ASSESSING THE DEXTERITY OF HUMAN HAND IN SOME DAILY MOVEMENTS THROUGH AN ACUPRESSURE AND CURVATURE DATA GLOVE

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Abstract

The human hand is a highly-precisely designed organ that helps us complete the most complex and delicate movements in our daily life. However, in the real world, people may lose part of their hand function. The rehabilitation of the patient's hand becomes extremely important. In this study we developed a wearable hand motion sensing system that combines curvature sensors and pressure sensors to assess the degrees of bending of fingers when people perform different hand motions and finger pressure. In this study, we first collected the data of curvature and pressure of people's fingers in various daily actions through the glove. We then investigated differences between finger curvature and pressure when people performed the same movements. Finally, we analyzed the similarities or differences in how people perform different activities of daily living. Experimental results show that people adjust how they use their fingers (curvature) and how they apply force (acupressure) depending on the size, material, and weight of the item. When people perform fine actions, certain fingers play an important role in both actuating force and auxiliary support. On the contrary, when the action requires relatively more force, some fingers play the role of action output and the others play the role of auxiliary support.

Keywords: *diagnosis, medical informatics, hand motion analysis, induction glove*

1. INTRODUCTION

The human hand is a highly-precisely designed organ. In addition to meeting our needs for many daily functions, it can also help us complete the most complex and delicate movements. However, in the real world, people may lose part of their hands due to trauma or endogenous diseases. This not only causes a lot of inconvenience and distress to the patient's daily life, but also may impact the patient's psychological trauma and regret. Under these circumstances, the rehabilitation of the patient's hand becomes extremely important. Traditional rehabilitation after hand injury does not have an objective system that can be used to assess the rehabilitation progress of patients after surgery. In the absence of proper rehabilitation information, the patient may suffer another degree of injury from inappropriate exertion.

However, before helping patients recover, we must first understand how normal people use and exert their fingers in different daily activities. A school of researchers suggests starting with the classification of hand movements [1] and hand-based functional assessment [2-5]. The research along this line basically belongs to the analysis and classification of static grasping data. Sometimes this classification is quite subjective. The main reason is that they have no dynamic grip data on the one hand, and no actual acupressure data (let alone acupressure dynamic change data) on the other. Under this limitation, it is difficult to actually understand how people use their fingers. Because of this, another school of scholars suggests using sensor gloves to actually collect data on the curvature and pressure of people's fingers in various daily movements and conduct further analysis from these data [6-10]. Several researchers have conducted investigations along this line of study [11-13]. In order to deeply understand the motion information of the whole hand, some investigators [14] even use several times more sensor elements than the above scholars to detect the motion information of the hand.

Currently relatively mature commercial and non-commercial data gloves include Manus Prime II Xsens [15], Cyber Glove III [16], 5DT DataGlove [17], Humanglove [18], IMU Smart Glove rev 2 [19], VR glove [20], ActionSense smart glove [21], Neofect's Rapael smart glove [22]. Each data glove has its own specific design and functionality, and of course its own pros and cons. Some emphasize the collection of curvature data, while others the collection of acupressure data. In addition, the curvature and pressure sensors used by each glove are not only different in number, but also different in the location where each sensor is installed. An up-to-date review of data gloves and its applications can be found in the literature [23-25]. However, these gloves are still not designed to be relatively economical for the average person in general.

We all know that the human hand is a highly delicate design. On the one hand, from an anthropometric point of view, everyone's finger structure (finger length and width) may be quite different. On the other hand, the usage habits of each person's fingers may also vary from person to person. In addition, the movements that people can perform with their hands, ranging from rough to fine, cannot be fully enumerated. Considering these factors, it is difficult to make a complete generalization of human hand movements using modern technology. With limited resources and time, when researchers focus on one end, the other end may be ignored. For example, while people focus on the use of finger curling, the use of acupressure may be slightly ignored. From another point of view, when the focus is on the precision of the instrument, one may lose the procedural handling of the operation. Of course, every researcher should take all the above factors into consideration and implement it carefully, however, it still has a problem. That is, people will move in a given known direction, but may ignore the possibility of exploring unknown areas (knowledge). The purpose of this paper is not to bring together state-of-the-art hand movement research techniques to produce concrete results with limited resources. If this were to be done, the project would be incredibly large and time-consuming, potentially becoming an impossible task. Because of this, the results obtained in this study are still part of the information on the delicate movements of the human hand.

