A Study on Pressure Modulation for Biomimetic Fine Manipulation for Soft Robots

Chapa Sirithunge[1], Xiaoping Zhang[1,2], Josie Hughes[3] and Fumiya Iida[1]

***Abstract*— The development of human-like skills in robots benefits from understanding how humans perform tasks. Leveraging tactile or haptic training information to develop robot controller training is still an uncultivated land according to our current knowledge. Furthermore, to benefit from the advantages of state-of-the-art learning models for fine-grained manipulation of thumb and forefinger, we must learn from the tactile interactions in addition to the kinematics. We propose a wearable soft sleeve for a human index finger and thumb which includes fluidic pressure sensors that provide tactile information across these two fingers from several 'taxels' or sensory receptors. By combining this with a means of capturing the location and form of contact, through the transfer of ink, we can create unique data sets which provide pressure and contact information. We captured the tactile interactions performed by humans to perform fine task execution such as turning pages. This was analyzed and interpreted to gain insights into human manipulation, and can also serve as a source of training data to guide a compliant robot hand to perform the same task. We consider this experiment as an effort to discover a solution for fine manipulation tasks based on limited tactile data while retaining dexterity and a way to demonstrate and realise fine-grained human-like skills.**

***Index Terms*— Soft hands, anthropomorphic hands, fine manipulation, soft robots, dataset generation**

I. INTRODUCTION

Hands, undoubtedly, play a key role in most common tasks, operations and environmental interactions performed in human beings' daily lives. Although the capabilities of robotic hands have shown significant advancements in recent years due to large AI models [1], advances in hand hardware [2] and improvements in tactile sensing [3], [4], fine-grained manipulation remains challenging. Providing more humanlike 'fine-grained' manipulation capabilities to robotic hands would extend robots' capabilities and applications. A key bottleneck for achieving this is developing the controllers which enable these behaviours [5]. For these to be adaptive to the task or environment we require haptic sensors in addition to means of rapidly learning or identifying controllers. However robots are equipped with limited sensory equipment due to space and technical constraints. Therefore acquiring the required skills with this limited sensory information together with the uncertainties within the environment will be challenging. This becomes even more difficult for soft robots [6].

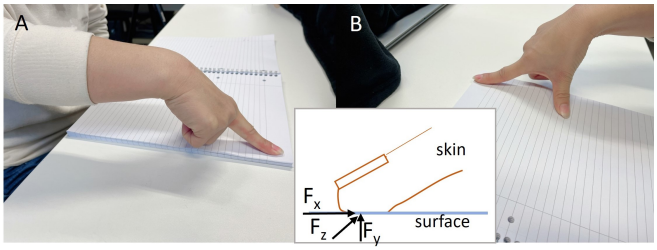


Fig. 1. A closer look at the thumb and forefinger coordination during a page turning task. A and B represent two viewpoints where two fingers have been used for the task. The force distribution over each finger's pad and the compliance of the skin contribute a lot to the successful completion of the task.

Imitating or learning from humans is a good way to realize a robot's human-like skill and is widely used for task planning and motion planning for robots. For example, in [7], based upon deep visual inverse kinematic models, a soft continuum robot learned how to fulfill static shape control from visual observation. In [8], a data-driven architecture was proposed to realize an anthropomorphic soft robot hand to learn how to grasp from observing human strategies. These studies show the effectiveness of learning controllers from demonstrations. However, in existing work, the observation information is typically only visual-based, leveraging the known kinematics of the hand for teaching. Imposing tactile or haptic training information to develop a robot controller training is still an uncultivated land according to our current knowledge. This focuses on learning the hand pose or morphology, as opposed to the tactile interactions limits the versatility of this approach to adapt to variations in the task or environment. Furthermore, we have limited experimental data sets that provide insights into the forces and means by which humans interact with the environment for fine-grained manipulation. An example task in this context is shown in Fig. 1. While a person is turning pages, there are various aspects to consider such as finger coordination and forces acting upon the paper and the finger, if a robot has to imitate the task with similar dexterity.

