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Novel Robotic Hand Design: Improving Handshake Realism Using Soft Granules

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ABSTRACT This paper presents a novel robotic hand design that aims to produce a realistic human-robot handshake. The key feature of the hand is the use of soft material components in the palm region. Subjective experiments were used to select the ideal material for realistic palm compliance and skin texture. A novel approach using granules to achieve a high material compliance was explored. Granular jamming was used to easily test a range of material hardnesses that exceeded the maximum unforced packing density of granules. Hydrated Polyacrylamide granules at -20 kPa were determined to perform best. The optimum grip strength of 9.5 N was concluded using a subjective experiment. The hand design, built from these findings, was tested against a baseline design. In which, the realism and comfort of each is compared to a real human handshake. Both a survey and analysis of electrodermal activity (EDA) were compared to determine validity of conclusions. The novel hand design showed statistically significant improvements.

I. INTRODUCTION

THE handshake is one of the most important human rituals. It uses haptics to convey social identity at the beginning and end of a social interaction [1] and plays a key role in the interpersonal communication in everyday life. Handshakes can convey emotion and assert the social dynamic of a relationship [2].

Research into the area of human-robot handshakes is of interest due to its growing relevance for industries such as social-care for an aging population [3]. The emulation of realistic humanoid features has been a key development of the social robot hand and affects the way interaction is perceived. This has been shown through varying physical properties and behaviour such as grip force, palm compliance, handshaking trajectory, and reaction agility [4] [5] [6].

Effective human like reflexes and compliance have been achieved by Arns, Laliberté, and Gosselin (2017) using novel mechanisms and feedback control of a tendon based robot hand [5]. While producing realistic hand shaking abilities, the study failed to emulate the softness of human palm.

Cabibihan (2011) achieved realistic finger compliance for a prosthetic hand by incorporating layers of varying materials and internal air pockets into the design [7]. This study encouraged further exploration of softer materials, and its findings have not yet been applied to palm design.

Granular Jamming is an exciting phenomenom that allows materials to achieve a varied hardness and stiffness. Unconfined, a granular medium behaves like a fluid where the granules can slide freely. When a negative air pressure is applied the space around the granules is confined and the inter-particle friction increases to a solid-like state, resulting in a hard structure [8]. Granular jamming has been used for variable stiffness joints and members. At the time of writing there has been little to no research published on the variation of Shore hardness (indentation) of jammed granules.

The expectation is that granule filled structures will provide effective softness to emulate the compliance of the human palm. The use of granular jamming will be useful for easily varying the hardness of the material to find the optimum. An interesting facet of research that this opens up is the ability to vary the stiffness of the robot hand when involved in different social interactions. This could allow a robot to communicate a greater emotional intelligence, adapting according to varying dimensions such as age, gender and culture. Identifying these preferences is outside the scope of the project.

This paper presents a novel robot hand that aims to achieve a realistic human handshake. The hand design was first developed using anthropometric data and understanding the contact and interaction during a handshake. Followed by testing different granules and pressures with human participants to find the most realistic material for skin texture and compliance. The optimum grip force of the handshake was also determined using subjective human testing. Finally, the new hand design was tested against a baseline design to determine whether significant improvements had been made in terms of realism and the comfort of interaction.

II. ROBOT HAND DESIGN

A. ERGONOMIC DESIGN

In order to recreate an anthropomorphic hand which would be comfortable and realistic, many features and constraints were applied to the design.

Using anthropometric data, it was ensured the dimensions of hand were to scale and in proportion. The average of 50^{th} percentile of adult male and female values were used to mimic the most representative adult human hand. As shown in Fig. 1, these values informed the length, breadth and thickness of the hand, each digit and the palm.