Faced with the above problems, if there is an economical and non-invasive method that can be used to detect the pointing force and usage of the patient's hand at any time, it can more or less help the patient to a certain extent. The research team in this study developed a wearable hand motion sensing system (to be referred to as an induction glove) that combines curvature sensors and pressure sensors to explore the degrees of bending of fingers when people perform different hand motions (to be referred to as curvature) and finger pressure (referred to as acupressure). In this study, we first collected the data of curvature and pressure of people's fingers in various daily actions through the glove. We then investigated differences between finger curvature and pressure when people performed the same movements. Finally, we analyzed the similarities or differences in how people perform different activities of daily living.

2. MATERIALS AND METHODS

In this section, we presented the design of this induction glove. Before any actual data collection, we tested each sensor for its reliability and validity. Then we explained the attributes of the invited participants. After that, we described the experiments the subjects underwent. Finally, we explained how experimental data were collected for each subject and how the data were assessed.

2.1. Device

Figure 1 showed the schematic diagram of hand's kinematic structure that finger joints are further divided into distal phalanges (*DIP*), proximal phalanges (*PIP*), and metacarpal phalanges (*MCP*) [26]. However, we must emphasize that each finger, although flexible, still has its inherent limitations. For example, each finger can only bend forward (i.e., cannot bend left, right, and back). However, each finger can be moved slightly from side to side. Unlike the other four fingers, the thumb has a relatively large left and right movement range due to one more degree of freedom [27]. It is thus the thumb plays the role of a critical finger when holding objects. In particular, the flexion and strength of the thumb is more critical than the other fingers when performing various movements.

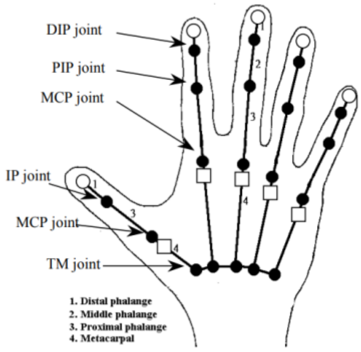

Figure 1. Schematic diagram of hand's kinematic structure [27].

The induction glove for this study was developed by manually sewing the curvature sensors and the pressure sensors on the glove made of polyurethane. After that, we connect these sensors to the Arduino Mega 2560 and use the sequence window provided in the Arduino IDE editor to capture the data. The Arduino Mega 2560 has 16 analog input pins and can accept 16 input signals. Five out of these 16 pins are connected to the curvature sensors while the remaining 11 pins are to the pressure sensors. A curvature sensor is sewn on the back of each finger near the joint to obtain the bending degrees of each finger when a person performs a certain action. A total of five curvature sensors are required for five fingers. In terms of finger pressure, each finger is connected to two pressure sensors. For the four fingers except the thumb, one of the two sensors is stitched above the DIP joint and the other is stitched below the MCP joint in each finger (as shown in Figure 1). Finally, considering that the thumb has more degrees of freedom than the other fingers, a pressure sensor is added below the IP joint of the thumb. The entire induction glove design is shown in Figure 2.