To benefit from the advantages of state-of-the-art learning models for fine-grained manipulation of thumb and forefinger, we must learn from the tactile interactions in addition to the kinematics [9]. We propose a wearable finger sleeve for the human index and thumb which includes fluidic pressure sensors that provide tactile information across these two fingers from several 'taxels' or sensory receptors. By combining this with a means of capturing the

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location and form of contact, through the transfer of ink, we can create unique data sets which provide pressure and contact information. Through user studies and experiments, we capture the tactile interactions performed by humans to perform fine task execution such as turning pages. This can be analyzed and interpreted to gain insights into human manipulation, and can also serve as a source of training data to guide a compliant robot hand to perform the same task. We propose this capturing of tactile information as a way to demonstrate and realise fine-grained human-like skills. The novelty lies in the wearable sleeves which cover only a small part of the finger instead of the entire hand and the use of embedded sensors which directly absorbs information from an interaction between two surfaces. In addition, an in-depth exploration of pressure patterns over a page turning task was analysed and discussed.

II. Related Work

A. Robotic finger coordination

Robotic finger coordination is important for manipulation tasks, and the coordination of fingers significantly affects the performance of a robot during a manipulation task. To improve robotic finger coordination, robotic fingers with humanlike spontaneous motion coordination have been developed through spatial multi-input spike signal multiplexing [10]. In tasks such as grasping, gripping, pinching, etc. the thumb always plays a different role to the rest of the fingers wherein many studies have explored the role of the thumb. Among various other reasons, maintaining stability is one major role of thumb when coordinating with other fingers [11]. Wang et al. designed soft pneumatic actuators for thumb movements in terms of flexion and abduction-adduction, which could realize multiple degrees of freedom for the thumb and further made use of the limited space of the hand's dorsal side [12]. In [13], a ball-joint thumb, together with a palm arch has been designed to realize dexterous in-hand manipulation of complex objects. Some researches considered the natural and implicit coordination between the supernumerary robotic (SR) fingers and the human fingers [14]. Similar work can be also found in [15], where an extra robotic thumb and exoskeleton robotic fingers have been used on patients with hand function disability.

For the close approximation of humanlike dexterity, learning from human hand manipulation of data and understanding the underlying mechanisms inside a task can be direct and efficient. On the other hand, real human data can be considered one of the most powerful tools for artificial hand design. A kinematic model of the human thumb with a foldable palm was proposed in [16], and an NDI Aurora electromagnetic tracking system and 6-DOF sensors were used to measure the thumb tip and Metacarpophalangeal (MCP) joint movement. The essential musculoskeletal behaviors in humans during grasping were analysed in this work. However we still lack knowledge in fine manipulation tasks which involve soft objects such as paper. Hence in this work, we focus on how pressure is modulated in a page turning task.

B. Wearable hand device and data collection

In this work, we made an effort to understand how human fingers coordinate for fine-grained manipulation through data capture of participants executing exemplar tasks. There are many existing wearable hand devices, but most focus on extending or aiding the human hand's ability. In [15], a wearable orthotic robot namely extra robotic thumb and exoskeleton robotic fingers was used to assist people whose thumb could not be moved and whose other four fingers had diminished function. Towards this end, electromyography (EMG) sensors were attached to the elbow to recognise and respond to the user's command. In this study, hand gestures can be interpreted by the Myo Armband. Another thumb exoskeleton was used to assist the thumb by providing a large range of motion in [17]. In this work, the motion of the human thumb was captured by an active marker motion capture system (PhaseSpace Inc.). An electromechanical robotic exoskeleton was designed for the rehabilitation of the wrist joint and MCP joint in [18]. The Supernumerary Robotic (SR) Finger proposed in [14], is a wrist-mounted robot to aid humans in performing prehensile tasks. It reads the hand posture using the positions of joints such as the wrist, the fingertips, and finger joints which are measured by a ShapeHand data glove by Measurand. Changes in neural body representation driven by the robotic hand augmentation were studied in [19], while motion control and compliance of a supernumerary robotic finger were shown in [20]. However, certain tasks can benefit from tactile information with zero or limited kinesthetic information. Towards this end, we focus on the active components during a fine task: the thumb and forefinger and their coordination using pressure application. We propose a novel wearable soft sleeve for human fingers based on embedded fluidic pressure sensors to read pressure information across finger pads and the relative behavior of fingers during a selected fine manipulation task.