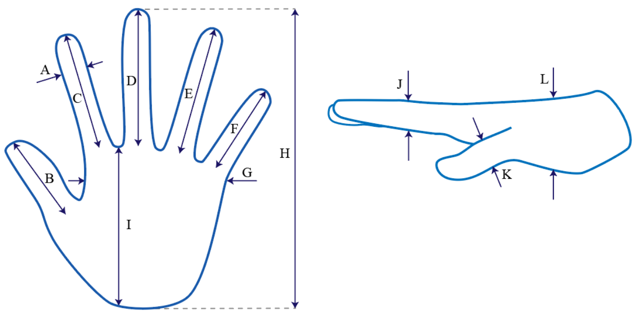

FIGURE 1. Anthropometric Data used for Hand Design

Label	Body Part	Dimension (mm)
A	Finger Breadth	19.5
B	Thumb Length	49
C	Index Finger Length	69.5
D	Middle Finger Length	80
E	Ring Finger Length	69
F	Little Finger Length	52.5
G	Hand Breadth (Metacarpal)	81.5
H	Hand Length	181.5
I	Palm Length	102
J	Finger Thickness	17.5
K	Thumb Thickness	20
L	Hand Thickness (Metacarpal)	31.5

TABLE 1. Anthropometric Dimensions for Fig. 1 [9]

In order to replicate the compliant nature of flesh in the hand, two regions of the palm were designated for granular jamming using small granules, as seen in Fig. 2 e). The lateral compliance of the palm is significant during a handshake, with up to an 18% compression of the palm width [5]. The metacarpal regions of the little and index finger experience the most compression during a handshake [7]. Therefore, these were chosen as the locations for the granular material (Fig. 2 e)). Granular jamming was not utilized in each digit, as this would add unnecessary levels of complexity to the design by including actuated air pressure.

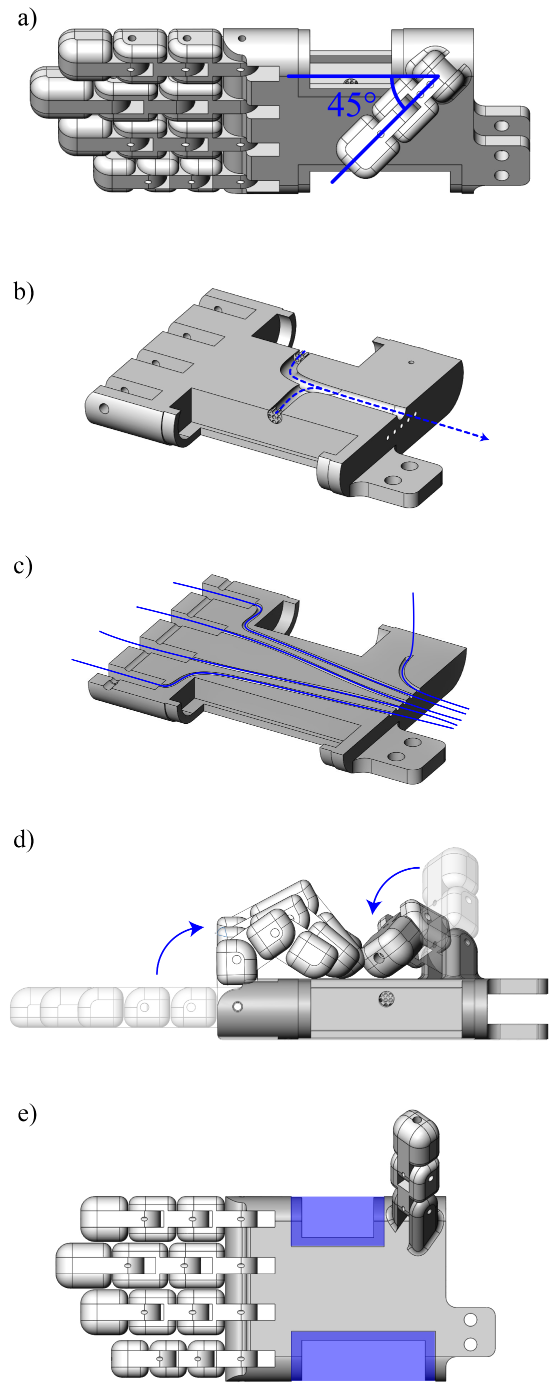

FIGURE 2. Design features of redesigned Hand - a) 45 degree Thumb Joint Angle, b) Air Pressure Duct for Granular Jamming, c) Cutouts for tendons to actuate phalanges, d) Design features to mimic human phalange joint angle range, e) Regions filled with granules

