three surfaces (*Soft, Medium, Hard*) were comparably demanding, performance data showed that participants overshot the intended force when applying pressure with the *Soft* surface at the *Very High* target level. This suggests that participants both experienced, and perceived greater difficulty controlling higher amounts of force to the *Soft* surface.

Deformation in the surface of soft materials as opposed to rigid surfaces offers an opportunity to engage human perception of material compliance as a form of sensory cueing (Fruchard et al., 2021). However, the exact sensation and human perceptual thresholds of 'squish' remains an understudied area within the research community. Some of this may be due to how difficult it can be to fabricate a system that can provide incremental 'squish' measurements, and subsequent feedback of real-time sensory information (Caldwell et al., 1996).

Understanding the perceptual thresholds of resilience, rebound, deformation and intensity of squish, can provide insight into the capabilities of the human somatosensory system. These elements could serve as controllable cues to interpret tactile feedback, regulate proprioceptive behaviors, and shape our understanding when interacting in physical and digital environments.

Squish has the potential to introduce unique perceptual avenues involving active and passive touch coupled with deformation and reformation to improve performance and engagement of human-machine systems. This study provides an opportunity to expand this knowledge by framing squish as a dual-phase material property (i.e., a combination of volume and surface). This interaction can be understood as the surface provides an immediate response, while the underlying material shapes how the interaction evolves over time. With this framework, squish unfolds through three temporally perceptual features: *Deformation*, *Compliance*, and *Rebound*. *Deformation* reflects the initial surface displacement. *Compliance* represents the continued compression of the underlying volume. *Rebound* describes the recovery of the surface and volume as the material relaxes towards its neutral state. Measuring this perceptive-physical interaction, this work aims to advance our understanding of how dynamic material properties are perceived, establishing a foundation for advancing the development of perceptually grounded, human-machine interfaces.

The Human Perceptual Mechanism

Fundamental work by J.J. Gibson (1966) proposed the theory of direct perception, in which information necessary for perceptual judgment is structured within the environment. This ecological approach contrasts constructivist theories, which propose that perception is the integration of sensory input with prior knowledge, expectations, and contextual cues. Gibson's ecological approach to psychology introduced the concept of affordances, a conceptual idea in which environmental features offer qualities that communicate opportunities for action. For example, a soft, pliable object may afford squeezing, manipulation, or delicate handling. In this context, the perception of squish is not just a tactile event but a dynamic relationship between the object and perceiver.

The experience of squish involves multiple sensory systems such as cutaneous receptors: Merkel discs, Meissner corpuscles, and Ruffini endings which respond to localized pressure, vibration, and skin stretch (Caldwell et al., 1996). Simultaneously, mechanoreceptors relay information about body movements and position during exploratory procedures (Lederman & Klatzky, 2009). For a signal to be generated, its intensity must exceed a threshold and trigger an action potential (i.e., encoded electrical signal) in sensory neurons (Gardner & Martin, n.d.). These neural signals then travel through the nervous system to form a reaction. The reaction can take the form of a motor response, reflex, or additional processing by the brain. Reaching the somatosensory system, a network of neurons in the brain, marks the transition from external sensory input to internally encoded information (Hsiao & Gomez-Ramirez, 2011).

The fidelity of stimuli-sensory information transfer depends on multiple factors, including receptor sensitivity, neural transmission speed, and integration of sensory inputs across different modalities (e.g., auditory and vision). Previous research shows that during object exploration without time constraints, material properties such as surface texture and compliance become more salient than geometric characteristics (Lederman & Klatzky, 2009). This distinction is critical for perceiving material qualities like squish, which rely on the ability to detect subtle variations in compliance, deformation, and rebound. However, tactile sensitivity tends to decline as humans age due to reduction in both receptor density and neural velocity (i.e., speed at which electrochemical impulses propagate down a neural pathway), leading to reduced perceptual resolution (Verrillo, 1980).

An absolute threshold is defined as the minimum stimulus intensity to be detected at least 50% of the time (*APA Dictionary of Psychology*, n.d.). When a stimulus changes over time, such as when pressure or deformation increases, another threshold becomes relevant. The *difference threshold* or Just Noticeable Difference (JND) which is defined as the smallest change in stimulus intensity to be detected at least 50% of the time. Notably, JNDs vary depending on the intensity of the stimulus, formalized in Weber's Law (Williams, 1936). For example, detecting differences in rigid materials with high stiffness levels, typically requires larger changes to be perceptible. Since squish involves soft, compliant materials, small changes may be more perceptually salient than in rigid materials. With less change required for a user to detect a difference, squish could be an efficient channel for communicating.

The perception of squish illustrates how the nervous system can transform dynamic physical attributes into information that supports interaction. Fundamentally, the perception of squish as a layered process could be defined as: environmental interactions translated into neural signals which are dynamically compared overtime to detect change which can then be used as a meaningful call to action. This process blends the mechanisms of cutaneous touch, proprioceptive information, and kinesthetic feedback, forming a robust multisensory construct. Squish offers the potential as an efficient communication modality for human-machine interfaces, as changes in soft materials may produce richer perceptual cues, resulting in continuous feedback aligned with the dynamics of touch.

Exploring Squish

Squish can be understood as a dual-phase material property, encompassing both its surface compliance and internal substance. When a person interacts with a 'squishy' material, the initial perception is largely influenced by its surface layer. The initial impact, which determines the first point of contact delivering rapid tactile cues including softness, texture, and immediate deformation. These experiences shape our assumptions about the materials overall structure. However, as exploration continues, perception can shift to the material's internal substance where factors like viscoelasticity, compressibility, and rebound behaviors may become more dominant.

This dual-phase interaction in therefore defined as the surface providing an immediate impression, and the underlying material dictating a temporal relationship. The outcome is a multidimensional human sensory experience. Non-linear responsive materials—such as those with variable stiffness, shape memory, or tunable elasticity—offer unique affordances because their properties change dynamically and include user interaction as a variable which influences the material's response. This is in contrasts to static materials that offer limited temporal variations. This aligns with Gibson's theory of direct perception which emphasizes the detection of stable invariants in the environment, with dynamic materials offer evolving affordances. As a result, the perceiver continuously recalibrates as the structure of interaction evolves, thus providing a salient modality to harness as a call to action for a human operating within an environment.

In essence, as these materials deform, stiffen, or reshape in response to input, perceivers are actively participating within a system where perception and action are intertwined. For example, a shape memory polymer that works to return to its original form exemplifies this temporal nature, where affordances unfold dynamically with continuously changing material states rather than being static. This shifting interaction places the perceiver into an iterative loop rather than receiving a steady stream of feedback. Unlike static conditions, where sensory neurons may adapt or diminish firing, dynamic materials continuously cross perceptual thresholds, re-engaging the sensory system through JNDs. This ongoing stimulation keeps the perceiver actively tuned, as the surface wraps around the fingertips and induces more tactile innervation (Fruchard et al., 2021). Coupling this notion with the potential for smaller changes in intensity to reliably detect change, makes squish an ideal candidate for human-machine systems, controllers, and physical experiences where users continuously adjust their actions based on changing feedback from the system.

The study of human perception builds on the foundational work of Ernst Weber in the 19th century. Weber's work resulted in the construction of Weber's law which describes a relationship between the ability to perceive a difference and the magnitude of the original stimuli (Cormier, n.d.). Weber's law explains that a person's ability to detect an increase of a stimulus is proportional to the intensity of the original stimulus. This leads to the terminology, "just notable difference" (JND) or "difference threshold" which is the smallest reliably detectable difference between two intensities (*APA Dictionary of Psychology*, n.d.). Gustav Fechner (1860) is accredited for formulizing Weber's law and Fechner's law, often written as Weber-Fechner law. Fechner's formulation is built on a logarithm relationship between the physical and perceived stimulus intensity. Fechner's work describes how progressively larger changes in physical inputs are required to produce the same perceived difference. This could help explain why subtle variations in dynamic materials can feel more perceptual rich at low intensities.

S.S. Stevens (1957) challenged Fechner's logarithmic model, arguing that perception follows a modality specific scaling power function rather than a universal logarithmic relationship (*APA Dictionary of Psychology*, n.d.). This means the relationship between physical stimulus and perceived intensity varies depending on the sensor modality (e.g., sound, pressure, brightness), each having its own exponent constant. This model was derived using magnitude estimation, in which participants directly assigned numerical values to perceived intensities rather than relying on JNDs. While Steven's power law has shown to potentially be a more accurate model for many sensory modalities, its validity remains controversial. Some researchers argue Steven's power law reflects cognitive decision-making rather than purely sensor processes. This distinction is relevant in the perception of squish, as sensations like force, compliance, deformation, and rebound may scale differently and align more closely with specific power functions for each feature of squish rather than a fixed threshold.

Literature Review

Previous research on human sensory identification, detection, and discrimination has typically centered on well-established modalities such as vision, hearing, grasping (Gibson, 1966, 2014; Hansen & Hillyard, 1983), size (Longo & Haggard, 2011), and duration of stimuli (Matthews et al., 2011). Indeed, the "intensity of vibratory stimuli on the skin has been examined many times" (Craig, 1972). Psychophysical research has characterized a select range of tactile thresholds of touch under both active (i.e., initiated by the perceiver) and passive (i.e., applied to the perceiver).

Studies specifically exploring tactile perception, have primary focused on applied pressure sensitivity (AIT ETH, 2018), vibrational frequency and pattern (Azadi & Jones, 2013; L. Brown et al., 2006), skin stretch (Aggravi et al., 2018; Chinello et al., 2016), and texture discrimination. These tactile experiences have been investigated by exploring thresholds in surface roughness (Di Stefano & Spence, 2022), hardness and stiffness (Fruchard et al., 2021), applied force (Basdogan et al., 2023), or sensory acuity (P. B. Brown et al., 2004).

Results from these studies indicate a high tactile acuity; however, the studies have relied on simplified mechanical inputs. In comparison, 'squish' involves a dynamic layered system, combining force, deformation, rebound, compliance, and temporal user-driven features. Despite the growing relevance of these interactions in applications such as soft robotics, medical simulators, teleoperations, and interface design, quantifiable thresholds for squish remain unestablished.

Unlike force or stiffness, squish perception involves temporal and volumetric deformation, triggering cutaneous, kinesthetic, and proprioceptive engagement. Although concepts such as compliance and elasticity have been addressed in biomechanical modeling and haptic interface studies, squish itself is not yet well defined as a perceptual category in psychophysical literature. In fact, few experiments isolate squish as a perceptual attribute distinct from stiffness or softness, despite clear relevance in interacting with shape change objects such as sponges, gels, or inflatable systems. Without this differentiation, current literature lacks a baseline JND or accuracy thresholds to benchmark against other advanced haptic system modalities.

Understanding perceptual thresholds is critical for designing task-specific haptics systems (Hatzfeld et al., 2016). These systems could replicate tactile sensations, communicate information, and assist humans in pathfinding. Emerging interest extends to healthcare, where the perception of squish is critical for replicating soft tissue in prosthetics (J. D. Brown, 2014; J. D. Brown et al., 2015), medical training, and feedback during teleoperations (Bolopion & Régnier, 2013; J. D. Brown, 2014).

Several psychophysical methods have been developed and applied to the study of perception to quantifying identification, detection, and discrimination of tactile thresholds using magnitude estimations (Kappers & Bergmann Tiest, 2013), method of limits (Craig, 1972), and adaptive procedures such as up-down, and one up, three down methods (Chinello et al., 2016; Israr et al., 2006). Magnitude estimation involves participants assigning numerical values to a stimulus intensity, while the method of limits relies on systematically increasing or decreasing a stimulus intensity to find the threshold. In contrast, up-down and staircase methods adaptively adjust stimulus intensity based on participant response to converge on a perceptual threshold. Tan et al (1992, 1993) measured the JND in compliance between two rigid plates grasping between the thumb and fore finger reporting values from ~8% to 99% depending on the availability of cues such as terminal grasp force and total work done. (Srinivasan & LaMotte, 1995).

These findings were determined using a one-interval two-alternative forced-choice paradigm (Tan et al., 1995). When surface deformation cues are removed, JNDs increase from about 15% to 50% of the reference value (Bergmann Tiest & Kappers, 2009). These findings indicate more information is derived from surface deformation than force/displacement cues (Kappers & Bergmann Tiest, 2013).

The diversity of haptic technologies and their applications—from virtual reality to medical simulators—makes it challenging to compare results across studies and integrate outcomes into the design of new haptic systems. For example, terminology such as 'softness', 'compliance', and 'stiffness' are often interchangeable within haptic/tactile research, despite being distinct properties. Squish, coupling a combination of these features and user-in-the-loop dependencies continues to confound a standard definition. This composite state highlights the need for a qualitative measure to be part of characterization of squish and why squish has the potential to induce a unique perceptual avenue for improved human-machine interactions. This study addresses these limitations by proposing squish as a distinct perceptual category.

The following research attempts to capture perceptions of squish interaction by using a low-pressure pneumatic apparatus to produce quantifiable measurements during a simulated 'squish' interaction. Findings from this research aim to establish preliminary perceptual metrics of a squish-like stimuli. This research aims to contribute to a broader understanding of human-object communication and inform the design of haptic systems that deploy soft, compliant, and dynamic material behaviors as a communication modality.

Measurement Techniques

Psychophysical methods provide structured approaches to measuring change in perceptual judgements of sensory stimuli. The Method of Constant Stimuli, used in this study, is a psychophysical technique to determine sensory thresholds by presenting stimuli of varying intensities in a randomized order (Wolf, 2020). This approach ensures that each level is presented multiple times, reducing biases associated with expectation or adaptation.

For this study, participants were asked to make a binary judgment of “LESS” or “MORE” regarding a sensory quality in comparison to a reference stimulus. This method is widely used in sensory research due to its ability to produce stable and reliable threshold estimates. The procedure developed in this study matches the widely used psychophysical technique two-alternative forced choice (2AFC) paradigm, which can be used to measure sensory thresholds and perceptual discrimination. In 2AFC tasks, participants are presented with two stimuli and must select the one that exhibits a particular quality (e.g., LESS or MORE pressure). Unlike simple detection tasks, 2AFC minimizes response biases by forcing participants to make a comparative judgment. By requiring a choice between two options, 2AFC aims to improve measurement precision and reduce individual variability.

Other methods were considered for this research such as Method of Limits, which is an approach where the stimulus intensity gradually increases or decreases until the participant detects a change (Wolf, 2020). However, the fidelity of the electromechanical system used in this study limited the practicality of this approach. In addition, Method of Adjustments, which would require participants to directly control the stimulus intensity until it matches a subjective perception was deemed unsuitable due to similar hardware limitation and concerns about precision. Magnitude estimation, in contrast, extends beyond detection, asking participants to assign numerical values that reflect the perceived intensity of the stimuli. This method is typically used to explore how perception scales with change. This foundational study focuses on identifying perceptual thresholds rather than collecting scaled numerical judgments.

Together, the Method of Constant Stimuli and the 2AFC paradigm form a robust framework for investigating perceptual mechanisms of squish. By analyzing response patterns across varying intensities, this methodology aims to uncover how people process 'squish' and assess how perceptual accuracy varies across individuals. This approach aims to support quantification of sensory threshold and provide insights into the competencies of human touch. With this methodology, the following section outlines the materials and equipment used to implement the experimental procedure.

Materials and Equipment

Each participant was asked to situate themselves comfortably in a room with limited distractions. In front of the participant is a cardboard divider with a cutout that allows ample space to maneuver their hand while acting as a visual barrier between them and the *Dynamic Interfaces*.

Dynamic Interfaces

The dynamic interfaces, shown in Figure 1, are inflatable balloon-like objects connected to a length of tubing with a ball valve to retain internal pressure. The system utilizes air pressure to set each interface to a different pressure, measured in millibars. The dynamic interfaces have a shape-memory polymer core. The shape memory polymer acts as a temporary fill to reduce the change in height that occurs during bag inflation, reducing reliance on thickness as a sensory modality for discrimination.