III. Skin, tactile stimuli and pressure

A. Background

Fine manipulation tasks essentially require precise and delicate control of objects which often involves intricate movements and coordination of hands. While robots at present have excelled at many tasks, certain fine manipulation activities remain challenging. The reason for this is the complexity of human-like dexterity and sensory abilities. Some challenging fine manipulation tasks for robots include page turning, playing string instruments, preparation of food, art and crafts, and handling fine tools [21], [22]. Lack of precise coordination, tactile sensing, controlled force, hand-eye coordination, need for tactile feedback, intricate finger movements, adaptability, sense of timing, touch, and force modulation are the reasons behind this, which can be challenging for robots to replicate. Furthermore, these tasks involve a range of intricate movements, sensitivity to varying forces and textures, and often the need for real-time adjustments based on tactile

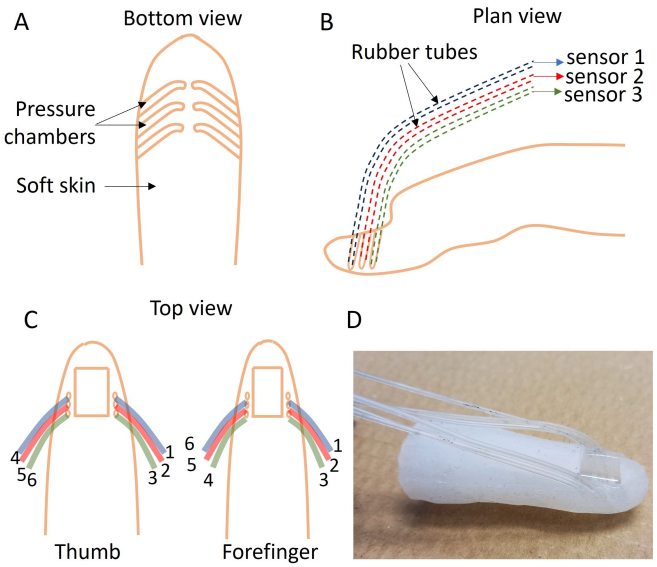


Fig. 2. A, B and C shows the bottom, side and top view of the arrangement of pressure chambers in soft sleeves D) The actual soft sleeve which is worn around the finger

feedback—all areas where robots still face challenges in replicating human-like skills and dexterity.

B. Methods

To capture this information we created a wearable soft sleeve that goes on the thumb and forefinger of a person to analyse the pressure modulation at pads during a fine modulation task. We selected page-turning as our task and analysed how the pressure at the fingertips is being modulated. We intend to explore how such an interpretation of pressure could be used for soft robotic manipulation in the future.

Turning a page in a book without damaging it involves a balance of forces and an understanding of the physical and biological aspects related to the paper and the hand. In addition, the attempt to turn a page gives a lot of information on how to proceed and adapt. Sometimes additional support, in addition to two fingers might be needed to complete the task successfully.

From a biological perspective, the sensitivity of one's fingers allows the application of the correct amount of pressure and control when turning the page. Human fingertips have a high concentration of touch receptors, which help gauge the amount of force required to turn the page without causing damage. From a physical perspective, it is essential to understand that paper is a delicate material. The forces applied when turning the page should be kept below the threshold, which causes the paper to tear or deform. By distributing the force evenly and turning the page slowly, the risk of damage to the paper was minimized. A close look at this task is given in Fig. 1 including the arrangement of fingers and the hand, and the force acting on a finger during the task of turning pages of a book.

IV. Soft Wearable Sleeves

The wearable sleeves used to capture data for the study are shown in Fig. 2. Two sleeves were made of Silicone (Ecoflex 00-30) by mixing parts A and B at a ratio of 1:1. To avoid restriction of finger joints, the length of the sleeves was determined to cover about three-quarters of a finger. The six pressure chambers were positioned at the tip of the finger to get as much information as possible from an interaction between the skin and a surface. The design of the sleeve and placement of sensors have been extensively discussed in our previous work presented in [23]. However, the difference between the two hardware used in our present and past work is that we left the inside of the finger hollow for present experiments. In our previous work, we filled the inside of the silicone sleeve with a 3D printed (PLA) bone inspired by the phalanges of a human finger. We tried to concentrate an adequate number of sensors towards the fingertip as the interaction between the skin and external body; in this case, the book, occurs around the pad. For safety reasons, electronics were placed in a separate assembly to avoid contact with the user's skin. Adjustable straps have been used to attach this assembly to the participant's hand. Due to the compressibility of air, an optimal length has been chosen for the tubing to reduce air compression within the tubes or air chambers. Therefore the plastic assembly has been attached as close as possible to the palm. However, the assembly has been designed considering the shape of the palm, not to restrict the finger movements during the given task. The two sleeves used in this experiment are identical.