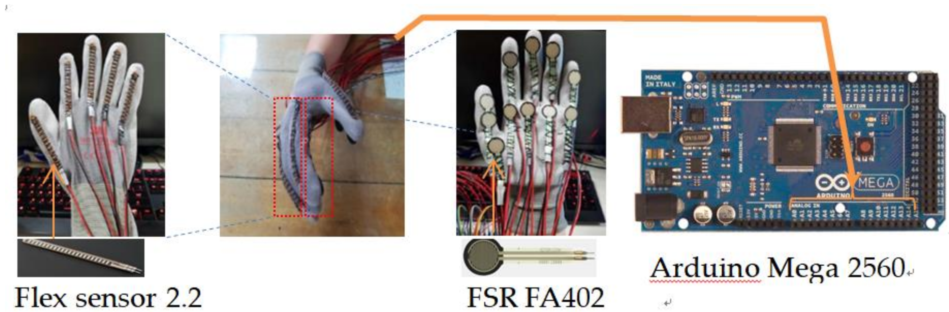

Figure 2. A homemade bending and pressure sensing glove. Flex sensor 2.2", a patented product of Spectra Symbol, shows an increase in the resistance as the sensor is flexed. FSR FA402, a patented product of Interlink Electronics, exhibits a decrease in resistance with increase in force applied to the surface of the sensor.

In order to enhance the sensing effect obtained by the sensor, we try to stick each sensor as tightly as possible to the glove during the sewing process. Plain stitch is the method used. This is the most commonly used needle method in daily life. Its basic requirement is that the stitches are uniform and neat. Using this sewing method can make the sensor and the glove close together to achieve a better sensing effect. However, although this method can obtain relatively good sensing results, its main disadvantage is that it cannot be changed according to the size of the subject's palm. In other words, this glove cannot be used to test subjects with large differences in palm size. Therefore, in terms of subject selection, only subjects who can apply to this glove were invited. We note that manual sewing may be a good option for custom perspective, especially for patients with hand rehabilitation needs.

There are two important factors in the production of gloves. The first is the choice of glove material, and the second is the way the sensor is sewn into the glove. In the choice of glove materials, this study has tried to use cotton, plastic and PU materials. The disadvantage of cotton gloves is that they are easy to be pulled, resulting in unstable sensor positions and poor sensing. Although plastic gloves do not have the shortcomings of cotton gloves, the subjects will be affected by the fit and flexibility of the gloves themselves when performing actions. This is because the friction between the fingers of the plastic glove is large, which makes it difficult for the subjects to stretch their fingers. When the subject needs to make a fist and other movements that require a lot of bending of the fingers, it will greatly limit the degree of bending of the fingers. After many tests, the glove MS-100M produced by 3M company does not have the above shortcomings (that is, the glove finally selected for use in this study). MS-100M is a foam-coated glove with excellent breathability, anti-slip, and oil-repellent properties. Its advantage is that the user can perform precise operations with the best feeling of wearing like an empty hand. Figure 3 shows how the sensor output nonlinearly changes in response to bending and pressure, respectively.

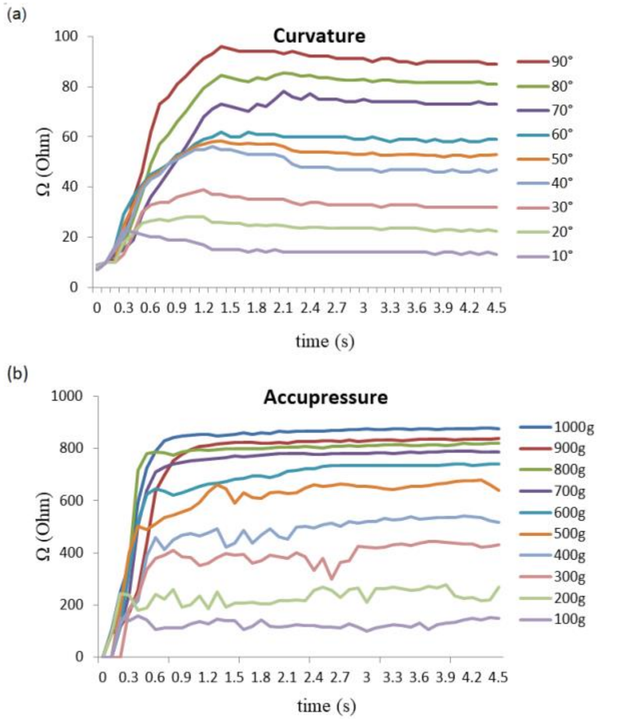

Figure 3. Sensor output changes in response to bending and pressure, respectively.