Utilizing a top and bottom connected inflatable system aims to produce incremental intensity of a squish feeling, where a surface acts differently than its density.

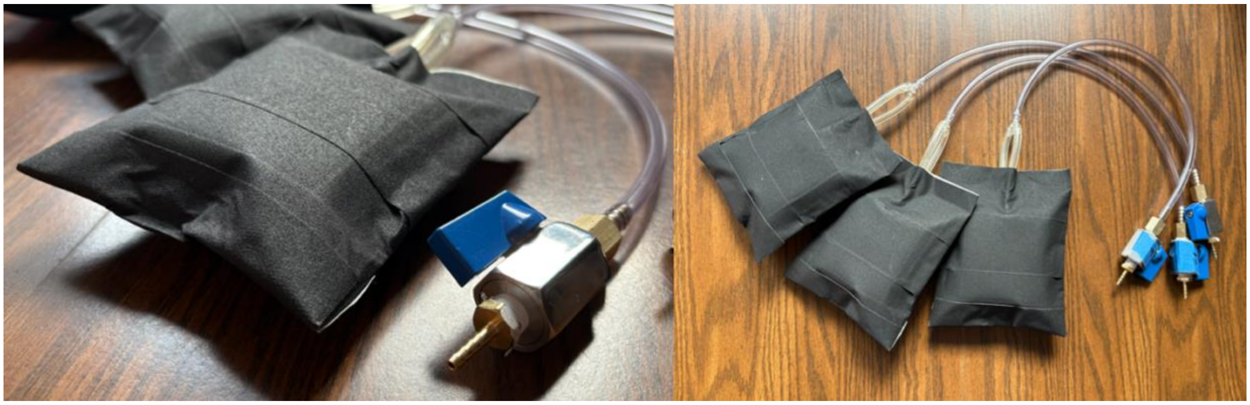

Figure 1. Dynamic Interfaces, pneumatic controlled system to simulate intensities of 'squish'.

When gripping, participants were asked to grab the interface with their dominate hand, placing their thumb on top of the interfaces and their fingers underneath.

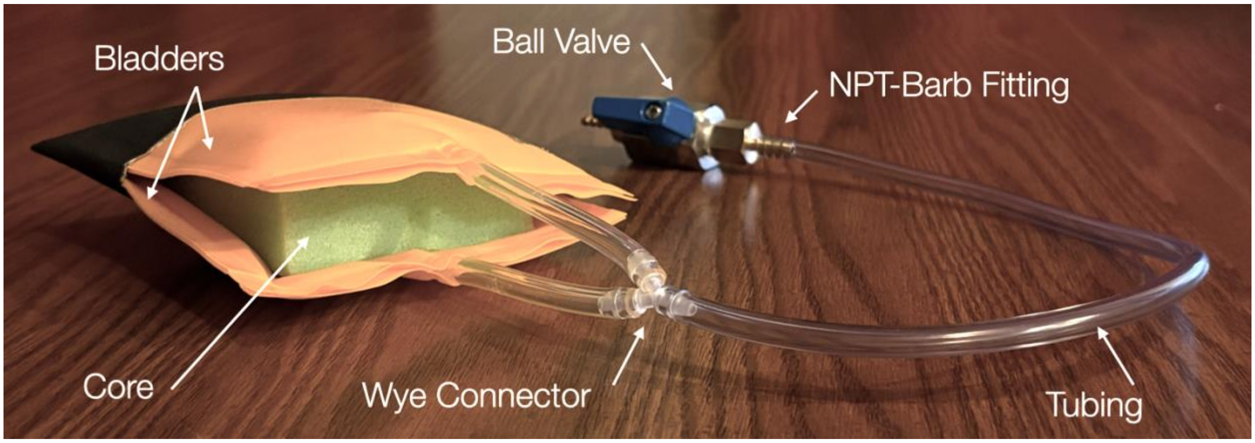

Figure 2. Labeled diagram of Dynamic Interface (deconstructed) illustrating primary components.

Each dynamic interface consists of two polypropylene bladders, each 4 x 4 inches, and heat-sealed with an integrated length of flexible tubing shown in Figure 1. Two bladders are connected via a wye connector to a 14-inch section of tubing, which serves as a pathway for inflation. This tubing interfaces with an NPT (National Pipe Taper) to Hose Barb fitting, which is threaded into a manually actuated ball valve. A sphygmomanometer bulb is temporarily attached to the opposing end of the ball value to pressurize the system. Once the target pressure is reached, the bulb is removed to prevent interference during participant trials.

Control System

During operation, the polypropylene bladders are pressurized to a defined pressure. When stabilized, the ball valve is closed to maintain consistent internal pressure. Prior to circulating through the dynamic interface, the air used to pressurize the system passes through a reservoir, shown in Figure 3.

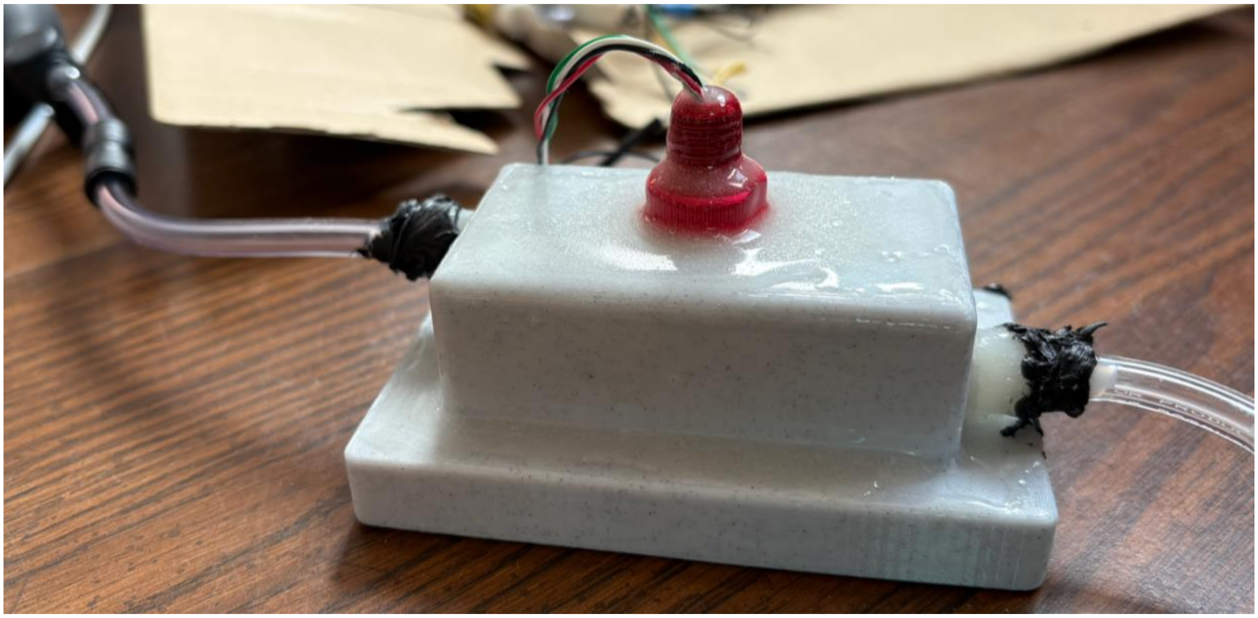

Figure 3. Reservoir with mounted barometric pressure sensor for interface inflation calibration.

The reservoir acts to reduce turbulent air during the filling and pressure reading process. The reservoir provides a secure mounting point for a Bar02 Ultra-High Resolution digital barometric sensor from Blue Robotics Inc. The sensor's standard operating pressure is 30 - 1200 millibar. It communicates by I2C with a supply voltage of 3.3 volts. In the current experimental setup, pressure control is performed manually; however, in earlier exploratory designs, a microprocessor controlled an air pump and solenoid system during inflation and deflation. Although this version adjusted pressure values automatically to achieve specific experimental conditions, the fidelity and responsiveness of the system was limited by latency, making manual control a more reliable option for this study.

Viscoelastic Core

Figure 4. Internal cross section view of interface revealing viscoelastic core.

At the core of each dynamic interface is a viscoelastic polymer component shown in Figure 4, measuring 3 x 3 x 1.5 inches. This core is secured between the two polypropylene bladders using adhesive tape along the edges, ensuring structural integrity and maintaining the relative positioning of the bladders in a layered configuration. The inclusion of the viscoelastic polymer core is critical for achieving controlled modulation of the haptic system. When the bladders are inflated with air they naturally expand, introducing height-based changes. Structural expansion produces pronounced sensory contrasts between pressurized states, which would interfere with the study's isolation of squish. By restricting vertical expansion, the viscoelastic core maintains a consistent external geometry during inflation ensuring perceptual difference are from internal changes. Since the two bladders are connected via the Y-connector, an applied force is shared during gripping, producing a dynamically changing surface modulated by internal air pressure.

Several alternatives were explored for their potential to generate a controlled, incremental squish-like tactile experience. Electroactive polymers (EAPs), offer the ability to produce shape and stiffness changes in response to electrical current. However, limitations including system complexity and calibration made this approach out of scope for this research. Multilayer structures with embedded internal channels using hydraulic or pneumatic networks were evaluated. These systems, often used in soft robotics, can produce localized deformation or compliance changes. However, they require complex, electromechanical integration and precise calibration placing them beyond the practical limits of this study.

Resins selected based on Shore hardness values were considered as a passive material for discrimination testing. Resins enable the fabrication of tuned deformation characteristics with varying levels of geometric complexities. However, achieving a fine gradation of Shore hardness values to support perceptual threshold testing would require the production of a large quantity of incrementally different samples. This level of precision requires specialized manufacturing processes and resources beyond the scope of this study. 3D-printed lattice geometries, designed with variable infill patterns and internal geometrics, exhibit similar limitations to resins, specifically, a large volume of precisely fabricated samples and the inability to dynamically modulate intensity. The selected pneumatic system, with a viscoelastic core offers the balance of controllability, repeatability and perceptual relevance required for this foundational tactile research.

Operating Parameters

For this study, the system function within a specific pressure range of 50 to 350 millibar. This range was selected based on the behavior of the assembled system. As pressure increases towards 350 millibars, the two bladders continue to expand, driving the polymer core to its fully compressed state. At higher pressure, the interaction with the user begins to diminish, as the core becomes non-responsive to gradual force and displacement. Instead, the two internal bags within the system fully compress the core, marking the point at which the pressure no longer contributes to surface-level haptic feedback. Within this range, 190 millibar was selected as a control value after being identified as a practical midpoint. This value represents a balance between the lower and upper pressure limitations of the system. By determining a specific transitional zone at a defined value, this midpoint offers a controlled starting point for understanding when users can perceive a noticeable change. This initial approach establishes a foundation for future comparison across a range of intensities, where perceptual sensitivity may vary.

Mechanical Characterization

To quantify the mechanical behavior of each dynamic interface, compression testing was performed using an Instron 6800 Series Universal Testing System. A method for compression was developed to simulate a repeatable 'squish' and mirror the interaction participants engage in during the study. Shown in Figure 5, a custom compression probe was fabricated out of aluminum to approximate a human thumb's surface area, which aims to replicate the participant grip orientation.

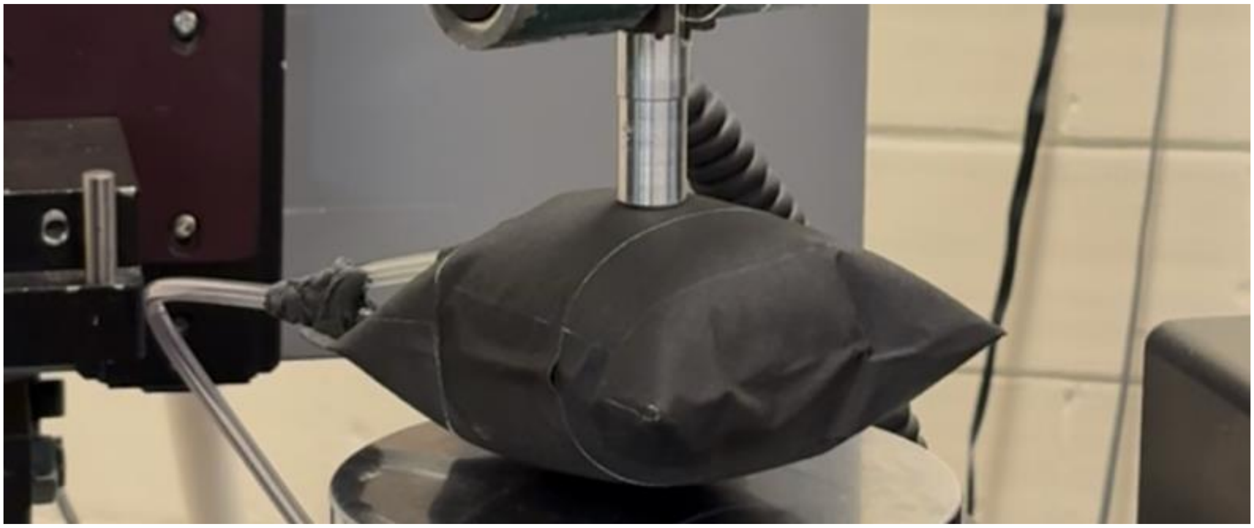

Figure 5. Custom compression prob mounted on Instron testing system.

Although this setup represents a simplified model of human touch, which does not fully capture the complex deformation of human skin, the system provides a consistent method for understanding material behavior. This approach aligns with the goal of this work to build a foundational understanding of squish as a modality for communication and inform the design of advanced haptic interfaces. Each interface was tested using a three-phase compression cycle, consisting of:

1. Ramp Down: where the testing probe was lowered at a controlled displacement rate of 2mm per second until it reached a force of 25N.
2. Hold: where the probe maintained the displacement for two (2) seconds to assess force and material response under load.
3. Ramp Up: where the probe was lifted at the same rate, returning the interface to a neutral, uncompressed state.

This sequence was repeated three consecutive times to evaluate material consistency across repetitions. A five (5) second pause was added to allow the interface to reach a neutral state. Displacement (millimeters, mm), force (newtons, N), and time (seconds, s) were recorded at a rate of fifty (50) samples per second. Four Interfaces were used during this study and were labeled E, I, F, and D to enable consistent tracking across participant testing and mechanical characterization conditions.

Figure 7 illustrates the force-displacement relationship for the 190-mbar control value across the four dynamic interfaces (E, I, F, and D). Interfaces F and D exhibited difference in overall thickness (approximately 2.5 and 4.5mm.) This variation was originally intended to be standardized by the internal structure core; however, since measurements were taken after the completion of the study, the interface may have experienced wear due to repeated use.