It was found that during the human handshake, compressive forces between 2N and 12N are applied to participants [7]. As a result, a high torque Dynamixel Xl-320 motor was attached to Nylon tendons via a pulley system (Fig. 8). This was able to achieve the appropriate grip force (See Section II-C).

B. SELECTING MATERIAL FOR COMPLIANT PALM

1) Experiment

As seen in Arns, et al. (2017), there is an ineffectiveness of rigid body structures to provide realistic skin texture [5]. The rigid regions of the hand were fabricated in PLA material by a FDM desktop 3D printer. However, there was a challenge was to emulate the compliance and texture of the human palm through the choice of material granule under a specific air pressure.

To establish the best material, an empirical analysis was conducted to examine the subjective responses to different materials. Four different granule based materials were tested; fine Coffee granules, Rubber beads, Polystyrene balls and hydrated Polyacrylamide Balls. In order to achieve a material hardness that exceeded the maximum unforced packing density of granules, granular jamming was implemented. Each granule type was tested at three different negative pressures; 0 kPa, -20 kPa, -40 kPa. Table 1 shows the sample numbers assigned to each material. Nine participants were asked two questions for each sample:

1) How similar is the material texture to human skin?
2) How similar is the material compliance to human palm?

A scale of 1-5 was used, 1 being unrealistic and 5 being hyper-realistic.

Material	Pressure (kPa)	Test number
Coffee Granules	-40	1
	-20	2
	0	3
Rubber Beads	-40	4
	-20	5
	0	6
Polystyrene Balls	-40	7
	-20	8
	0	9
Polyacrylamide Balls	-40	10
	-20	11
	0	12

TABLE 2. Materials

FIGURE 3. Granule Test Samples - a: Coffee granules, b: Rubber beads, c: Hydrated Polyacrylamide Balls, d: Polystyrene balls

Each material was fitted inside identical 3D printed casings and sealed beneath a latex membrane. as seen in Fig. 3. These were fixed to a table using Velcro and held in a consistent vertical orientation. During the experiment, participants were blindfolded and asked to explore each sample with their finger while answering the questions, as seen in Fig. 4. A negative pressure vacuum was used to adjust the pressure of each material. The order of samples was randomized to avoid sequential biasing. Between each sample, the participant was asked to return their finger to an empty container covered with latex, to create a baseline comparison. Expected realistic palm compliance to be maximum 16 % of palm width suggested by [5].

FIGURE 4. Experimental Set-up

2) Results

The results of this experiment are illustrated in Fig. 5 and Fig. 6. One material stands out above the rest. Polyacrylamide scored highest for both categories. In order to check if these conclusions are valid statistical tests were carried out.

The data follows a non-Gaussian distribution and was independent, therefore a Kruskal-Wallice test was carried out.

Fig. 5 shows that for question 1, test 11 (Polyacrylamide at -20 kPa) has the highest mean value ($\mu = 3.66, StDev = 0.55$). The Kruskal-Wallice test (χ^2 = 65.96 , $p < 0.001$) showed that there was a significant difference. A post-hoc Dunn test showed that the difference was significant between test 11 and 3, 4, 5, 6, 8, and 9. This means that the subjective score for how human-like the material texture felt was significantly better for Hydrated Polyacrylamide balls at -20 kPa for 6 out of the 12 samples. This was the highest scoring material.