2.2. Experiments

This research refers to 32 people's daily life actions listed by [1] and selects 8 of them as the experimental actions of this study (Figure 4). These actions include taking a wine bottle, taking a flat water bottle, taking a mug, squeezing toothpaste, taking a ping-pong ball, taking a marble, holding a mouse, and writing a Chinese character. The above eight actions may be simply classified as grasping, squeezing, manipulating, taking, and writing. But from another perspective, it can be roughly divided into gross and fine movements. The above classification is only a rough way to classify. Strictly speaking, certain actions are difficult to categorize clearly.

hold a wine bottle | hold a flat water bottle | hold a mug | squeeze toothpaste

operate a mouse | hold a ping-pong ball | hold a marble | write a Chinese character

Figure 4. Eight daily actions

The following is a detailed explanation for each of these 8 daily actions. The first experiment was to let the subjects actually hold a wine bottle. The second experiment was to have the subjects actually hold a flat water bottle. The difference between these two bottles is that the former is made of plastic and the latter glass. In general, holding a flat water bottle requires more tactile information than holding a wine bottle. The third experiment was to let the subjects actually hold a mug with a handle. Generally speaking, there are many ways to hold a mug. In this study, the subjects were first asked to place their thumbs on the belt handles. They were then asked to place their little finger outside the belt handle and the remaining three fingers inside the belt handle. The above three actions (from the first to the third experiment) can be roughly classified as grasping actions. The fourth experiment was to ask the subjects squeeze toothpaste. There are many ways to squeeze toothpaste. In this study, the subjects were invited to put toothpaste on their four fingers (palms facing up), and then use their thumbs to squeeze out the toothpaste little by little.

Whether it is a grasping or squeezing action, the subjects may need to use the muscles of the upper and lower limbs to generate appropriate force to complete the action. From a certain perspective, these were movements that required force. Compared with the previous action, the following action experiment emphasized finer manipulations. The fifth experiment was to let the subjects operate the mouse. There are two important steps for ordinary people to operate a mouse. The first is that the subject must place the elbows at the sides of the body so that the forearms are parallel to the ground (their palms are facing down and the palms are in the position of the hand knife). The second step is that the subjects grasp the mouse with four fingers including the thumb, index finger, middle finger, and ring finger to operate (the little finger plays an auxiliary role). Because of this, the major difference between holding the mouse and any previous actions of holding an object is that it does not need to overcome the gravity of the object, but needs to use four fingers to hold the mouse to move and click.

The sixth experiment was to invite the subjects to use their fingers to hold a ping-pong ball (or called table tennis). We know that compared with the former, table tennis is relatively small and relatively light. In order for the subject to complete these movements, he (she) must use relatively fine-tuned movements to be able to pick it up. From a certain perspective, it means that they must exert a high degree of finger control, finger strength and finger coordination to complete the above action. In this study, the subjects were further invited to use two fingers to hold a marble (the seventh experiment). The requirement of this action is more delicate than the requirement of holding a ping-pong ball. This is because a marble is relatively smaller than a ping-pong ball. Also, it has a more rounded and smooth surface. It is generally believed that this is a rather delicate movement, which requires more delicate interaction between the fingers to complete the lifting of the marbles. In the eighth experiment, the subjects were asked to write a very special Chinese character "永" (Figure 5). This character has eight strokes: point, horizontal, vertical, hook, pick, bend, skew, and press. These eight strokes are the basic strokes in regular script. Each stroke has its own characteristics and echoes each other. This means that from the beginning of the first stroke to the closing of the last stroke, there is a trajectory that is interrelated and echoed between the strokes. In other words, the continuous strokes between the stippling and painting make the whole character flow smoothly. In writing this Chinese character, a high degree of brushstroke skills are required to complete the writing of the character.