Rubber tubes attached to the sleeve lead to absolute pressure sensors (MPXH6300A) attached to the electronics assembly. Data from these sensors were read by an analog-to-digital converter (ADS1115) and are interpreted by the controller. Each sleeve consists of 6 tubes in which the pressure is converted into pressure data. This pressure data was collected from the 6 barometric pressure sensors. Pressure data was collected every 0.1 s. Altogether we analysed pressure data from 12 channels attached to 12 absolute pressure sensors. A moving average filter of a window size of 3 has been applied to data to reduce noise. The pressure range of the pressure sensors is 20-300 kPa. The thickness of the soft skin around the pad of the finger is approximately 2mm.

The sleeve was inverse molded with silicone (shore hardness 00-30) poured into 3D-printed molds. This consisted of 6 cavities into which rubber tubes were inserted later and the gaps were sealed with Silicone. These rubber tubes act as pressure chambers which lead to barometric pressure sensors assembled with the other electronic components that go on top of the user's hand. A detailed illustration of how the fingertip of the sleeve was designed is shown in Fig. 2. Fig. 3A shows the entire assembly of the wearable together with the electronics and the soft sleeves and 3B shows how it is worn on a hand before a task. Fig. 4 demonstrates how the wearable looks on a user while turning pages of a book.

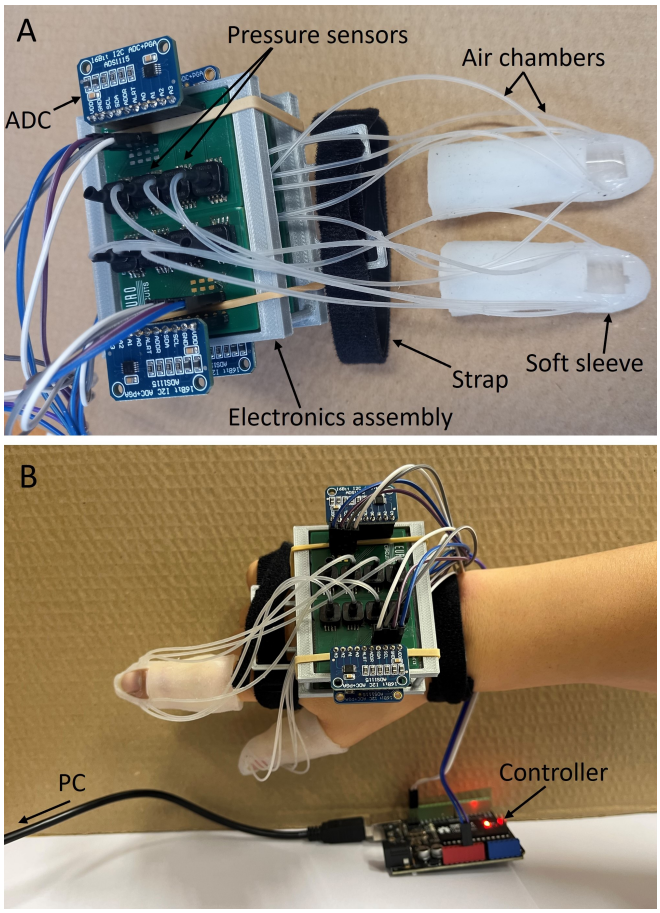


Fig. 3. Wearable setup used for the experiments A) Wearable sleeves for the thumb and forefingers together with the electronics assembly B) A demonstration of the hand with the wearables on, before performing the selected task

V. Human Study

A. Experiment

The experiment involves analyzing the pressure patterns applied by individuals while performing a fine motor task, for instance turning pages of a book, using a soft sleeve wearable on the thumb and forefinger. This method allowed the measurement and recording of pressure patterns using barometric pressure sensors attached to each sleeve. The primary goal was to understand how humans apply pressure with their fingertips during fine motor tasks, such as page-turning. By using the soft sleeve wearable equipped with sensors, we aimed to capture and analyze the pressure variations across the fingertip during this specific action.