Fig. 6 shows that for question 2, test 11 (Polyacrylamide at -20 kPa) has the highest mean score ($\mu = 4.11, StDev = 0.33$). The Kruskal-Wallice test (χ^2 = 55.7 INPUT, $p < 0.001$) showed that there was a significant difference. A post-hoc Dunn test showed that the difference was significant between group 11 and 2, 3, 5, 6, 7, 8, and 9 and between group 12 and 2, 5, 6, and 9. No other groups were significantly different from each-other. This shows that the subjective score for how human-like the material compliance felt was significantly

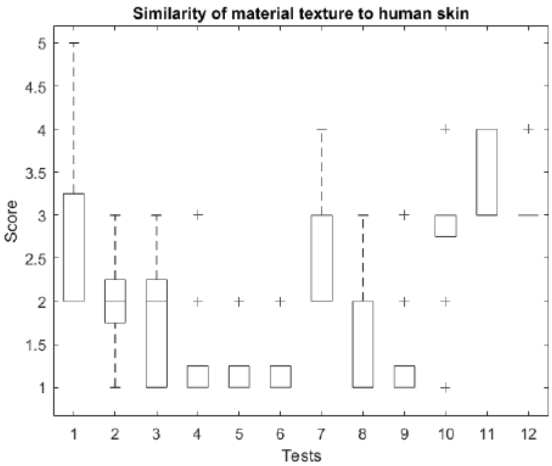

FIGURE 5. Rating of material texture similarity to human skin.

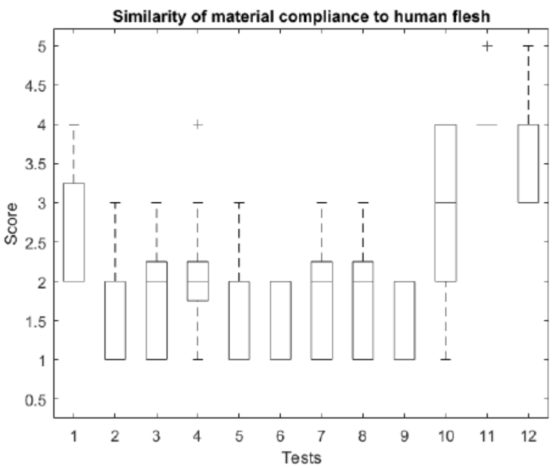

FIGURE 6. Rating of material texture similarity to human skin.

better for Hydrated Polyacrylamide balls at -20 kPa for 7 out of the 12 samples. This was the highest scoring material.

3) Conclusions

Based on the results of this experiment, Hydrated Polyacrylamide granules jammed at -20 kPa are the most effective choice for achieving a realistic human skin texture and compliance. Hence, this material was used for the main human-robot handshake experiment.

C. GRIP FORCE

1) Experiment

Cabibihan et al. (2011) reported that the forces applied during handshakes between two humans ranged between 2N and 12N, however for our experimental test we required on optimum grip force value to remain constant as a control variable.

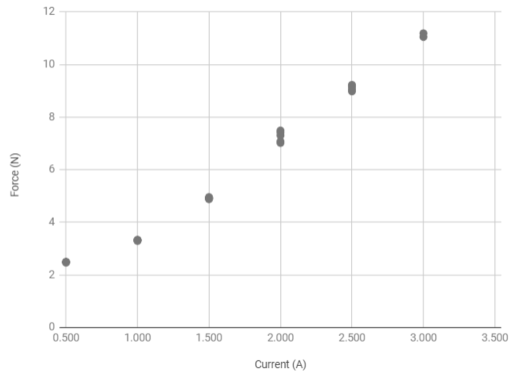

FIGURE 7. Relationship between Grip Force and Current

To establish the optimum grip force, ten participants were asked to compare each force level with a comfortable human handshake. A scale of 1 to 5 was used, 1 being very uncomfortable and 5 being very comfortable. Each user tested 6 different force levels: 2.0N 4.5N, 7.0N, 9.5N, 12.0N, 14.5N. To calculate and limit the maximum grip force for each test scenario, the proportionality between current draw and motor torque was utilised. A weighing scale was placed perpendicularly to the gripping fingers to calculate the force of the gripping at different current draw cutoffs. This showed a linear relationship, as seen in Fig. 7, between grip force of the hand and the current draw of the DC motor; this enabled accurate testing at 6 different grip force levels on users as the current draw was limited at 6 different levels.