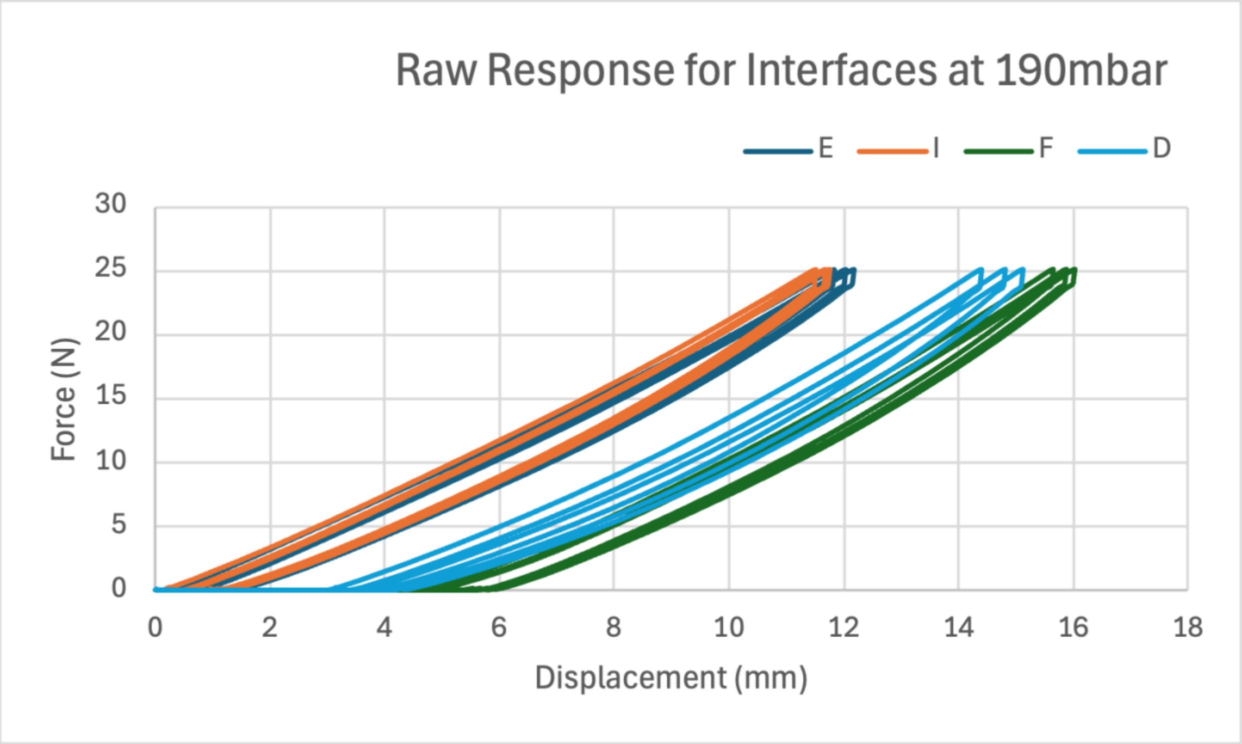

Figure 6. Raw force-displacement response for interfaces E, I, F, and D at 190mbar control value.

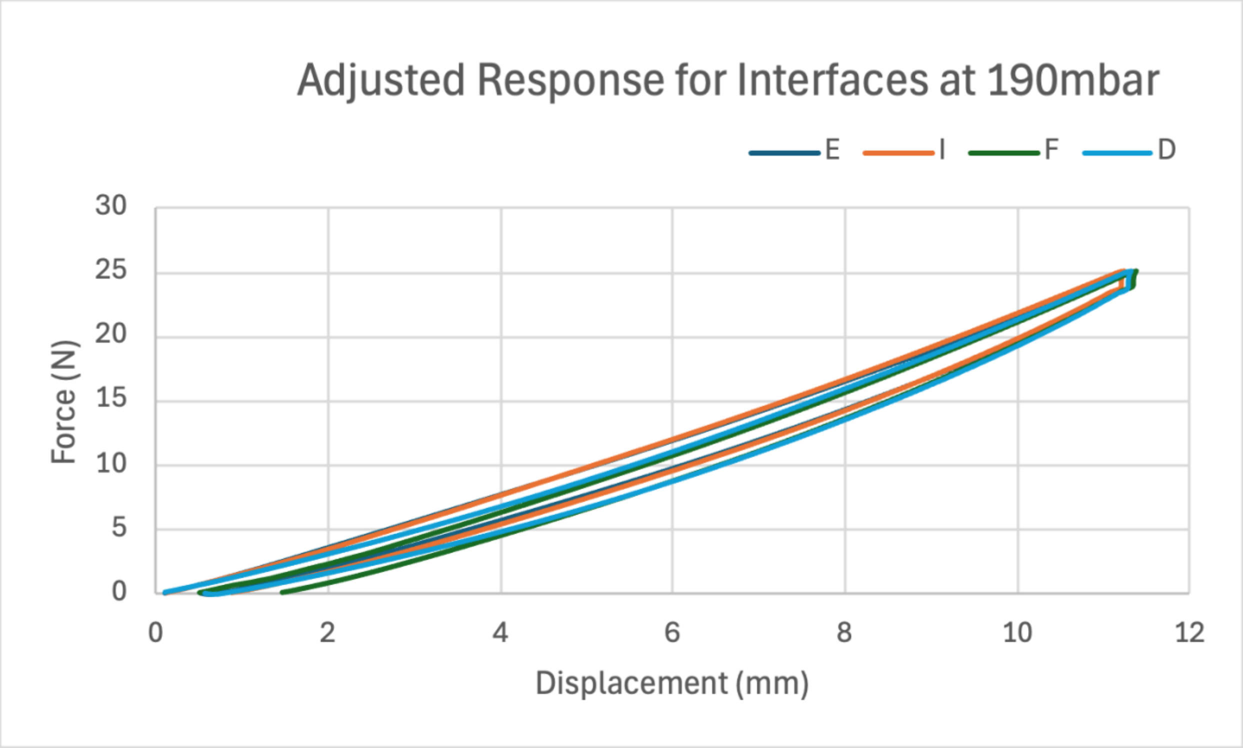

Figure 7. Adjusted Force-Displacement results at the control value of 190mbar.

Assessing if the physical discrepancy in thickness led to significant variation in mechanical response, a displacement offset was applied to the first repetition of loading and unloading cycle. Shown in Figure 7, this offset aligns the starting position of all the interfaces and accounts for baseline structural difference, enabling a more appropriate comparison of the loading and unloading of each interface. The overlayed, adjusted curves indicate consistency in the response across all interfaces, which follows a similarly shaped, nonlinear increase in displacement relative to applied force. The clustering of curves demonstrates repeatability during compression cycle and suggests stable mechanical behavior across trials. Despite the measurable difference in physical height, the adjusted curves suggest this variation alone does not modify the system's response behavior.

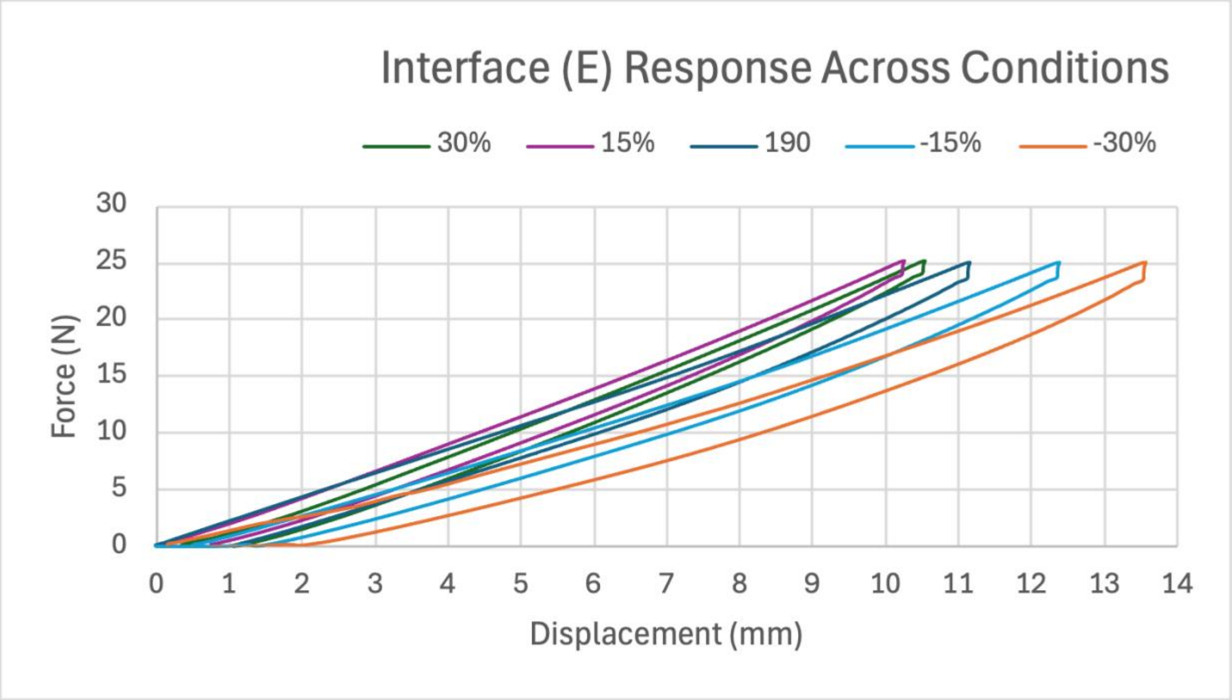

Figure 8. Force-Displacement results of interface E across condition values.

Focused exploration of interface 'E', across a range of inflation conditions aims to assess the mechanical behavior at varying intensities is shown in Figure 8. All curves demonstrate the ramp-hold-release compression method developed for this study with higher inflations levels (e.g., +30% & +15%) exhibiting steeper force curves, earlier peak force onset during the ramp up, and more rapid return during release. Conversely, lower inflations levels (e.g., -30% & -15%) require greater displacement to achieve a similar force output, exhibit more pronounced hysteresis during unloading, and show a larger drop off during the hold phase, indicating a more compliant mechanical response. Notably, the 15% condition deviates from the expected pattern, reaching peak force earlier than all other conditions, which may reflect a unique transitional point in the interaction between the viscoelastic core and bladder system. Despite this discrepancy, the overall waveforms support mechanical reliability and highlights its nonlinear behavior across pressure levels. This mechanical characterization reinforces the interface design is suitable for perceptual threshold testing.

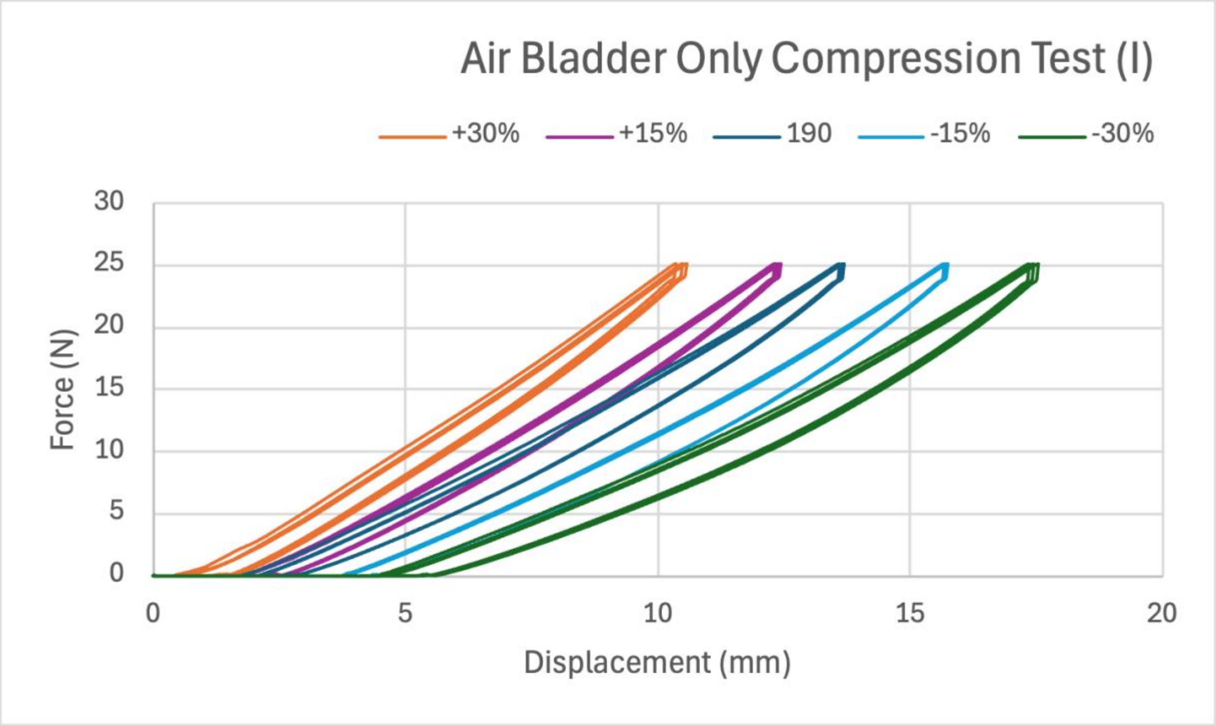

Figure 9. Airbladder only from interface I compression test across multiple condition values.

To further explore the mechanical contributions of each component, additional testing was performed on the air bladder system and viscoelastic core components in isolation. Figure 9 illustrates force-displacement curves for the bladder only configurations across a range of inflation levels. Unlike the fully assembled interface, these trials isolate the behavior of the bladders without the internal support from the viscoelastic core. The resulting curves exhibit a smooth, nonlinear increase in force with displacement, with each inflation level forming a distinct trajectory. Higher inflation conditions (e.g., 30%) exhibit a steeper curve, reaching the peak force over a shorter displacement range, indicating increased stiffness and resistance to compression. In contrast, lower inflation conditions require more displacement to reach similar force levels, indicating a more compliant and deformable structure. Comparisons of the return curves suggest greater hysteresis at lower inflation levels indicating underinflated bladders exhibit a wider separation between loading and unloading paths.

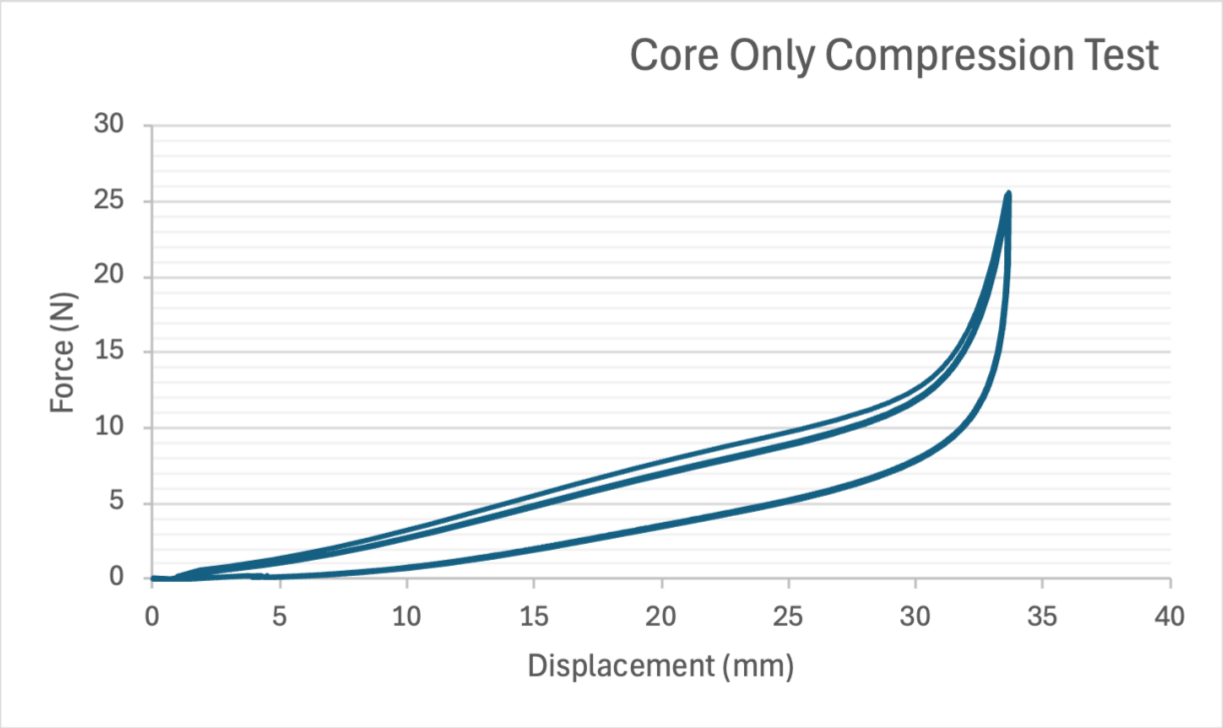

Figure 10. Core only, Force-Displacement response over three (3) repeated compression cycles.

Compression testing of the viscoelastic core in isolation aims to understand the contribution of the internal structure within the system. The force-displacement graph, shown in Figure 10, reveals interesting mechanical behaviors. From 0 to roughly 30mm displacement, the load rises gradually and then accelerates sharply producing a pronounced spike. This late-stage stiffening suggest that the material becomes more resistant to compression once a certain threshold is exceeded. Each repetition producing nearly overlapping curves, indicates a high degree of mechanical consistency across repeated trials. Unlike the bladder only compression test, which exhibits a smooth scaling tied to inflation pressure, the core's mechanical behavior remains relatively uniform across initial displacement. Together, these finding justify the design choice to use a dual layer system, where the bladders modulate a change in squish intensity and the core maintains structural consistency.