The experiment involved 7 participants (4 male, 3 female, mean age-28.85, SD-7.12). Participants were tasked with wearing the soft sleeve on their thumb and forefinger and instructed to turn the pages of a book one by one. This continued until 10 pages were turned. Pressure readings of the barometric pressure sensors were collected for the entire duration where they turned all the pages successfully. Only the successful events were used for further analysis of results. Soft sleeve wearable and the controller were the key components used in this study. It's designed to be worn on the thumb and forefinger, providing a comfortable interface between the sensors and the skin. The sleeve contains barometric pressure sensors (a total of six sensors on each sleeve) strategically placed to detect and record pressure patterns spread over the finger pad. We provided participants with 5 different paper weights for this task: 60, 75, 80, 100, and 160 GSM. The participants would consecutively turn 10 pages, allowing the sensors to capture the pressure variations, changes, and patterns generated by their fingertips during this action. An example scenario when a participant was performing the given task with the wearable on is shown in Fig. 4.

When the participant reached the final page, paint was applied on the pads of the sleeve before performing the task. The paint was applied only on the area covered by the pressure chambers which leads to barometric pressure sensors. Hence we could observe where the page is touched by each finger during the page turning task.

The data collected from the six sensors on each sleeve will be thoroughly analyzed. This analysis would involve examining pressure variations, patterns, and the distribution of pressure on the thumb and forefinger during different stages of the page-turning process.

From this data, we could derive insights into how humans apply pressure during fine motor tasks involving their fingertips, specifically in the context of turning pages. This information could have implications for various fields such as ergonomics, robotics, prosthetics, or human-computer interface design. These results are analysed thoroughly in section V-B. This information is hence used to select one among a set of human-inspired primitives, which define the evolution of the soft hand posture as a combination of anticipatory action and touch-based reactive grasp.

This study underwent a light touch ethical review and was granted approval by the Research Office of the Department of Engineering-University of Cambridge. A light touch review was deemed appropriate due to the minimal risk posed to participants, involving only non-invasive procedures and anonymised data collection. All participants provided informed consent, and measures were taken to ensure the confidentiality and privacy of participant data throughout the