2) Results

9.5 N grip force had the highest mean score ($\mu = 3.80, StDev = 0.84$). The Kruskal-Wallice test (χ^2 = 19.62 INPUT, p = 0.0015) showed that there was a significant difference. A post-hoc Dunn test showed that the difference was significant between the 9.5 N and the 2 N grip.

Therefore, from the people we tested the 9.5 N grip was found to be the best choice.

III. MAIN EXPERIMENT

Results from the preliminary experiments informed the decisions for a 9.5N grip force from the anthropomorphic hand, the use of hydrated Polyacrylamide Balls for shape and material of granules and a jamming pressure of -20kPa. These factors came together to produce the final designed hand as seen in Fig. 8. The hypothesis that the main experiment aims to answer is:

- Does the redesigned robot hand create a more realistic handshake experience compared to a rigid body design?
- Does the redesigned robot hand create a more comfortable handshake experience compared to a rigid body design?

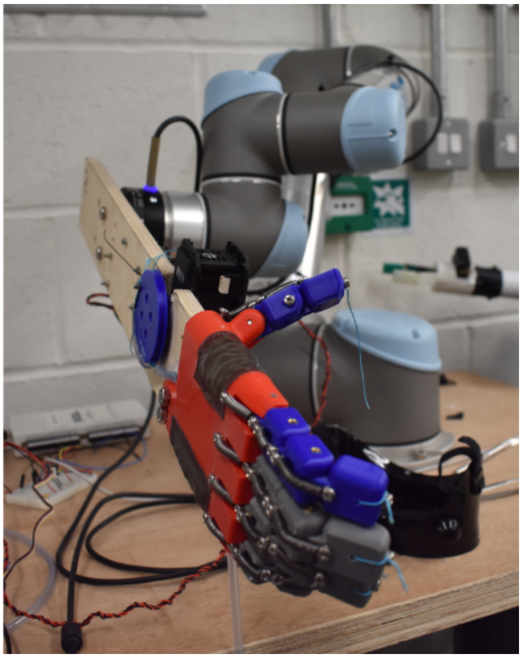

FIGURE 8. Final Designed Hand Attached to UR5 Robot

A. TEST SETUP

During the experiment, 10 participants were blindfolded to ensure they were not impacted my any visual biases. Participants were asked to shake the hand of a human to give a baseline to compare to the robot hand. The person giving the baseline handshake to participants wore a plastic glove to reduce the biases about hand temperature and skin moisture. The rigid body design shown in Fig. 9 has the same dimensions as the novel design. The only differences were the use of a soft compliant palm and an active grip. The order of the handshakes were randomized to eliminate the affect of any order bias.

Both the rigid and novel designed hand were attached to UR5 Robots to replicate the movement of a robotic arm. The robot was placed in Freedrive mode allowing the participant to lead the interaction.