Study Design

This research employs a within-subject design, where each participant completes all experimental conditions rather than being assigned to a single condition. This approach aims to reduce variability by allowing direct comparisons with the same individual. By ensuring each person experiences all levels of the independent variable (i.e., pressure value), the study maximizes statistical power while controlling for individual differences.

Participants engage in a comparative judgment task where they assess the relative pressure of various dynamic interfaces compared to a control. Participants first interact with the control interface to form a baseline before comparing to the various experimental conditions. This structure is designed to measure perceptual thresholds and differences in pressure sensitivity by capturing participants' binary decisions on whether a given stimulus has "more" or "less" pressure than the control. Collecting binary data allows for the use of statistics modeling as a for quantitative analysis to determine perceptual thresholds by mapping probability of a response for a given stimulus intensity through logistic regression. A trial-based data collection method is used in which multiple independent trials provide repeated measures for each stimulus condition. This repetition aims to capture a summative perceptual judgment rather than an isolated response.

Human Subject Research

This study was reviewed by the Institutional Review Borad (IRB) at Tufts University to provide approval that all planned procedures adhered to ethical standards for research involving human subjects. Recruitment was conducted through flyers (available in Appendix C) on the Tufts University, Medford, MA campus. The flyer directed interested individuals to reach out to the Principal Investigator by phone or email. Prior to accepting a recruit into the study, a screener was performed to assess eligibility. Acceptance into the study required participants to be at least 18 years hold, be fluent in English, and not have any conditions that might affect tactile perception. Individuals with a history of injury, surgery, or chronic pain in the fingers, hands, wrist and arms were excluded, as were any participants who have been diagnosed with neurological or sensory processing disorders. Additionally, exclusion criteria included current use of medication that could influence motor skills or cognitive function. This study was open to individuals of all genders and ethnic backgrounds. Upon completion of all tasks, each participant was compensated with a $50 USD gift card.

Experimental Procedure

1. Background Questionnaire: the participant completes a background questionnaire that includes demographic information and physical activity level (available in Appendix A).
2. Edinburgh Handedness Inventory (EHI): participant completes a 20-item task list to assess if their hand preference is for the right or left (available in Appendix B).
3. Grip Strength Assessment: the participant squeezes a handle like object (dynamometer) to determine baseline grip strength.
4. With the participant hand extended, the following measurements are recorded in millimeters: Hand Length, Hand Breadth, Palm Length, and Finger Lengths.

5. Participants place their hand through the visual barrier and interact with the control dynamic interface with their thumb on top and fingers beneath, and continue to press, squeeze, and manipulate the interface until it feels familiar.
6. Comparative Judgment Task:
   - The participant is presented with one of three comparison interfaces and asked whether it has “MORE’ or ‘LESS’ pressure than the control.
   - The participant re-interacts with the control interface before evaluating the next comparison.
   - This is repeated with the third comparison interface to complete one trial set.
   - The sequence is repeated across 10 trials sets, presenting the comparison interfaces in random order, to complete one condition.
   - The entire process is repeated for each of the seven conditions.

To prevent fatigue and help maintain accuracy in responses, breaks are incorporated between conditions. These breaks occur while the next set of dynamic interfaces are prepared, which aims to reduce the likelihood of participants experiencing sensory adaptation, cognitive overload, or tiredness. This pacing helps sustain engagement and aims to minimize bias introduced by discomfort over time. The experiment consisted of 7 pairs of conditions. Each condition differs in a reduced pressure between the control (190mbar) and comparison end-effectors (+/- 30%, 25%, 20%, 15%, 10%, 5%, 2%). Participant data collection was completed on average in two (2) hours.

Combining anatomical assessments, behavioral screening, and structured psychophysical tasks, the methodology offers a robust framework for investing perceptual thresholds related to squish. Inclusion of multiple comparison conditions across a calibrated pressure range enables development of psychometrical curves to quantify perceptual accuracy.

Results & Analysis

Results from this study indicate that human perceptual thresholds for squish vary across individuals and appear to be influenced by anthropometric characteristics, fine motor ability, and behavioral tendencies. Analysis was performed by fitting psychometric functions to individual datasets and performing regression analysis to explore how perceptual thresholds relate to anthropometric and behavioral measures. For each participant, the percent difference required for a participant to detect a change with at least 75% accuracy was estimated from the fitted curve. This criterion reflects a confident level of discrimination, consistent with the study's focus on real-world, human-machine interactions where perceptual certainty is essential.

Participants

The study included five (5) subjects, ages 18 to 23, consisting of three males and two females, with self-reported heights ranging from 62 to 69 inches and body weight between 108 to 180lbs. Grip strength, measured in pounds using a dynamometer, showed male participants averaging 101.5lbs and female participants averaged 36.8lbs. One participant ('P4') demonstrated the highest average grip strength of 123lbs consistent with his larger hand dimensions (177mm hand length, 93mm hand breadth) and self-reported physical activity. In contrast, P2 exhibited the lowest grip strength of 31.5lbs and had self-reported less frequent engagement in fine motor activities, with smaller hand dimensions (170mm hand length, 75 hand breadth.) Hand dominance assessment revealed that all 5 participants indicated a strong preference for, or were exclusively, right-handed based on the 20-task list. Background questionnaire responses indicated fine motor activity frequency ranged from 'occasionally' to 'several times a week' with four participants rating their fine motor skills as average or above. Hand length ranged from 150mm to 190mm, and hand breadth ranged from 70mm to 93mm. Thumb lengths varied from 57mm to 61mm, and index length from 65mm to 75mm. Overall, a diverse set of abilities and experience relevant to dexterity was observed across participants.

Difference Threshold – Absolute Percent

Difference Threshold – Absolute Percent represents the *difference threshold* or just noticeable difference (JND) by measuring the absolute value of deviation from the control stimulus, capturing both the positive and negative variations in pressure. All psychometric curves in this study utilized *Generalized Linear Model* (GLM) in R via the base "stats" package. This approach allows for estimation of the probability of correct as a function of the magnitude of change from the control, enabling threshold estimations base on observed behavioral data.

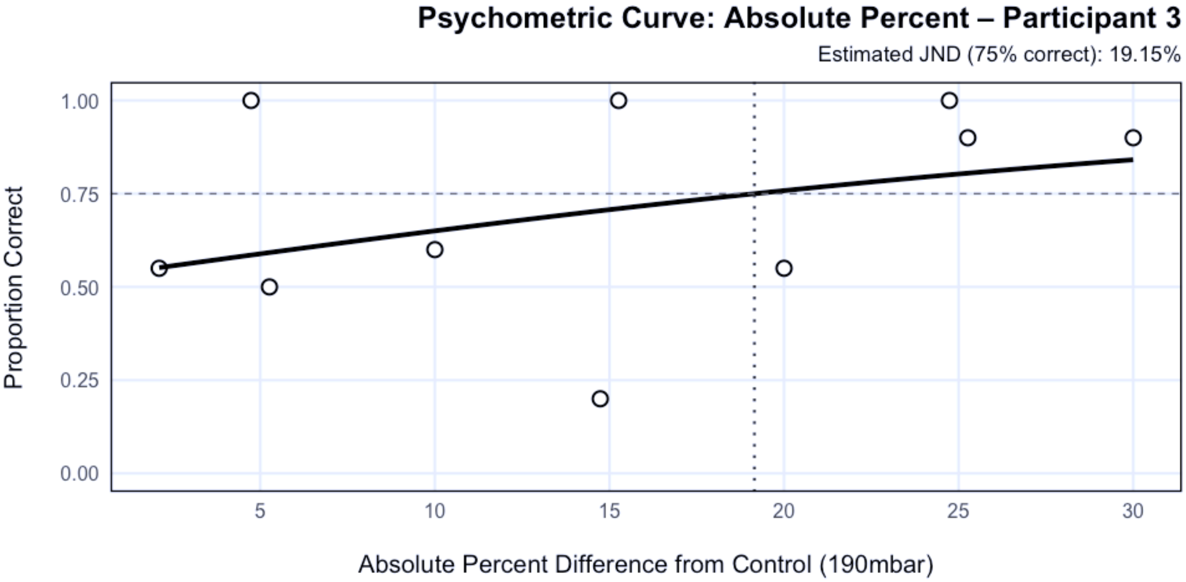

Figure 11. Psychometric Curve, P3, Difference Threshold – Absolute.

Figure 11 illustrates that P3's discrimination ability aligns with observations reported in existing psychophysical studies, where accuracy increases with greater deviations from the control value. The psychometric curve (solid black line) indicates P3 reaches 75% (horizontal dotted line) accuracy at an absolute difference of approximately 19.15% (vertical dotted line) change from the control interface. The plot illustrates variability in P3's responses, with some high accuracy at small differences (~5%) and a lower point at 15%. These inconsistencies may be caused due to perceptual noise, experimental setup, or response bias. The moderate perceptual sensitivity of P3 suggests they require a fairly large change to detect a difference, with any changes below this JND (19.15%) as likely was difficult to perceive reliably, and where guessing could be more utilized.

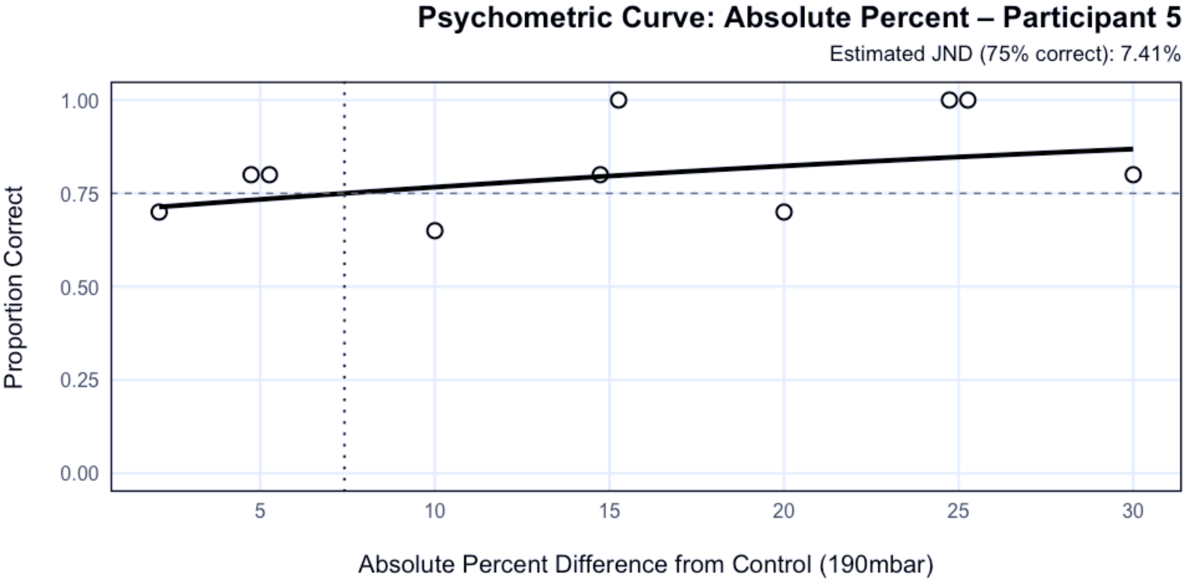

Figure 12. Psychometric Curve, P5, Difference Threshold – Absolute.

Figure 12 represents data from participant, P5, who, with a flatter curve than P3, also aligns with expectations based on prior psychophysical literature. P5's ability increases with greater deviations from the control value, reaching 75% accuracy at an absolute percent difference of approximately 7.41%. This indicates a smaller threshold compared to P3 and could imply that discrimination of squish varies across participants.

Group level observations of absolute percent threshold values for P1, P2, and P4 vary widely and point to inconsistencies in individual sensory resolution, task strategy, or experimental setup. Figure 13 reveals a discrepancy between expected patterns and observed data where a -1.74 percent difference is necessary to reach 75% accuracy for P1. In this context, a negative threshold is not meaningful and may suggest an artifact caused by calculating the psychometric curve using the absolute percent change rather than accounting for the directionality of the intensity change.

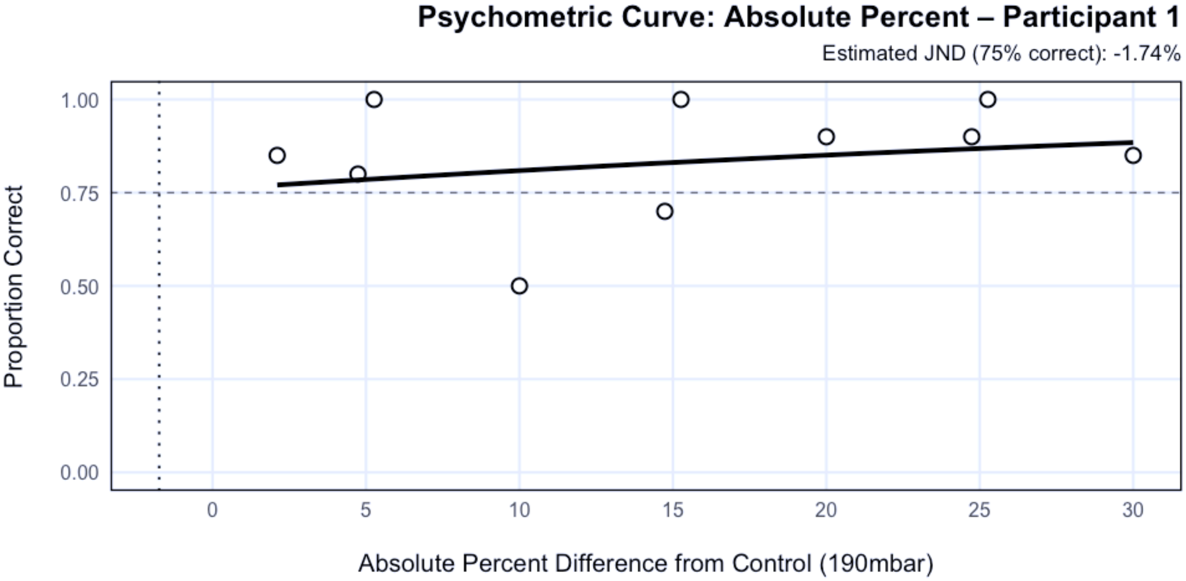

Figure 13. Psychometric Curve, P1, Difference Threshold – Absolute.

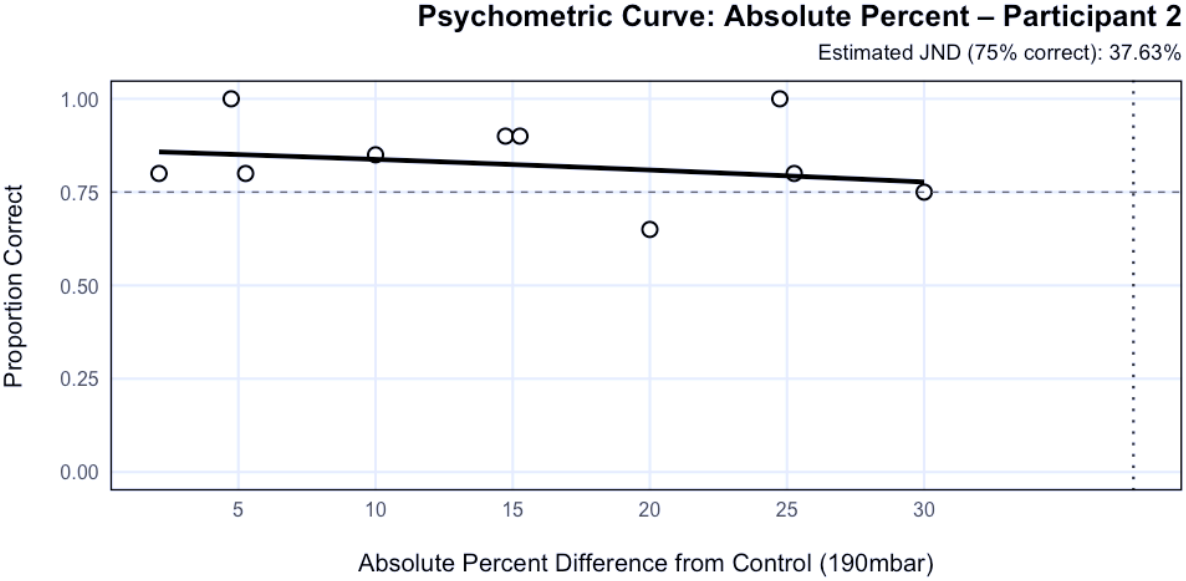

Figure 14. Psychometric Curve, P2, Difference Threshold – Absolute.