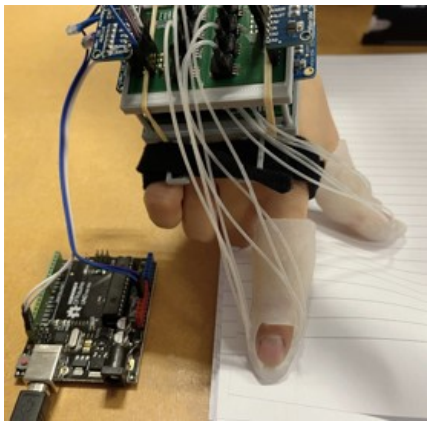


Fig. 4. How a participant turned pages of a book with the wearable on

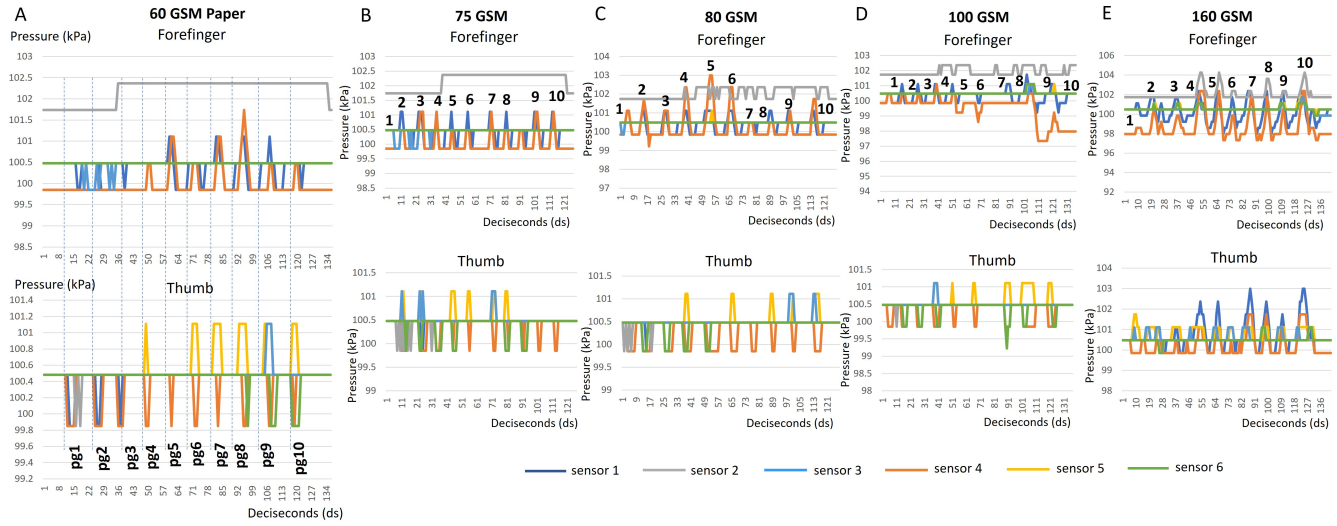


Fig. 5. Pressure recorded by the sensors on each sleeve is plotted against time for a single participant when turning 10 pages and this has been repeated for papers with different weights. Each color indicates a sensor out of 12 sensors attached to 2 fingers. pg1-pg10 denote the event of each page turning from page 1 to page 10. Numbers in bold on the graphs denote the event of each page turning as well. A-E denotes the pressures recorded at each sensor over time during the 10 events (page turns) for the paper weights 0, 75, 80, 100 and 160 respectively. One event is considered as one successful attempt to turn a page.

research process.

B. Results and discussion

Pressure variations inside the chambers during the 10 attempts of page turning were recorded and plotted against time as in Fig. 5. This shows the pressure variations recorded for one participant for different paper weights. Page numbers are indicated on the plot against each spike which identifies each page turn. Sensors 2, 3 and 4 in the forefinger were able to capture more pressure according to the plots. Similarly, sensors 4, 5 and 6 in the thumb have been widely pressed during the task. It can also be seen that the forefinger has been used more, hence the pressure variations are more prominent here. While the thumb has been supportive, a large variation of pressure values could not be observed in the thumb as in the forefinger.

Variation of minimum and maximum pressure variations of a participant for the given set of paper types is plotted in Fig. 6. We observed a noticeable difference in the pressure applied on each finger during this task. Minimum and maximum pressure variations for the entire group of participants have been plotted against paper weight in Fig. 7A and B. A minimum and maximum pressure of 97.33 and 104.25 kPa have been observed for the forefinger. Similarly, a minimum and maximum pressure of 99.22 and 102.99 kPa have been observed for the thumb. Overall pressure experienced by the forefinger during the task has surpassed that of the thumb for most of the cases. When the weight of the paper increases, the force applied on the forefinger has been increased while this isn't the case for the thumb. This fact can be further studied from the plot in Fig. 7C. This shows the average pressure variation for all the participants during all their attempts (10*7 events for each sensor and there are 12 sensors). When the paper weight increases, the average pressure applied on the forefinger increases rapidly and that of the thumb increases slowly. Hence it can be deduced that the passivity of the thumb increases as the forefinger becomes more active. Therefore the combination of active and passive organs/parts for fine tasks such as turning pages of a book will be an inspiration for soft robotic hands in the future. Furthermore, there is an observable difference in the pressure applied on papers with different weights. Pressure applied on paper increased as its weight