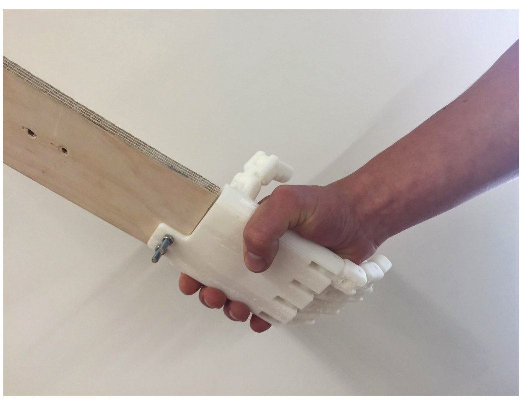

FIGURE 9. Rigid Hand

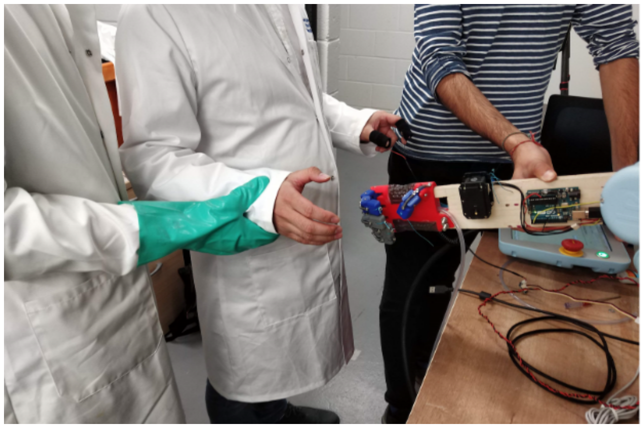

FIGURE 10. Participant taking part in experiment

B. GALVANIC SKIN CONDUCTANCE

Electrodermal activity (EDA) is a measure of sweat gland permeability, observed as changes in the electric resistance of the skin. It may be triggered by general emotional arousal, fear, or surprise [10]. Participants wore the sensor on their left hand to measure Skin Conductance Level (SCL). This was used to measure the difference in emotive responses between the interactions of the rigid hand and the designed hand in comparison to the baseline handshake. Data was collected using a LabView USB-6211 DAQ at a sampling rate of 1,000 Hz which is more than sufficient to capture the EDA fluctuations [11].

Environmental conditions such as temperature and humidity can greatly affect the results of EDA [11]. Therefore, each experiment was undertaken inside a building with fairly stable conditions. The data was collected within a short period of time to prevent any significant environmental changes.

EDA generates a constantly moving baseline [11], therefore a measurement of the peak change in SCL between just before the event and after a latency period of 10 seconds following the event [12] was used Fig. 11. EDA is also inherently different at different times of day, environmental conditions or between individuals [11]. Therefore, standardization allowed comparison between different participants. An adaptation of the standardization formula described in [12] was used. See Equation 1.

$$y = \frac{\Delta SCL}{SCLmax - SCLmin} \tag{1}$$

This allowed the SCL measurements to be described as proportion of the participants maximum range of psychophysiological response [11].

Each experiment was filmed and later reviewed to establish the timing for each handshake event. Fig. 11 shows the handshake events overlayed onto the time series data of one experiment. Time series data was smoothed using moving average filter using window width of 10000 samples (1 second) to eliminate high frequency noise.

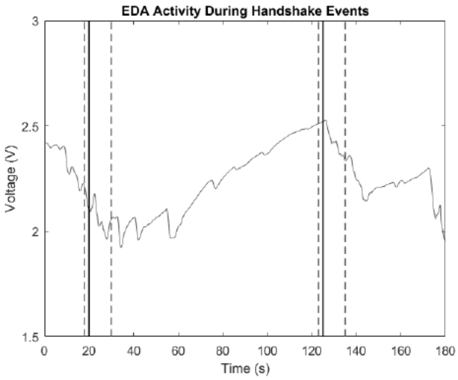

FIGURE 11. EDA time series data from one experiment. Vertical lines indicate handshake events. Dashed line to the left of vertical line indicated baseline period and dashed line to the right indicates latency period that measurements were taken within.

C. SURVEY

Participants were also asked a series of questionnaires to gauge the level of anthropomorphism and the attitude towards physical contact with the robot as well as future cooperation with social robots. Before the experiment participants were asked:

- On a scale of 1 to 5, how comfortable do you feel interacting with robots via handshakes? Where 1 is very uncomfortable and 5 is very comfortable.