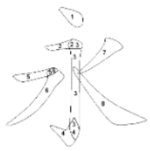

Figure 5. Eight strokes of the special Chinese character

2.3. Data Collection and Assessment

The entire experiment of this study is to invite each of the 30 subjects to perform the above-mentioned 8 actions. In order to achieve the consistency of all subjects performing the same actions, this study pre-recorded a video tape of each action in advance. During the data collection phase, the subjects were asked to watch and perform the same actions according to the instructions of the tape. For the same action, each subject was asked to perform four times. When the subjects completed each run of the experiment, they were allowed to rest for 30 seconds before continuing to the next run of the experiment. In each experiment, curvature and acupressure data were collected at a rate of 10 sets per second. The duration time of performing each action is five seconds. Therefore, each experiment has a total of 50 sets of curvature and acupressure time series data. This study used Pearson correlation (*CR*) analysis to explore the similarity of two time series data. Through it, we can understand the similarity of the same action between two different people from the beginning to the end of the action. We call it dynamic time series data analysis. Equations 1 and 2 show how to calculate the *CR* values from the collected curvature and acupressure time series data (C_{srt} and P_{srt} represent the curvature and acupressure data, respectively, when the s^{th} subject performs a certain action for the r^{th} operation). The higher the value is, the more similar the process of the subjects performing the same action.

The investigation of time series data helps us understand the changes in the curvature and pressure of the subject's fingers throughout the action. However, sometimes the maximum finger curvature and pressure for the subjects to perform an action is also important. Because of this, we find the maximum value of a certain action for each person, and then take the average of all as the value of that action. We call this static maximum data analysis. Equations 3 and 4 show how to calculate the average curvature μ_c and average pressure μ_P from the maximum values of the 30 subjects. Then, we calculated the standard deviation of curvature σ_c and the standard deviation of acupressure σ_p.

$$CR_c = \overline{\sum_{\substack{s_i=1,\\ s_j=1}}^{30} \sum_{r=1}^{4} \frac{\sum_{t=1}^{50}(C_{s_irt}-\overline{C_{s_irt}})^2 (C_{s_jrt}-\overline{C_{s_jrt}})^2}{\sqrt{\sum_{t=1}^{50}(C_{s_irt}-\overline{C_{s_irt}})^2}\sqrt{\sum_{t=1}^{50}(C_{s_jrt}-\overline{C_{s_jrt}})^2}}} \quad (1)$$

Where s_i, s_j=1,2 ,…,30; *r*=1,2,3,4; *t*=1,2,…,50

$$CR_p = \overline{\sum_{r=1}^{4} \sum_{\substack{s_i=1,\\ s_j=1}}^{30} \frac{\sum_{t=1}^{50}(P_{s_irt}-\overline{P_{s_irt}})^2 (P_{s_jrt}-\overline{P_{s_jrt}})^2}{\sqrt{\sum_{t=1}^{50}(P_{s_irt}-\overline{P_{s_irt}})^2}\sqrt{\sum_{t=1}^{50}(P_{s_jrt}-\overline{P_{s_jrt}})^2}}} \quad (2)$$

Where s_i, s_j=1,2 ,…,30; *r*=1,2,3,4; *t*=1,2,…,50

$$\mu_c = \overline{\sum_{i=1}^{30} \max_{\substack{1\le r\le 4\\ 1\le t\le 50}} C_{s_irt})} \qquad \sigma_c = \sqrt{\sum_{i=1}^{30}(\max_{\substack{1\le r\le 4\\ 1\le t\le 50}} C_{s_irt} - \mu_c)^2} \quad (3)$$

$$\mu_p = \overline{\sum_{i=1}^{30} \max_{\substack{1\leq r\leq 4 \\ 1\leq t\leq 50}} P_{s_i rt}} \quad \sigma_p = \sqrt{\sum_{i=1}^{30} \left(\max_{\substack{1\leq r\leq 4 \\ 1\leq t\leq 50}} P_{s_i rt} - \mu_p \right)^2} \qquad (4)$$

3. RESULTS

Generally speaking, for a certain action, if a finger has obvious force in acupressure, we will call it an actuating finger. In contrast, if it is an auxiliary finger, it will not have a significant value in acupressure, but will show a relatively high value in curvature. However, if a finger has significantly high values in both acupressure and curvature, the finger will have both actuating and auxiliary functions. The following description will be discussed from the perspective of the actuating and auxiliary functions.