Meanwhile, Figure 14 presents an atypical psychometric pattern for P2, where accuracy decreases as the intensity increases to reach 75% accuracy at +37.63% different from the control. This inverse pattern may reflect several contributing factors: initial confusion during the earlier trials of the discrimination task, a response bias characterized by a tendency to favor one option, or error in the experimental setup such as a lack of counterbalancing, potentially introducing bias across conditions.

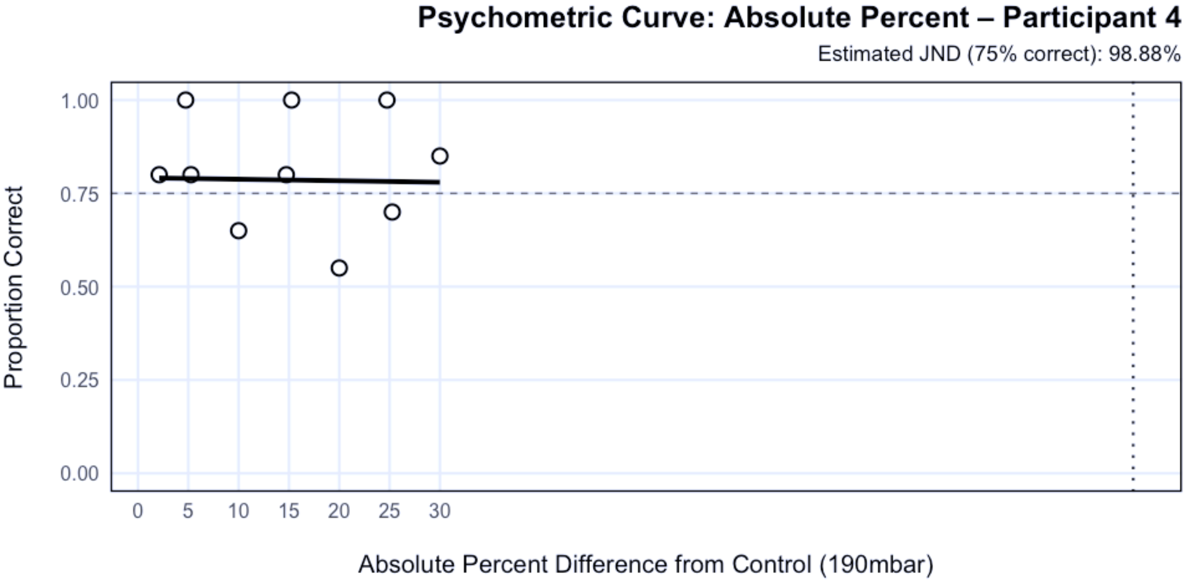

Figure 15. Psychometric Curve, P4, Difference Threshold – Absolute.

Figure 15 shows results from P4, where the flatness of the curve indicates a lack of change in response accuracy across conditions, undermining the reliably of the threshold estimation. This pattern may reflect guessing behavior, mechanical inconsistency in stimulus, or response bias unrelated to the actual difference.

While the general trend across participant supports theoretical predication in tactile discrimination (improving with greater stimulus intensity) the magnitude of the difference threshold varied considerably across participants. These discrepancies may account for individual difference in perceptual sensitivity or may indicate that absolute values obscure threshold estimates, prompting the need to split the data by direction (i.e., the comparison pressure was more than, or less than the control) to account for asymmetry when exploring perceptual thresholds of simulated squish.

Difference Threshold - LESS

Percent Difference Threshold - LESS represents the *difference threshold* or JND for trials where the stimulus intensity was lower than the control. The analysis focuses on participants' ability to detect reductions in interface pressure and estimates the threshold at which a difference becomes reliably noticeable.

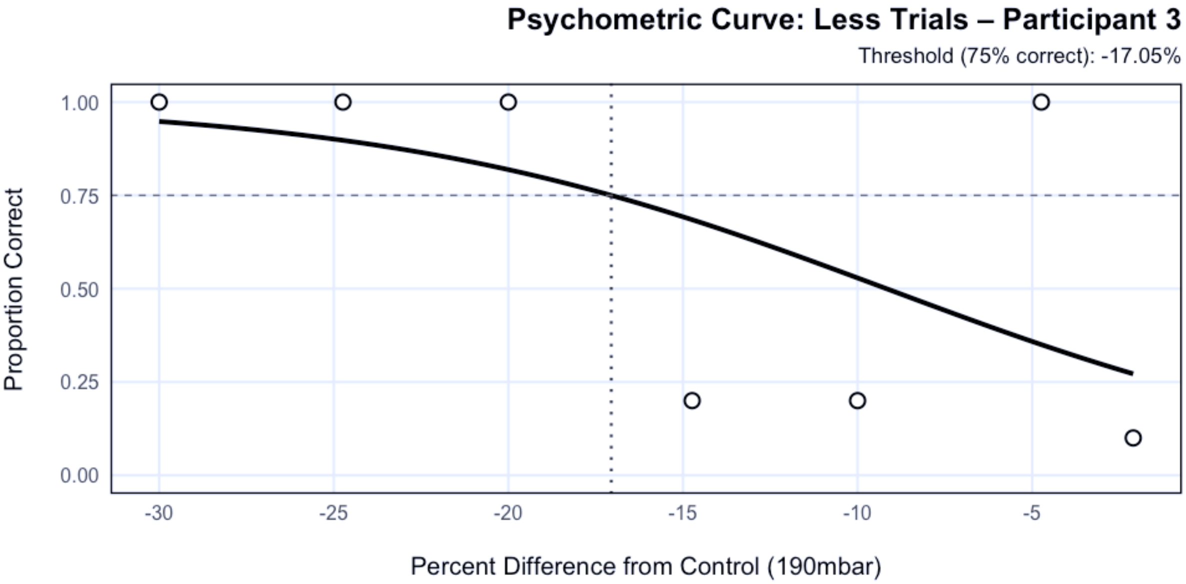

Figure 16. Psychometric Curve, P3, Difference Threshold – LESS.

Figure 16 illustrates a distinct and expected psychometric curve for P3, showing a clear increase in discrimination accuracy as the percent difference from the control increases in trials where the dynamic interface was less pressurized than the control. The curve indicates a JND of -17.05%, meaning P3 required a 17% reduction in pressure relative to the 190mbar control to achieve 75% accuracy in detection. The shape and fit of the curve align with standard psychometric models of perceptual thresholds; low accuracy near small differences, a smooth sigmoidal curve reflecting a transition from guessing to confident detection. The curve exhibits a flat upper tail at large negative percent difference, where accuracy remains consistent, indicating that these stimuli are easily and reliably distinguishable from the control. However, accuracy declines sharply around -15%. This rapid drop suggests a narrow perceptual boundary, where small changes near the threshold produce large shifts in response behavior. While large differences are easily detectably, P3 shows a limited gradient effect near thresholds and intermediate intensities.

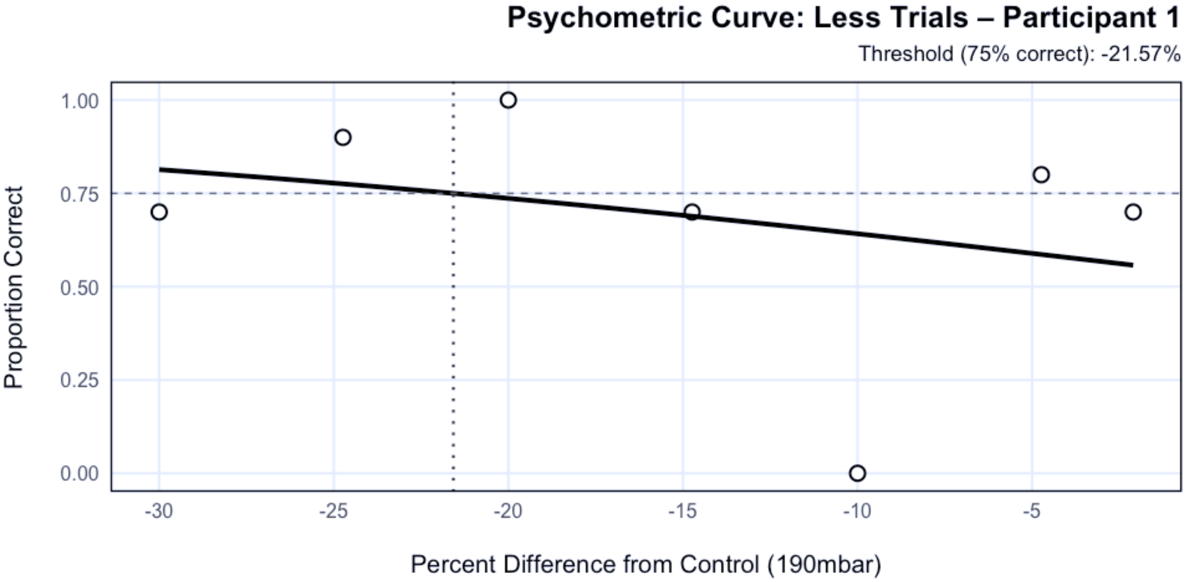

Figure 17. Psychometric Curve, P1, Difference Threshold – LESS.

Psychometric curve of P1, shown in Figure 17, indicates a JND of -21.57% change from the control was required to reach 75% accuracy in detecting a difference for lesser interfaces. Compared to P3, P1's curve displays a relatively flatter slope, suggesting a more gradual and less distinct transition from guessing to accurate detection, Notably, P1 fails to reach 100% accuracy even at large differences tested, implying that the stimulus range may have been insufficient to fully capture their perceptual boundary. While P3, consistently detected large reductions in pressure, P1 exhibited great response variability, even at high intensity difference. This contrast reinforces the idea that perceptual thresholds and sensitivity can vary across individuals. This finding reiterates the importance of examining participant specific patterns to understand the range of perceptual abilities and inform interface design.

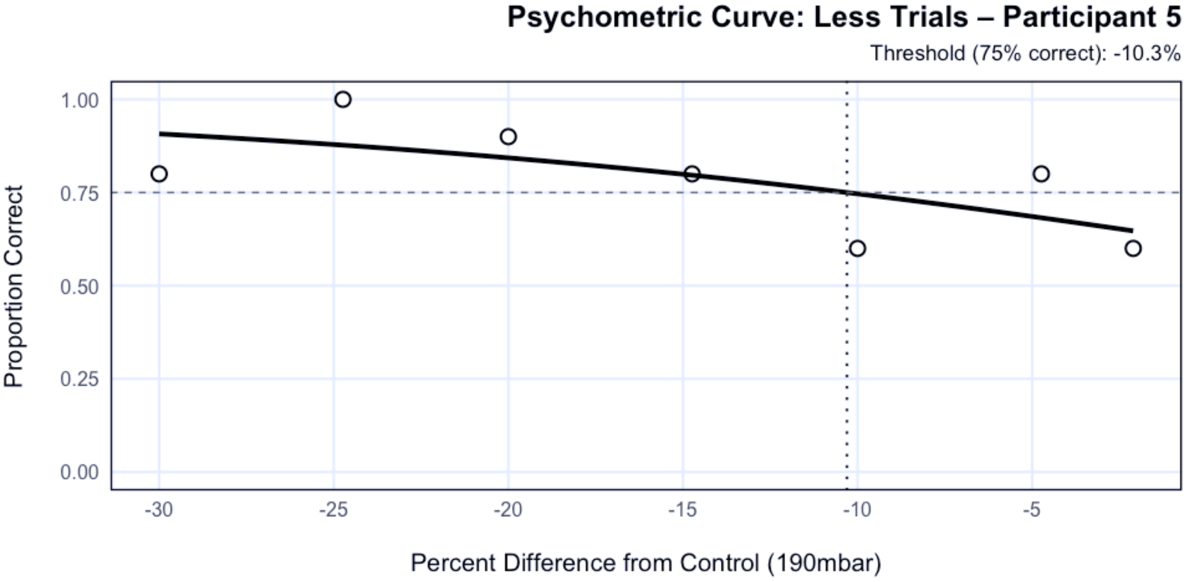

Figure 18. Psychometric Curve, P5, Difference Threshold – LESS.

Figure 18 displays the psychometric function for P5 during trials involving stimuli with reduced pressure relative to the 190mbar control. The estimated JND of -10.3% suggest P5 was highly sensitive to decreases in interface pressure. The shape of the curve shows a smooth, gradual decline in accuracy across percent differences, indicating stable perceptual discrimination. Unlike P1 and P3, P5 maintained high accuracy even at mid-range stimulus difference, with minimal drop off near the threshold. This pattern reflects lower perceptual variability and a refined sensitivity to subtle reduction in tactile changes. The psychometric curve, exhibiting a gradual progression to confident detection could suggest the stimuli presented required larger percent changes, and finer gradations to fully capture their perceptual transition zone. The current systems may not sufficiently extend into the P5's full perceptual detection range, underestimating the steepness and confidence of their threshold estimate.

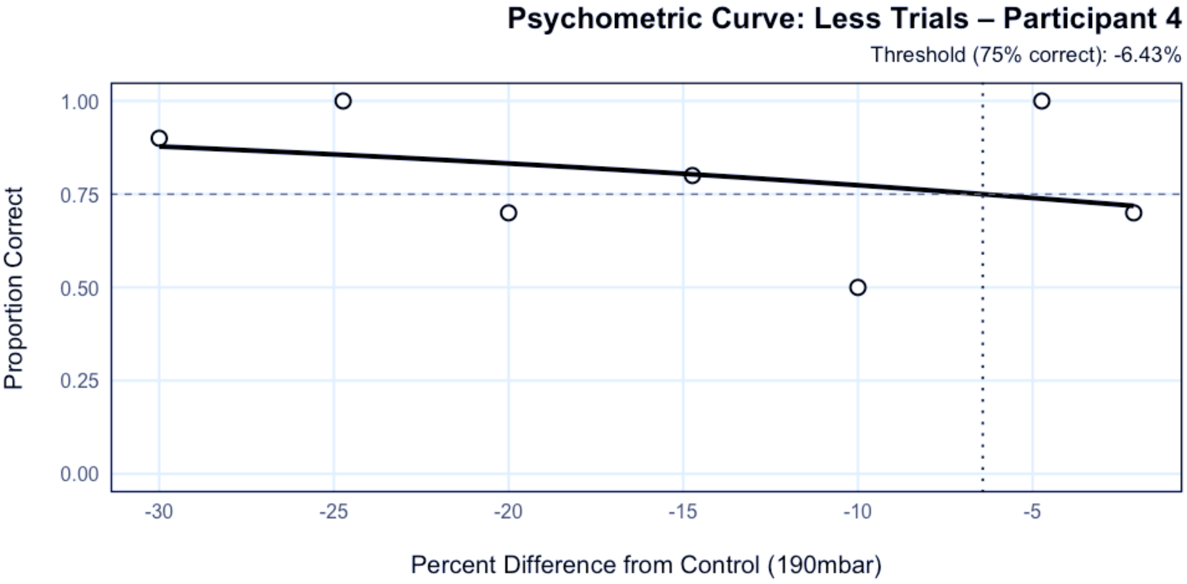

Figure 19. Psychometric Curve, P4, Difference Threshold – LESS.