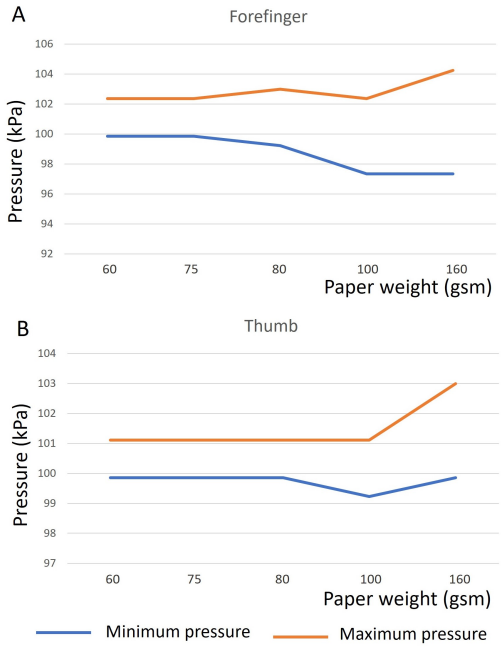


Fig. 6. Variation of minimum and maximum pressure recorded for all 10 events of a participant, plotted against time.

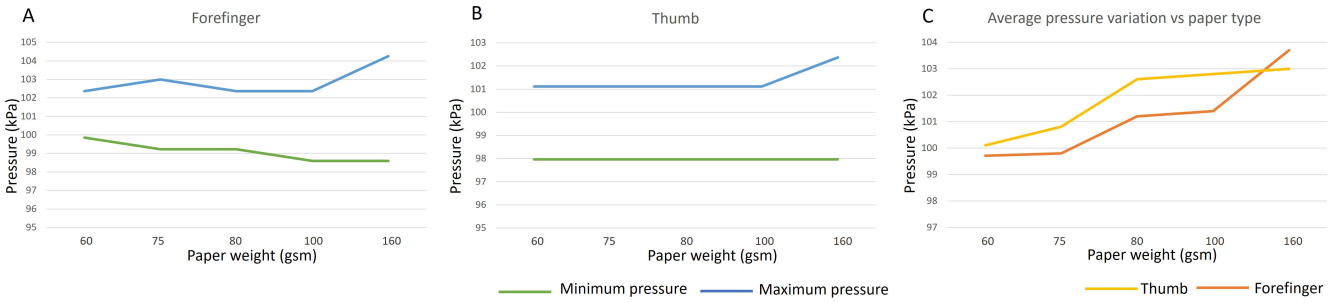


Fig. 7. A) Recorded minimum and B) maximum pressure values recorded for all the participants for all the events, plotted against time C) Average pressure variation plotted against time during the entire experiment

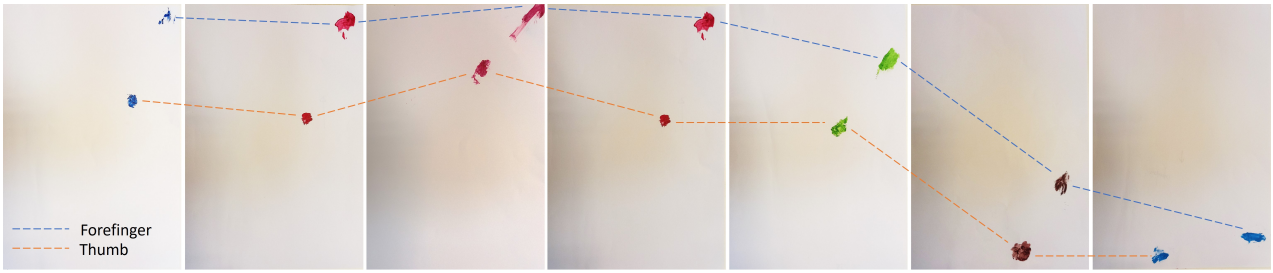


Fig. 8. Thumb and forefinger prints retained after each participant attempted turning a page. All these prints are recorded on 60 GSM paper.

increased.

Fingerprints retained from each attempt by the seven participants are shown in Fig. 8. It is worth observing that all the participants either went for the top right or bottom right corner when they attempted to turn the page. While some attempted slightly beneath the edge, some went to the very edge of the paper. When measured the angle between the thumb and forefinger prints w.r.t. the horizontal edge of the paper, it was within the range of 45-75°, with an average of 59.7° and a standard deviation of 12.73. Two out of seven participants went for the bottom right of the page and for them, this angle was within 15-25°, with an average of 17.5° measured from the horizontal edge of the page. We assume that these ranges will be useful for the finger coordination of a soft robotic finger for better accuracy.