In the experiment of the subjects grasping a wine bottle or a water bottle, the results show that the five fingers except the little finger have relatively high CR_c values. This result indicates that all fingers, except the little finger due to individual habit, play an important auxiliary role in the posture of grasping objects. But if we look at the temporal variation of finger pressure, we can find that the CR_p value of each finger (including the little finger) is relatively high. This result (Figure 6) shows that each finger acts as an actuating finger to prevent items from falling.

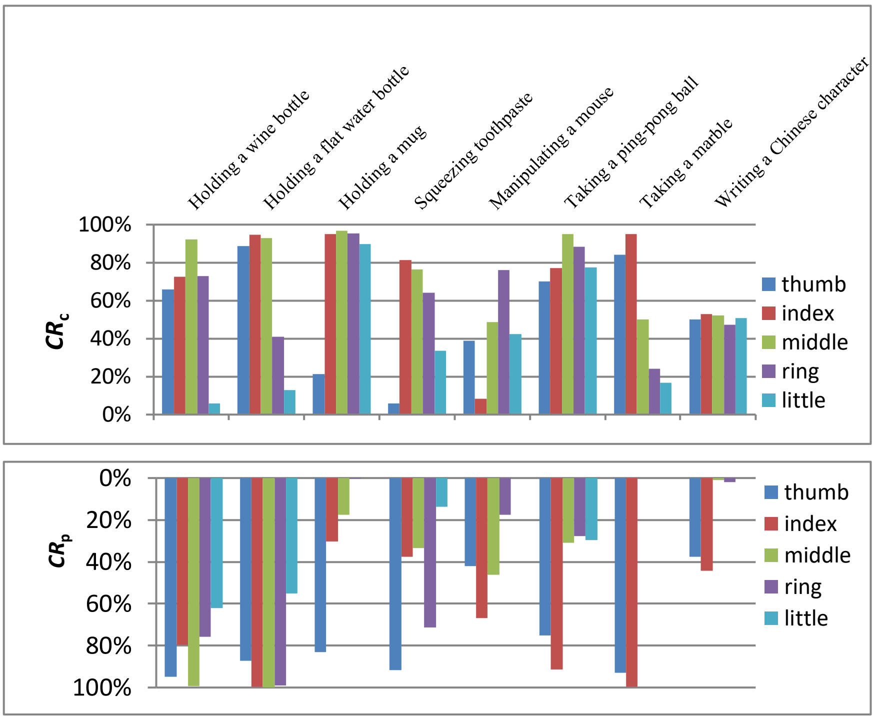

Figure 6. CR_c and CR_p values of each finger on 8 actions

When the action was changed to holding a mug or squeezing toothpaste, except the thumb, the remaining four fingers showed relatively high CR_c values. In other words, the four fingers other than the thumb play the role of assisting in stabilizing the object in these two movements. However, if we look at the CR_p value, we can see that the value of thumb is very consistently high. This result indicates that the thumb is the main actuating finger and the other four fingers are the fingers that assist in stabilizing the object.

Regarding the action of operating the mouse, the most obvious difference between it and the above four actions is the index finger. Among the five fingers, the index finger had the lowest CR_c value but had the highest CR_p value. This is because the index finger is the primary actuating finger (which the user uses to tap the computer screen). We can also see that the CR_c values of the four fingers except the index finger are not very high, but they are basically maintained at a certain level. This means that these four fingers act as an aid to stabilize mouse operations (including movement).