Figure 19 illustrates P4's estimated JND of -6.43%, overall, the smallest percent change from the control required to reach 75% accuracy in detecting lesser interfaces. The fitted curve shows consistently high performance across most levels. Unlike other participants, P4 displayed stable and constant accuracy even at near-threshold stimuli, suggesting refined perceptual sensitivity and lower variability in detection. Notably, the curve does not reach 100% accuracy within the tested range, which may reflect response strategy or limitations in the stimulus system itself. This could imply the tested comparisons did not fully span the participants perceptual boundaries, underestimating their discrimination capability and reducing the confidence in their estimated thresholds.

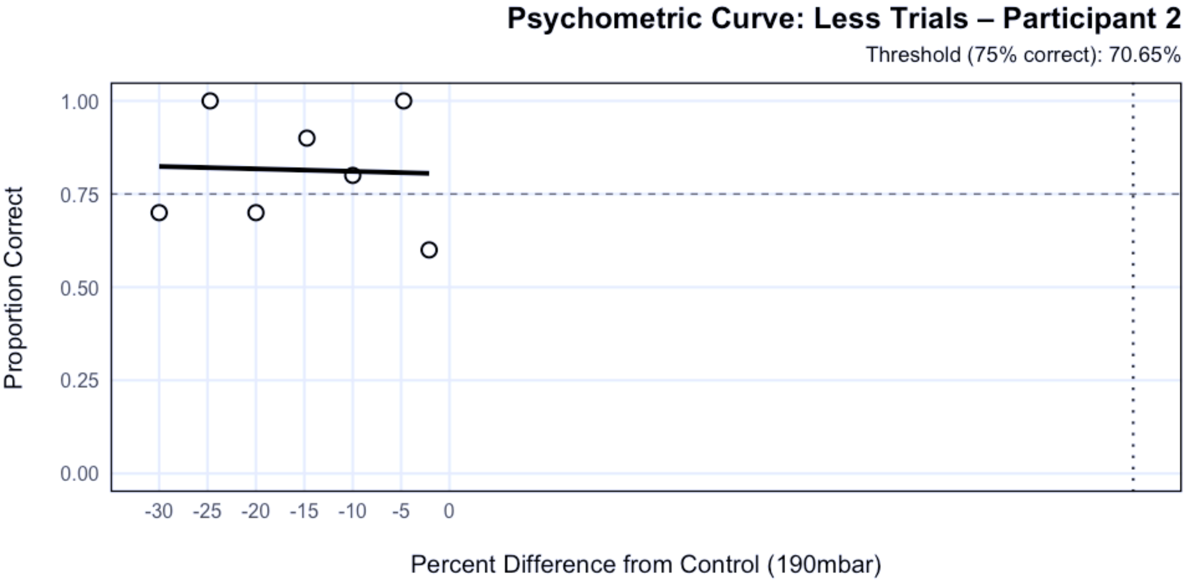

Figure 20. Psychometric Curve, P2, Difference Threshold – LESS.

Figure 20 presents an obscure psychometric pattern for P2, similar to the results discovered in the Difference Threshold – Absolute by P4 illustrated in Figure 15. With a 75% threshold calculated at +70.7%, a substantial deviation from the control and significantly higher threshold was observed as compared to participants. The fitted curve remains nearly flat and elevated across the tested range, suggesting consistently high detection accuracy regardless of stimulus intensity. A lack of discernible slop or transition zone suggest P2's responses were not systematically related to stimulus intensity. This atypical response may reflect a response bias, misinterpretation of task instructions, or limitations of the tested stimulus to capture the participants true threshold producing a misleading JND.

Difference Threshold - MORE

Percent Difference Threshold - MORE represents the *difference threshold* or JND for trials where stimulus intensity was higher than the control. The analysis focuses on participants' ability to detect elevation in interface pressure and estimates the threshold at which a difference becomes reliably noticeable at

75% accuracy. Across participants, the "MORE" condition revealed unexpected trends, in three of five cases (P2, P3, P4), discrimination accuracy decreased as intensity increased.

This pattern may suggest interplay of tactile features of squish (i.e., Surface Deformation, Material Resilience, and Rebound Characteristics) introduces a masking effect at varying intensities. This finding reveals the importance of further investigating the perceptual mechanism that define squish, specifically, the threshold for distinct feature cues. A deeper understating of these dynamics could inform the design of more realistic, responsive, and efficient human-machine interfaces.

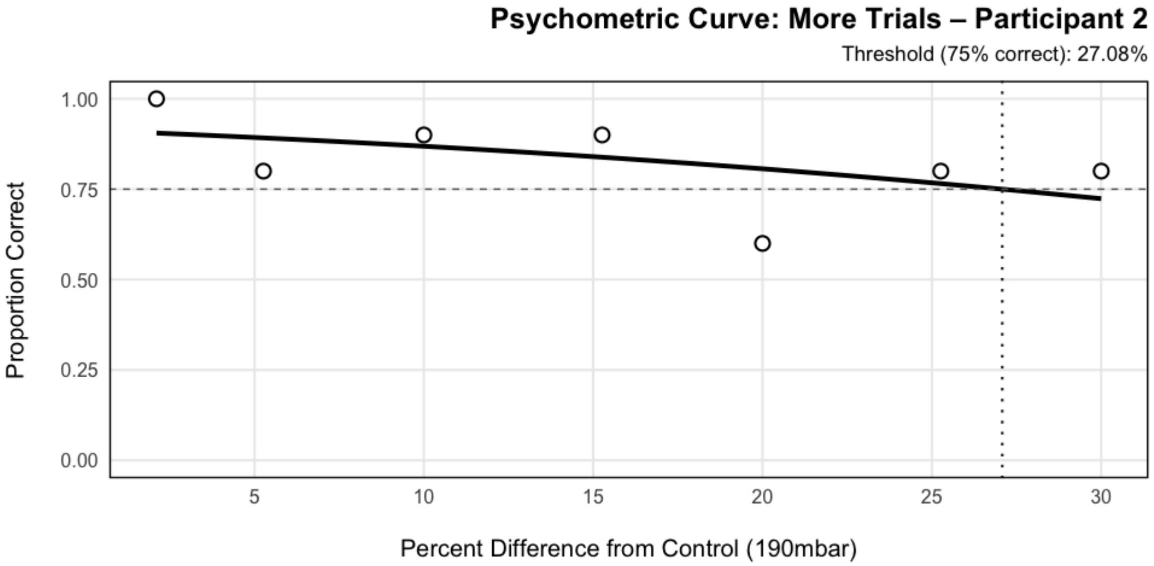

Figure 21. Psychometric Curve, P2, Difference Threshold – MORE.

Figure 21 illustrates the psychometric performance of Participant 2, showing the Percent Correct response plotted against the Percent Difference from the control for comparisons that were 'MORE' than the control. Unexpectedly, discrimination accuracy decreases as the percent change increases from the control, a reversal of the expected trend. A threshold of +27.08% change to the control to reach 75% accuracy in no longer detecting a difference indicates the less intense stimuli changes were reliably perceived. This pattern contrasts with their results from the "LESS" trials where the fitted threshold was implausible. The discrepancy between conditions suggests potential confusion with responses, reduced sensitivity or misaligned perceptual strategies. Overall, P2's data highlights the internal variability and expresses the need to examine both the curve shape, task interpretation, and consistency across conditions when assessing psychometrics of tactile discrimination.

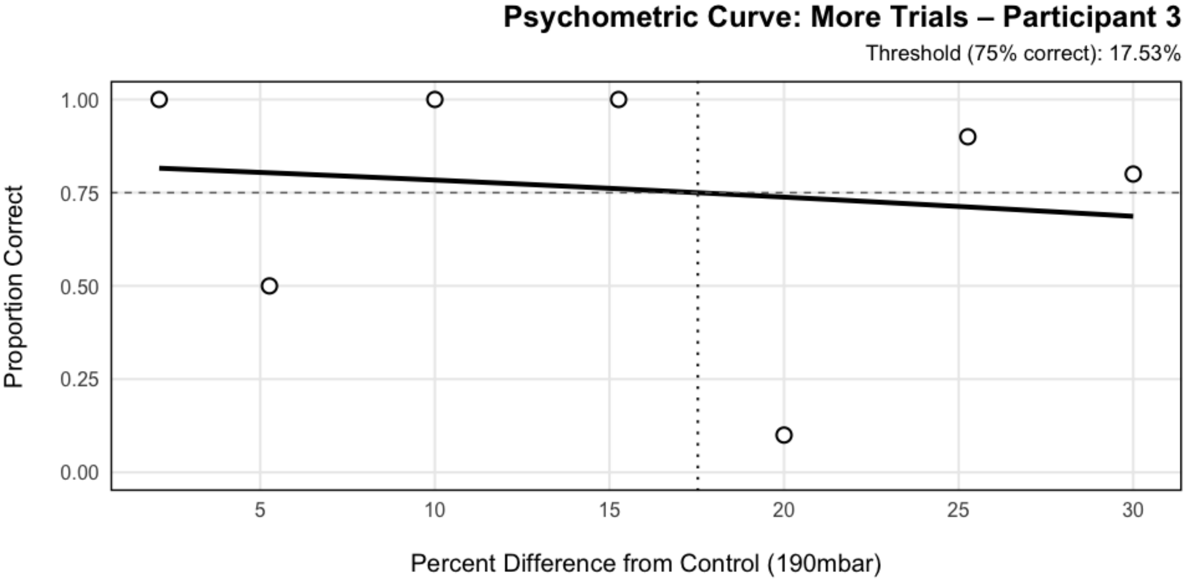

Figure 22. Psychometric Curve, P3, Difference Threshold – MORE.

Consistent with the results from P2, Figure 22 indicates P3's discrimination accuracy decreases as the percent change from the control increased, requiring +17.53% change to the control to reach 75% accuracy in detecting a difference. This trend is unexpected as greater stimulus difference are typically associated with improved perceptual accuracy. One possible explanation is that rebound behavior of the interface, characterized by mechanical hysteresis, plays a critical role in the perception of squish. At higher levels of inflations, the temporal delay may no longer be salient, reducing the available cues for participants to rely on for judgments. Rather than relying on a single tactile dimension, squish inherently involves multiple mechanical features that could support the transmission of layered sensory information. This multidimensionality could be advantageous for the development of innovative interface designs. Rather than relying on a single tactile dimension, squish could provide a rich sensory experience that conveys layered information through dynamic feature cueing (e.g., compliance, deformation behavior, and temporal dynamics.)

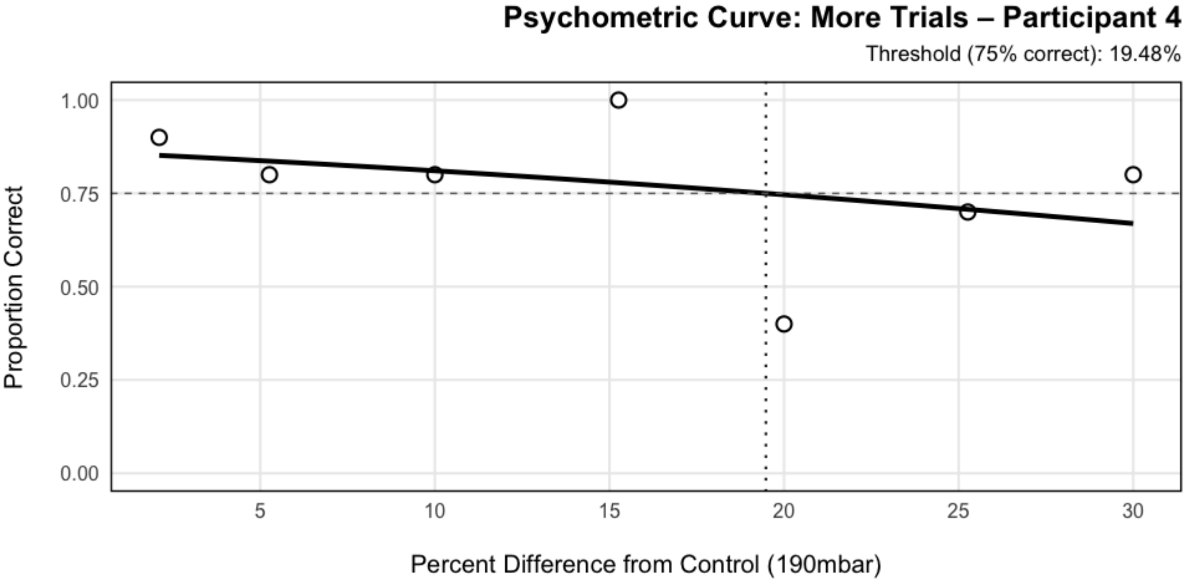

Figure 23. Psychometric Curve, P4, Difference Threshold – MORE.

Consistent with the results from P2 and P3, P4's discrimination accuracy decreases as the percent change from the control increased. Figure 23 shows P4 required +19.48% change to the control to reach 75% accuracy in detecting a difference. The trend reinforces the possibility that higher pressure comparisons introduce perceptual noise due to overlapping, conflicting sensory cues such as deformation or rebound, or a saturation of sensory receptors. Increases in inflation may diminish temporal contrast or a consistent tactile definition for participants, making it harder to reliably perceive a difference, pointing to a response bias in which they are defaulting to guessing 'MORE'.

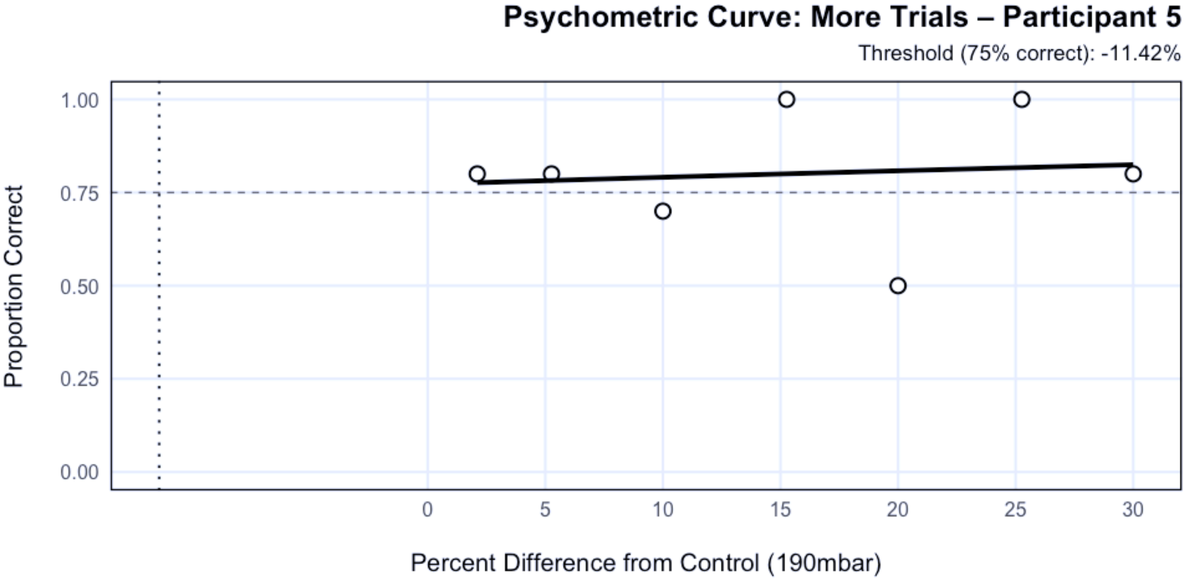

Figure 24. Psychometric Curve, P5, Difference Threshold – MORE.

Figure 24 shows results from P5 where response accuracy remined consistently high across differences in the 'MORE' direction. Although this indicates heighten sensitivity to increasing pressure, the lack of variation in responses limits the model's ability to reliably estimate a threshold, resulting in negative threshold value (-11.42%) which is both outside the stimulus range and in the wrong direction. This discrepancy may originate from guessing behavior, stimulus inconsistencies, or a response bias unrelated to actual physical change.