This question was to gauge what spread of participants we had in terms of their confidence with interacting with humanoid robots to ensure the experiment was not biased to a certain type of group.

After shaking each of the robotic hands the participants were asked:

1) On a scale of 1 to 5, how human-like was this interaction? Where 1 is not human-like and 5 is very human-like like the baseline handshake.
2) On a scale of 1 to 5, how comfortable did you feel during the interaction? Where 1 is very uncomfortable and 5 is very comfortable.

These questions were used to gauge if participants had different emotive responses with the two different robotic hands in comparison to the human baseline. From quantitative responses we could determine if participants felt the novel hand design led to a significant difference in human-likeness and comfort experienced during the handshaking interaction.

IV. RESULTS

A. SURVEY RESULTS

1) Analysis

Statistical analysis of Q1 and Q2 comparing rigid and novel design.

Fig. 12 shows that for Q1 (similarity to human hand), the redesign had a higher mean score ($\mu = 3.20, StDev = 1.03$) compared to the static, rigid body hand ($\mu = 1.70, StDev = 0.82$). The Mann-Whitney U test ($p < 0.001$) showed that this difference was significant and the null hypothesis was rejected. Hence, the interaction with the redesigned hand was significantly more realistic than the static hand.

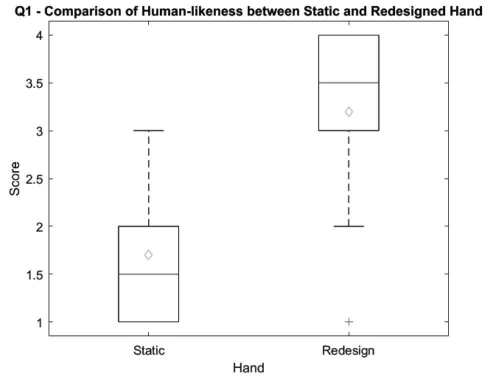

FIGURE 12. Q1 - Rating of similarity to human hand.

Fig. 13 shows that for Q2 (Comfort levels experienced during handshake), the redesign had a higher mean score ($\mu = 3.50, StDev = 0.85$) compared to the static, rigid body hand ($\mu = 2.60, StDev = 1.26$). However, there is a visible overlap between the sets of data. The Mann-Whitney U test (p = 0.0784) showed that this difference was not significant and the null hypothesis was accepted. Hence, the interaction with the redesigned hand was not significantly more comfortable than the static hand.

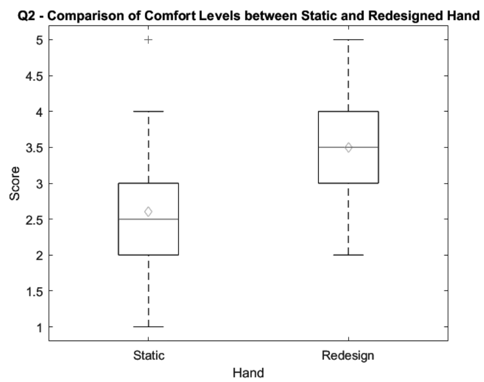

FIGURE 13. Q2 - Rating of comfort experienced during handshake.

B. EDA MEASUREMENTS

1) Analysis

Fig. 14 shows that for the redesign had a lower mean value ($\mu = 0.12, StDev = 0.20$) compared to the static, rigid body hand ($\mu = 0.32, StDev = 0.16$). The Mann-Whitney U test (p = 0.031) showed that this difference was significant and the null hypothesis was rejected.