From Fig. 5, it could be seen that some sensors have been triggered more than the rest. For instance, sensors 4, 5 and 6 in the thumb and sensors 2, 3 and 4 in the forefinger are noticeable upon the rest of the sensors in generating patterns during each turn. This numbering is according to Fig. 2. Fig. 9 illustrates this idea. The thumb and forefinger of a right-handed person has been considered for this demonstration and the areas where a higher pressure has been applied are highlighted. Sensors mostly active in the highlighted areas are mentioned in brown. While compliance at the fingertip plays a major role in achieving success in this type of task, the application of the right pressure is crucial to accomplish the task without causing damage to the pages/any other fine objects being manipulated.

1) Limitations: As air can be compressed, the chambers that lead to pressure sensors will be slightly compressed. Therefore the pressure reading of the sensor can be slightly drifted from the actual pressure inside the chamber. In addition, although light in weight, the wearable covers the entire back of the hand. hence the design will be improved in the future. This study covers pressure modulation related to only the thumb and forefinger which might be not the case for some people. Occasionally, people who tend to use middle and ring fingers for this task can be found. Therefore more studies should be performed to cover the overall pressure modulation for robots to mimic more human tasks.

2) Implications: Humans use various dexterous approaches for fine manipulation. Hence biomimicry can be challenging when all the possibilities are considered. Therefore there is a requirement of limiting or benchmarking this in the realm of robotic applications. Dynamics and implementation, power consumption and efficiency can be some common attributes to consider in this regard. Furthermore, acquiring humanlikeness for soft robots can sometimes be challenging given the number of options to mimic. Hence this type of studies could help realise humanlike motions in soft robots in performing fine, dexterous tasks with accuracy.

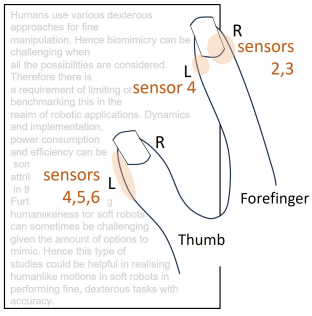


Fig. 9. Areas with higher pressure distribution during the task are marked here. R and L denote right and left sides of the hand respectively.

In addition to softness and flexibility, there are other aspects of soft robots that can be interesting to study in terms of achieving humanlike dexterous behaviors. We identified humanlike pressure modulation at the fingertips to be a motivation for achieving success in fine manipulation.

Results found that the function of a thumb in book reading is supporting the forefinger which makes it passive at some point in the task. Therefore it is worth considering that there can be a mix of passive and active fingers when designing hands for future robots. This can be true for manipulation tools in general, not only for fingers. However fine tasks involve a lot more parameters than we analysed during our study. Hence it is worth exploring deeply.

Furthermore, humans use various ways to turn the pages of a book. This analysed one particular way to combine the thumb and the forefinger in turning pages. Sometimes an individual might use different ways to turn pages at different times and this involves palms and different fingers. Therefore it is worth exploring all these possibilities comprehensively to see the best soft robotic approaches for motor coordination, task completion, energy efficiency, etc.

VI. CONCLUSIONS

In this paper, we presented a human study conducted to explore pressure modulation in humans when performing fine manipulation tasks. In this regard, we created a soft wearable sleeve to be worn on the thumb and index fingers to observe how humans modulate pressure when they turn the pages of a book. We investigated pressure patterns during the task through the use of barometric pressure sensors embedded in a soft wearable sleeve revealing intricate insights into fine motor manipulation. Analysis of the data highlighted distinct pressure distributions across the thumb and forefinger, indicating varying pressure dynamics during consecutive page-turning. Furthermore, we revealed that the passivity of fingers can vary across the timeline of a task as force requirements change. We believe that these findings hold promise for enhancing ergonomic design, human-machine interfaces, and rehabilitation strategies, offering potential applications in product development and further research into understanding and optimizing fine motor tasks in robots. Furthermore, this has the potential to be extended towards the generation of large-scale data sets for soft robots to perform fine tasks. Soft robots will retain a greater capability in this regard due to their compliance. In the future, more fine tasks will be analysed in depth to create effective soft robots.

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