Interestingly, this performance mirrors P5's 'LESS' results, (Figure 15), where a -10.3 % change was needed to reach 75% threshold. Despite difference in direction, both threshold values cluster around -10%. This responsiveness contrasts other participants who showed directional asymmetries. However, the relativity flat curves in both conditions also suggest the stimulus set may not have fully captured the transition region, potentially underestimating the true slope and P5's perceptual thresholds.

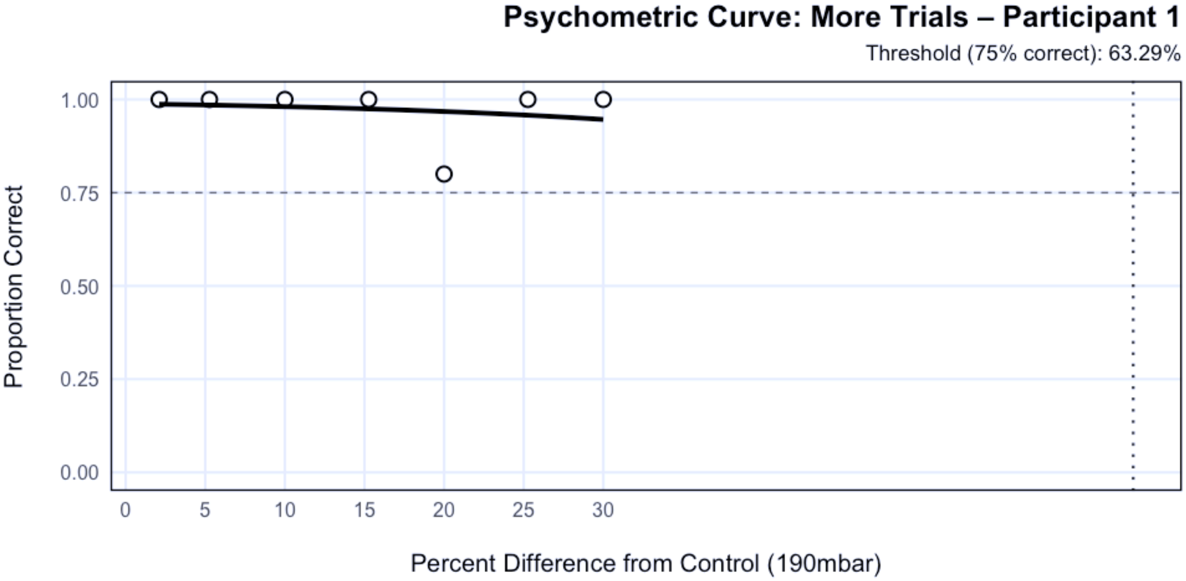

Figure 25. Psychometric Curve, P1, Difference Threshold – MORE.

Figure 25 represents the psychometric pattern for P1. The plot's inconsistency which indicates the participant required a +63.29% change to detect a change from the control and significantly higher than the threshold observed in other participants. The fitted curve remains nearly flat and elevated across the tested range, suggesting consistently high detection accuracy regardless of stimulus intensity. The unexpected trends illustrated in other participants and this atypical response may reflect a response bias. These findings highlight a key proposal of squish, where the perceptibility of change in squish may be asymmetrical and be a dynamic relationship between different features of squish. It is possible that small changes between deformation and rebound may amplify the perceptibility of minor changes when intensity increases; and follow a more typical pattern when the intensity decreases.

Percent Difference - NONE

Participants were required to provide a 'MORE' or 'LESS response for trials where the comparison interface was the same as the control, serving as catch trials to reveal any baseline response tendency in the absence of a difference. Isolation of these same stimulus trials aims to assess response bias to determine if participants favored one response over the other. This exploration provides an opportunity to understand the bias and likelihood of choosing a specific response at a specific percent difference and across conditions.

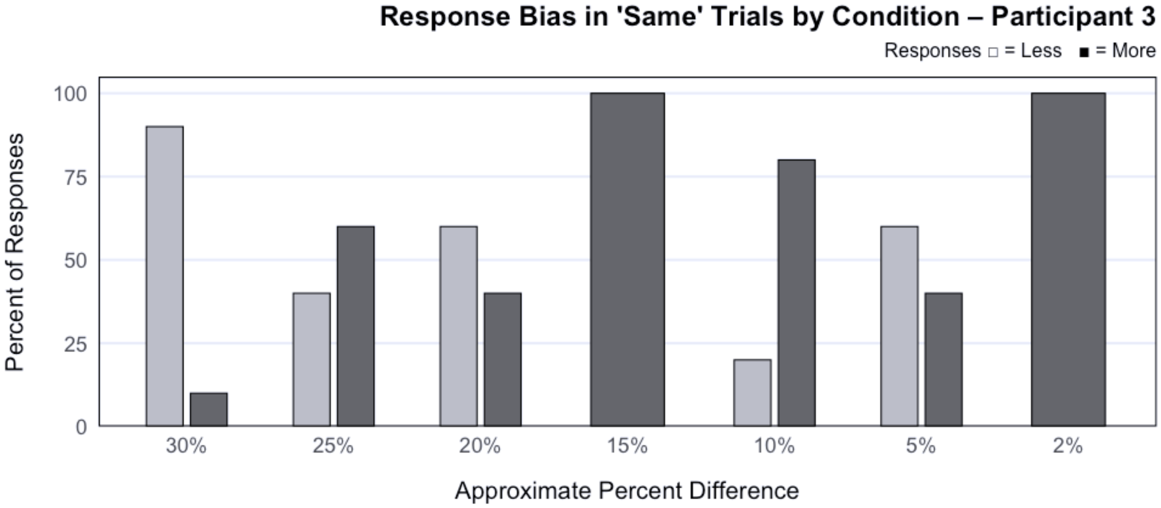

Figure 26. 'Same' interface condition P3.

Figure 26 illustrates trials in which the comparison interface matches the control exactly. P3 showed bias toward reporting 'More' at smaller precent differences. The bias towards 'MORE' may indicate uncertainty and defaulting to a 'MORE' response when unsure. This suggests that increased intensity was perceptually favored when no stimuli was present. Interestingly, the results of the 15% inflation condition showed the participant defaulted to 'MORE' every time. This behavior is comparative to the result from the mechanical characterization data where 15% inflation condition exhibited the steepest ramp-up in the force-displacement curve. The mechanical profile may have introduced a disproportionality salient cue, unintentionally reinforcing the perception of 'MORE'. The aligning between mechanical acceleration and perceptual bias underscores how sublet material behaviors can shape user interpretation.

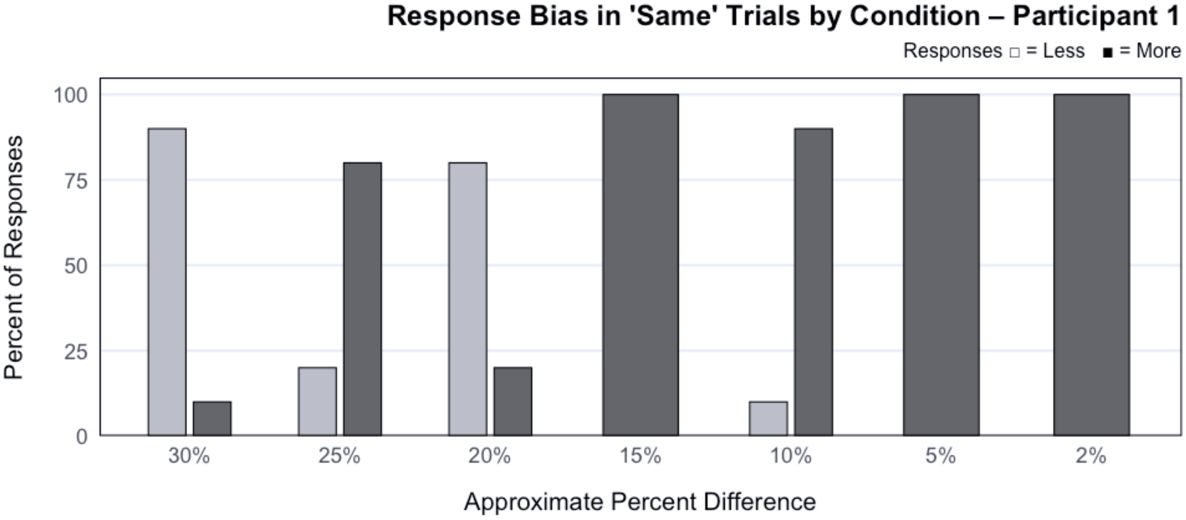

Figure 27. 'Same' interface condition P1.

Consistent with P3, Figure 27 shows P1's exhibited a systematic bias toward reporting 'MORE' in catch trials when neighboring trials involved smaller differences. This repeated directional preference suggest that response bias may be a shared tendency in low stimulus or uncertain context. However, P1's threshold was more random, with poor psychometric fits in the directional conditions. This inconsistency may indicate their responses were driven by guessing or an internal perceptual strategy rather than sensory detection.

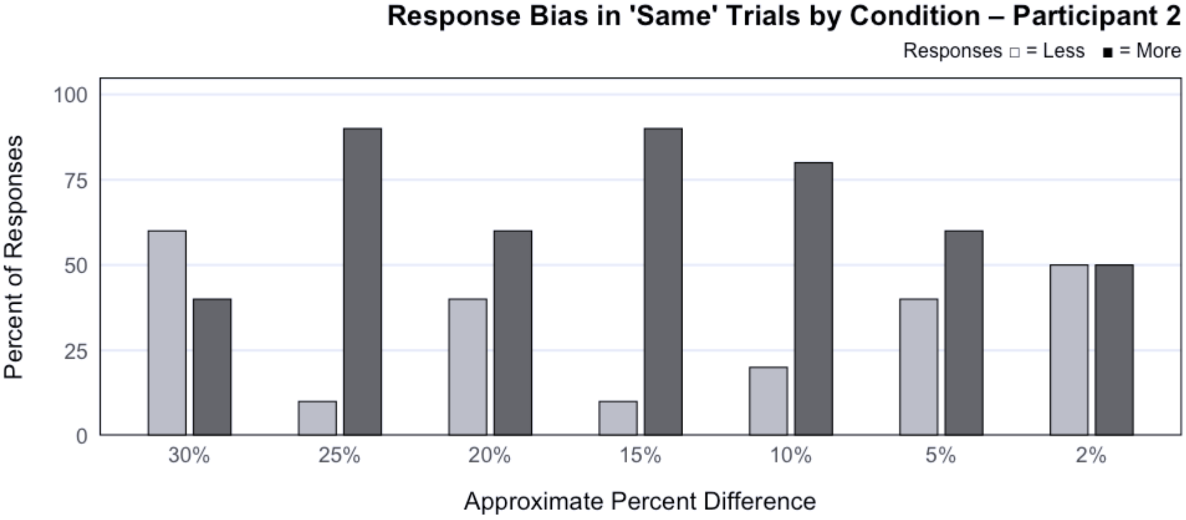

Figure 28. 'Same' interface condition P2.

Exploring the SAME trials for P2, Figure 28, revealed a potential bias shift across stimulus conditions. At larger surrounding percent differences, P2 responded "More" more frequently but as intensity levels approached the control value their responses began to favor an even split reaching a precise 50/50 split at 2% change from the control. The even distribution at the smallest percent different could indicate complete uncertainty, leading to pure guessing. Interestingly, the true 50/50 response pattern suggests indecision and a consistent behavioral strategy in the absence of perceptual cues. Rather than exhibiting fluctuating bias, P2 appeared to adopt a neutral stance, possibly reflecting an internal belief where neither 'MORE' nor 'LESS' felt justifiable, revealing how uncertainty can trigger deliberate equalized response in ambiguous tactile context.

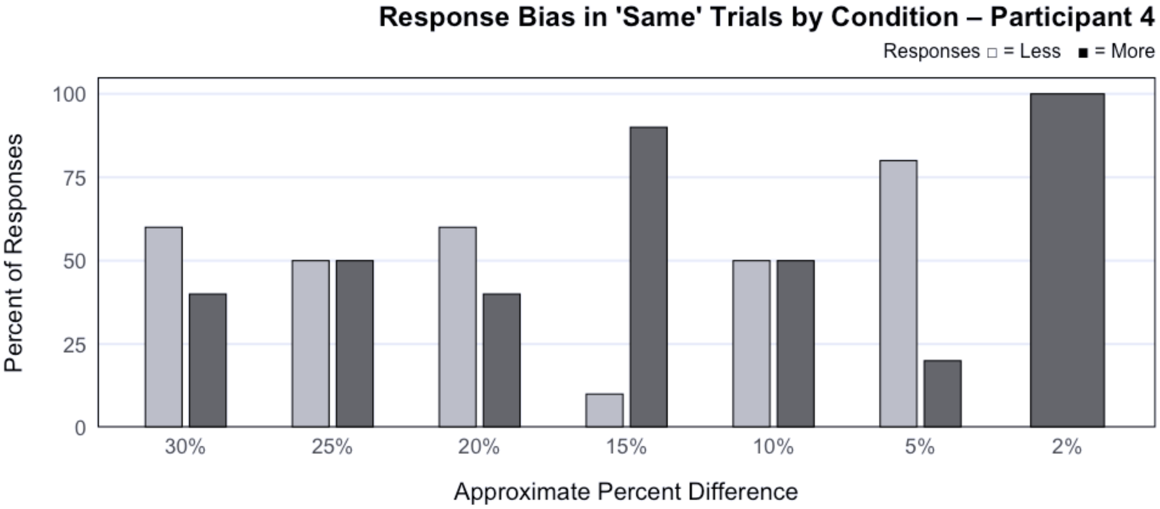

Figure 29. 'Same' interface condition P4.

Shown in Figure 29, P4's responses at larger differences were relatively balanced or leaned towards Less, suggesting minimal bias when comparison context was more distinguishable. However, as the stimulus intensity decrease, the bias became more apparent. At 5% there is a dramatic increase in Less responses and at 2% a dramatic increase in More responses. This inverted pattern from biases observed in P1 and P2 provide evidence towards individual asymmetries in perception and decision making.

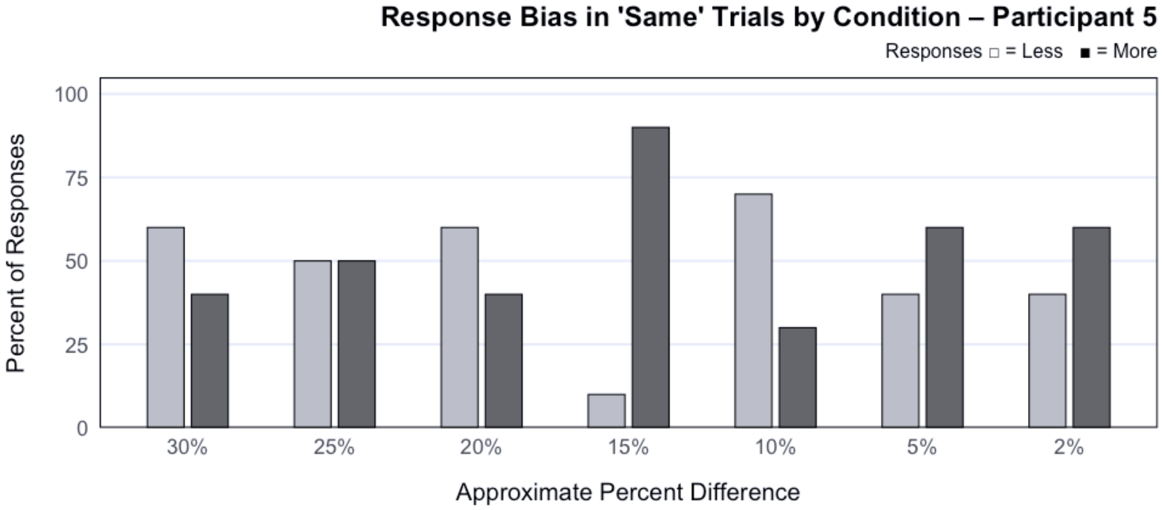

Figure 30. 'Same' interface condition P5.