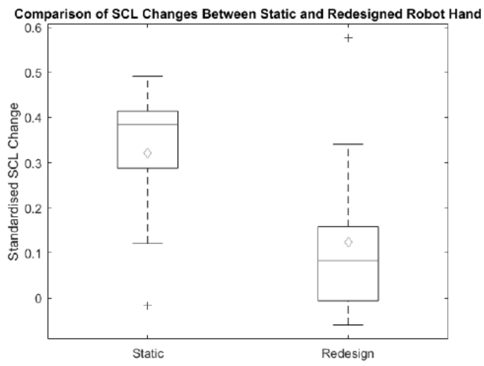

FIGURE 14. EDA response comparison.

The handshake with the redesigned hand had a significantly lower SCL change. This lower emotional response is indicative of a more relaxed participant interaction.

C. DISCUSSION

The data collected aimed to answer two key questions;

- Did the new design improve the realism of human-robot handshake?
- Did the new design improve the comfort experienced during human-robot handshake?

Based on the results of the survey, the redesigned hand was significantly more realistic than the rigid model. This significance was also validated by a Sample Size Power Test score of 0.999, showing the use of 10 participants was sufficient.

Although, the novel hand scored generally higher, it failed to significantly improve the comfort experienced by participants during the interaction, according to the survey. The Sample Size Power Test score of 0.614 shows a need for more participants before a statistically significant results could be concluded.

However, the EDA analysis showed that the redesign achieved a significantly smaller SCL change, indicating a lower psycho-physiological response. It must be made aware that a measurement of psycho-physiological response is neither positive nor negative, but can indicate how relaxed or aroused the participant is. These results indicate that the participants felt significantly more relaxed while interacting with our redesigned hand compared to the static hand.

Perhaps participants felt more at ease with the increased realism of the compliant palm while interacting with the redesign. However, others may have felt uncomfortable during the interaction as it infringed upon the uncanny valley.

Evaluating comfort levels is especially difficult because there are many factors that can effect this response. For instance, the conditions of the experiment are not that of a natural interaction setting. Being blindfolded removes visual biases between each hand but sight is an important part of handshake experience. Sight was not used to reaffirm the idea that they were shaking the hand of a robot and not a human, thus increasing the feeling of unease. Sound can also have a impact on reaction; the sound of the vacuum pump is likely to make participants uncomfortable. Other environmental conditions such as temperature and humidity are very important and affect EDA. These were not measured and maintained accurately within each experiment. Also, the static hand did not grip whilst the redesigned hand did, so it not possible to separate the effect of the grip from material compliance changes.

V. CONCLUSION & FUTURE WORK

A novel tendon based robot hand design is put forward in this paper. Informed by user testing, the design mimics human compliance and skin textures by incorporating soft features with granular based jamming of Hydrated Polyacrylamide balls at -20kPa. The optimum grip force was also found to be 9.5 N through other participant experiments. Based on these insights a comparison of the redesigned hand with these features was undertaken. When compared to a rigid and static hand design, the redesign was found to be significantly more realistic with participants feeling more relaxed during the interaction. These results were concluded through the use of participant surveys and Electrodermal activity signal responses.

Based on the feedback from participants, the design of the hand could have been improved. Many of the participants suggested that the compliant material could have been extended to other areas of the hand such as the fingertips. Additionally, the arm and wrist joint could have been smoother and follow a more realistic trajectory instead of being passive.

The findings from this study have shown the potential for using granular based jamming for creating human flesh like compliance. The potential of this is being able to intelligently adapt hand shaking style to end user preferences or to the type of interaction. Future work should aim to understand the preference differences between cultures, genders, and ages. Another, exciting application is the adaptability of the end-effector to other flexible, semi-rigid and rigid purposes.

Although this study utilized the variable softness achieved through granular jamming, it did not quantify the hardness using the Shore hardness scale. Future work should aim at quantifying the relationship between air pressure and hardness.

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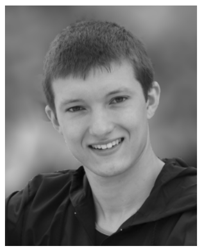

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