Unlike Participants 1, 3, and 4, who displayed mixed direction biases, P5 demonstrated a highly consistent and evenly split response pattern for trials where the no difference was present, illustrated in Figure 30. The results reinforce that bias is not merely noise, but rather a reflection of how participants internally resolve uncertainty, shaping perception and decision making. P5, with clear psychometric threshold and a consistent 'MORE' bias under uncertainty, illustrates how bias and perceptual sensitivity can influence response behavior.

Notably, during the 15% difference trials, all participants showed clear bias towards reporting 'More' in the catch trials. This group level tendency aligns with findings from the mechanical characterization data, where the 15% inflation condition reached peak force earlier than all other conditions. This early peaking may mark a unique point in the interfaces' response where features of squish, such as rebound or deformation become more perceptually dominate. Even in the absence of a true difference, this combination of mechanical cues may be interpreted as "more" due to a heightened salience. Alternatively, this pattern could stem from a discrepancy in the fidelity of the inflation system, where, despite calibration, inconsistencies in interfaces introduce unintended bias. These observations emphasize that direction bias and perceptual thresholds are not isolated phenomena, but interdependent mechanical and temporal features.

Correlations

Pearson correlation coefficients were computed to assess the strength and direction of linear association between perceptual thresholds (i.e., Absolute, LESS, MORE) and a range of physical, anatomical, and behavioral variables. In this analysis, correlations greater than r = 0.7 were considered strong and used to identify key contributors to individual differences in tactile perception. Results from the Pearson correlation, indicates strong negative correlations associated with Absolute Percent, LESS/MORE thresholds and physical, anatomical, and behavioral variables.

Exploring Absolute Percent Threshold Correlation coefficients:

- Fine Moter Task Frequency (r = -0.975) indicated participants that engage in fine motor activities more often demonstrated greater sensitivity to squish stimuli.
- Physical Activity Leve (r = -0.869) suggests higher physical activity is associated with better perceptual discrimination performance.
- Grip Strength (r = -0.818) provides evidence that strong hands correlate with lower threshold values.
- Fine Motor Skills (r = -0.869) indicates that self-reported higher fine motor skills demonstrated greater tactile discrimination abilities.
- Anatomical metrics for Little Finger and Ring Finger Length showed similar trends of longer fingers correlating with improved tactile resolutions.

Exploring LESS Threshold Correlation coefficients:

- Physical Activity Leve (r = -0.975) indicates active individuals were better at detecting smaller deviations in lesser interfaces.

Investigation of MORE Threshold correlations:

- Fine Motor Skills (r = -0.979) suggests individuals with highly rated motor skills were more sensitive to changes in stimuli for interface with more pressure than the control.
- Fine Motor Task Frequency (r = -0.902) supports the trend of greater sensitivity to squish stimuli with higher frequency in fine motor activity.
- Little Finger (r = -0.810) and Ring Finger (r = -0.800) supports the correlations between anatomical measurements and threshold discrimination values.

Interpretation of these correlations suggest that individuals who possess greater dexterity, engaging in frequence fine motor activity exhibit a higher sensitivity to tactile discrimination. This supports a model of squish perception that integrates both Gibson's ecological theory of perception, which emphasizes the relation between action and perception and constructive theories, where prior experiences influence perception. This research suggests that the perceiver utilizes embodied skills developed through daily activity to extract meaningful differences in soft, compliant stimuli. These insights highlight the need to tailor haptic interfaces to account for the diverse tactile capabilities among users. In addition, these finding suggest perceptual sensitivity to squish may not be fixed, rather can improve over time through repeated interaction; pointing to the idea that it is a skill that can be learned, refined, and developed with experience.

Conclusion

While an ideal psychophysical model would predict smooth, sigmoidal psychometric functions with a clearly defined transition from uncertainty to certainty**,** outcomes of this study reveal a more complex and inconsistent response pattern. Although performing the same test, participant exhibited distinct thresholds varying in magnitude and curve shape. Variability in threshold estimates, directional asymmetries, and individual bias reveal an opportunity for continued investigation of detection and discrimination of squish. These deviations from the ideal exemplify the challenge of modeling real world haptic experiences, specifically, incremental intensity in dynamic materials. These findings prompt further analysis to explore how cognitive strategy, perceptual biases, and tactile discrimination interact with the multidimensional features of squish to shape a perceived intensity. Mechanical characterization of the interfaces revealed nonlinear force-displacement behavior and hysteresis. This coupling between mechanical behavior and perceptual response complicates threshold estimation, however, it provides design opportunities where material dynamics could be tuned to amplify or suppress tactile signals.

It is possible that participants interpretation of 'squish' may have varied, with some relying on force while others focusing more on displacement or deformation cues. Participants were instructed to judge whether the second interface felt 'MORE' or 'LESS' squishy than the first; however, no specific definition of "squish" was provided. This open framing was intended to allow natural perceptual strategies to emerge, however, it may have introduced variability across trials and individuals, potentially influencing the consistency of participants" responses. Fatigue or participant strategy changes over time could have influenced the consistency of participants' responses. The dynamic interfaces were controlled using the same pressure system; however, the fidelity of the sensor and inconsistency in interfaces may have introduced variability during inflation process.

Future studies might consider introducing confidence ratings to help separate perceptual noise from true uncertainty. Balancing presentation order and increasing randomization may also reduce carry-over bias. A higher-resolution pressure control system would help detect JNDs with more precision and provide an opportunity to engage with additional threshold estimation methodologies. Moreover, directional asymmetry was not fully accounted for, highlining a need to explore perceptual framing and stimulus presentation more deeply.

Reflection

This study represents a first step towards quantifying ‘squish’ as a perceptual quality, being a term commonly used in design, robotics, and haptics however rarely defined in measurable psychophysical terms. By treating ‘squishiness’ as a perceptual threshold, this research helps bridges a gap between subjective tactile impressions and objective interface design. This work seeks to formalize squish perception, enabling future development of tactile systems that can simulate the multidimensionality of squish in a controlled, measurable way.

The results of this study showed that participants had predicable sensitivity to differences, however, exhibited bias and inconsistency. Theses variabilities confirm the complexity of utilizing tactile cues for decision making and highlight the value of continued exploration of psychometric methods in characterizing squish in general, and the features that define it. Despite calibration, the hardware (i.e., dynamic interface, pressure control) may have impose error in the precision of simulated realistic squish. This introduces an opportunity to refine hardware for feature control and physical realism. The study’s methodology was robust enough to capture perceptual thresholds, however, limitation in the interfaces ability to produce fine-grained, consistent intensity increments reduced the precision. The study reinforced the idea that tactile interface design cannot rely on mechanical specifications like force or displacement alone.

Several aspects of the experimental design of the study are worth noting. The force-choice paradigm, combined with logistic modeling, confirmed the effective methodology for estimating perceptual thresholds. Using a control-centered percent different metric allowed for clear visualization of sensitivity ranges for participants. Future research should explore squish perception across a broader range of intensity levels to better understand how JNDs vary with the baseline stimuli magnitude. In addition, isolation and characterization of the individual features of squish would aim to better understand how these perceptual dimensions combine to influence tactile judgments. Use of repetitive trials for multiple conditions of this study generated usable behavior data. While the use of multiple dynamic interfaces enabled efficient testing by easily cycling through trials, it did introduce additional variability. Participants engagement and interest contributed positively to the overall execution and quality of this study.

Several limitations constrained the precision and generalizability of findings. Smaller sample size and limited number of trials per comparisons: 10 rounds of 3 Comparisons (MORE, LESS, SAME) for 7 conditions, totaling 210 reduces statistical power and may have limited the ability to detect consistent trends. Variability across dynamic interfaces suggest that hardware consistency may have influenced outcomes. The mechanical resolution of the system may not have been enough to capture robust perceptual difference threshold estimations. The order of interface presentation was not fully counter-balanced, which may have introduced additional unintended bias. These observations highlight the need for finer graduations and expanded range of comparisons to more confidently characterize perceptual threshold in future studies.

Given the exploratory focus of this study, formal error quantification was not included in the participant testing protocol. Although each condition involved repeated stimulus interactions, each set was only presented once, limiting the ability to assess trial-level variability, intra-participant consistency, or establish confidence intervals around individual perceptual thresholds. Sources of mechanical variability were observed during interface characterization, which is recognized as a potential source of error. Minor inconsistencies in inflation and structural dimensions may have introduced physical discrepancies between trials. Although these variations did not undermine the overall patterns of perception, they increase the potential for perceptual noise. Future iteration of the work would benefit from expanded trial counts and repeated presentation of condition sets to enable estimation of error margins and response consistency. Incorporating repeated exposures would also allow for analysis of perceptual learning, adaptation, and strategy refinement overtime.

Despite these limitations, the current study establishes a conceptual foundation for future research into the tactile perception of squish. The results demonstrate that dynamic, deformable interfaces can reliably evoke and quantify perceptual differences, supporting the potential of squish as an expressive, functional modality for tactile communication.

Discussion

This study explored the perceptual dynamics of squish as a tactile quality and its potential as a communication modality in human-machine interfaces. Several key features of squish emerged: Surface deformation, material resilience, rebound characteristics, and user-in-the-loop interactions, contributing to a rich sensory experience. These features provide a layered and time-dependent interaction, making squish a compelling candidate for conveying layered information tactilely.

Using a forced-choice paradigm and logistic modeling, the study estimated perceptual thresholds and observed variations across participants. While the expectations for same stimulus catch trials was a 50/50 split between 'MORE' and 'LESS' guesses, participants' results revealed directional biases. This means perceptual judgment may be influenced by internal expectations, prior trial context, and individual decision strategies under uncertainty. These finding are consistent with the ideas that stimulus perception is shaped by the physical properties of the interface, individual tactile sensitivity, and contextual framing of surrounding stimuli. Together, these results highlight the importance of accounting for cognitive and perceptual biases when interpreting psychometric behavior in near-threshold conditions of squish. Limitations such as small sample size, limited trial count per condition, and inconsistencies in dynamic interface behavior hinder the generalizability of threshold estimations. To improve future iterations of this study, several refinements are suggested:

- Increase the number of participants and trials to strengthen statistical power and improve reliability of perceptual threshold estimations.
- Explore perceptual thresholds across different populations (e.g., aging individual, children, individuals with sensory differences, high dexterity users) to examine demographic and tactile variability.
- Expand the range of control values to investigate how baseline intensity influences perceptual sensitivity and how JNDs scale across different stimulus magnitudes.
- Enhance the fidelity of the autonomous system to improve control and expanded the range of psychophysical methods that can be used to assess thresholds.
- Implement finer pressure steps to more precisely resolve perceptual boundaries
- Improve mechanical consistency and calibration across dynamic interfaces to reduce hardware induced variability.
- Incorporate confidence rating and observational data (e.g., response time) to capture participant's certainty and enrich the interpretation of response patterns.

Successfully demonstrating that soft, deformable materials can support perceptual discrimination, positions squish as a promising tactile communication modality and supports the original intent of this study. As a perceptually rich, and directionally sensitive cue, squish may enable more intuitive, expressive interactions for advancing human-machine systems. Its unique combination of compliance, deformation, and rebound that unfolds over time suggests that squish could function as a tunable tactile dimension, similar to the use of amplitude and frequency in vibrational stimuli. This perspective expands our understanding of controllable tactile feedback from discrete, event-based signals to an evolving interaction. The ability to make perceptual judgments from subtle pressure modulation suggests that squish can be leveraged in applications requiring low-intensity, continuous, and directional feedback, such as assistive technologies, soft robotics, teleoperation systems, and immersive aids for virtual environments.

Integrating compliance, deformation, rebound, and human-in-the-loop interactions, squish enables the development of interfaces that exhibit lifelike qualities and convey information through continuous, multidimensional gradients. This capability engages users in an ongoing physical exchange. Quantifying perceptual thresholds of squish reframes tactile feedback as an evolving, interactive process, expanding the design space for how users interact and interpret physical systems. This work lays the foundation for developing systems that can dynamically respond to human input and actively engage in a tactile dialogue, where perception and action are continuously shaped through mutual interaction.

Appendix

Appendix A Background Questionnaire

1. What is your age?

2. What sex were you born/assigned at birth (i.e. sex written on original birth certificate)?

3. What is your approximate height and weight?

4. How much physical activity have you engaged in over the past 4 months?

    - Regular Exercise (e.g., 3 or more times per week)
    - Moderate Exercise (e.g., 1-2 times per week)
    - Occasional Exercise (e.g., less than once per week)
    - Little to No Exercise

5. How often do you engage in activities that involve fine motor skills such as threading a needle and aligning small parts?

    - Daily
    - Several times a week
    - Once a week
    - Occasionally
    - Rarely

6. How would you rate your fine motor skills?

    [Excellent]   [Good]   [Average]   [Below Average]   [Poor]

7. How would you describe the quality of your handwriting?

    [Very Neat]   [Neat]   [Legible]   [Messy]   [Very Messy]

8. How well do you consider your hand-eye coordination?

    [Excellent]   [Good]   [Average]   [Below Average]   [Poor]

9. How would you rate your reaction time

    [Excellent]   [Good]   [Average]   [Below Average]   [Poor]

Thank you for your responses.

Appendix B, Edinburgh Handedness Inventory

This questionnaire is to help understand which hand you prefer to use for everyday tasks.
Below is a list of activities. For each one:

- Mark “**X**” in the box for the hand you usually use (**LEFT**, **RIGHT**) to perform each task.
- If you always use the same hand for that task, place two marks “**XX**” in that box
- If you sometimes use the other hand, put one “**X**” in the box for your main hand and one “**X**” for the other

TASK	**LEFT**	**RIGHT**
WRITING		
DRAWING		
THROWING		
SCISSORS		
COMB		
TOOTHBRUSH		
KNIFE (WITHOUT FORK)		
SPOON		
HAMMER		
SCREWDRIVER		
TENNIS RACKET		
KNIFE WITH FORK		
BASEBALL BAT		
GOLF CLUB		
BROOM		
RAKE		
STRIKING A MATCH		
OPENING A BOX (LID)		
DEALING CARDS		
THREADING A NEEDLE		

Appendix C, Recruitment Flyer

! Help Contribute to Cutting-Edge Research!

A Tufts University graduate student in the Human Factors Engineering Department is seeking volunteers to **participate in a study on how people tell the difference between soft objects.** Understanding squish perception requires exploration of how people perceive object characteristics such as compressibility and rebound. Recognition and adaptation to these is essential for a range of daily and specialized tasks, (i.e., manipulation of objects, control of physical and digital systems, and navigating through space). This study stems from the growing interest to improve the interactions between people and machines, especially with the rise of technologies like augmented reality (AR) and virtual reality (VR). In these settings, sensations such as "squish" can be critical for richer, more effective user experiences.

Eligibility

All genders and ethnicities are eligible for participation. Participants must:

- speak /understand English
- be at least 18 years old
- not have and disorders or conditions (e.g., arthritis) in the finger, hand, wrist or arm or a history of finger, hand, wrist, or arm injury or surgery or impairments that could affect tactile perception.
- not have been diagnosed with a neurological disorders or sensor processing conditions.
- not have any chronic pain in your hands, wrists, or arms.
- not be on any medication that could influence motor skills or cognitive function.

What You Will Do

1. Complete a brief screening questionnaire.
2. Allow researchers to test your grip strength and measure your hands
3. Answer demographic and background questions about yourself
4. Participate in a series of tests that compares two balloon-like objects by squeezing, pressing, touching, and lifting.
5. Perform testing at Tufts University, which takes about 2 hours.
6. Be compensated with a **$50 gift card** on completion of all procedures.

Interested?

If you meet the eligibility criteria and would like to participate, please use the contact information below to reach out. This study possesses no more risk than squeezing a sponge. **Email:** jason.lasser@tufts.edu

Privacy Matters

All data collect during the study will be securely stored in a password-protected system accessible only by the research team. To ensure privacy, responses or results will not be labeled with any identifiable information that could link it back to you.

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