The following two experiment are to invite the subjects to take a ping-pong ball or and a marble. These two items are relatively smaller and lighter than the items taken in the previous experiments. What is more difficult is that the surfaces of these items are round and fairly smooth. Since the surface material of the induction glove designed by our team is plastic, everyone needs to treat it with caution. In order to hold these items, subjects must use a relatively meticulous manner to hold these items in their hands. In other words, they must exert a high degree of finger control, finger strength and finger coordination to complete the above actions. The results show that, in the case of holding a ping-pong ball, the curvature of each finger exhibits a high degree of similarity during actuation. This result is slightly different from the predictions made before the experiment. From the size of a ping pong ball, we would expect to only be able to hold it with our thumb, index and middle fingers (probably not needing the ring and pinky fingers at all). However, the results of this experiment showed that it still required the tester's thumb and four other fingers to complete the action of holding the ping-pong ball. This result shows that there are no fingers that need not be involved in order to perform a certain action. Instead, each finger requires the participation and cooperation of the other fingers to achieve a comfortable and stable posture.

Among the five fingers, the CR_p values of the thumb and index finger are particularly high. This result shows that all fingers are involved in holding the ping-pong ball to some extent. However, the main actuating fingers are the thumb and index finger. This result is interesting because it means that most subjects will make good use of the curvature of each finger to achieve the effect of holding a ping pong ball. However, in terms of force, it must rely on the cooperation of the thumb, index finger and middle finger to use the acupressure function to complete the task of picking up ping-pong balls. Holding a ping pong ball is a very balanced exercise that requires a high degree of finger control and coordination to achieve. Among the five fingers, the thumb and forefinger play the role of the main actuating fingers, while the remaining three fingers play the auxiliary role.

This study further invited the subjects to do the action of holding a marble, which is a more delicate action than holding a ping-pong ball. The difference is that holding a ping-pong ball is generally a three-finger grasp (thumb, index finger, middle finger), while holding a marble is a two-point grasp (thumb, index finger). In addition, while marbles are slightly heavier than ping pong balls, they are relatively small and have a rounded and smooth surface. In general, holding a marble requires finer, more coordinated finger control than holding a ping pong ball. The CR_c of the thumb and index finger are the highest two of the five fingers, while the remaining three fingers decrease with the distance from the index finger. This is because the five fingers are the role of matching each other to complete the auxiliary stabilizing item. However, in terms of CR_p values, only the thumb and index finger have relatively high CR_p values. That is to say, the subjects used the thumb and index finger as the main actuating fingers, while the middle finger played the role of auxiliary stabilization. It should be added here that since the marble is not very large and not very heavy, people can easily pick it up with only the thumb and index finger. But we know from experimental results that there are no fingers that need not be involved when performing an action. Instead, each finger requires the participation and cooperation of the other fingers to achieve a comfortable and stable posture. Therefore, it can be seen from the experimental results that the curvatures of the other three fingers except the thumb and index finger also show a certain correlation, but they decrease with the increase of the distance from the index finger.

The experimental results of writing the Chinese character showed that each of the five fingers had a CR_c value close to 50%. This value is neither too high nor too low. It shows that, although it cannot be said to be very similar, each person has a certain similarity in the stable holding pen and writing posture. By contrast, from the CR_p value, only the thumb and the index finger have high similarity. The summary is that the five fingers have little difference in the performance of all subjects in terms of curvature, but there are obvious differences in the performance of acupressure. This result is very similar to that of holding a marble. That is, the thumb and index finger are the primary actuating fingers, while the other three fingers play auxiliary roles.

4. DISCUSSION

We note that the contribution of any study to the sensor forum can be discussed from the technical and scientific aspects. From a technical perspective, research in this area emphasizes that the sensor is a tool. In this direction of thinking, it emphasizes how to increase the integrity of a tool, or how to progress towards the state-of-the-art. Accuracy and standardization are indispensable requirements. However, if viewed from a scientific level, the emphasis is on the discussion of its fields of application and possibilities. Under this kind of thinking, people may be more concerned about how to involve different people and apply it in different fields. The advantage of this approach is that it opens up the possibility of finding possible answers (explanations) or some heuristics to unknown areas of knowledge. The most obvious example is the results of people's research on drugs. We know that the ultimate effect of some drugs can be quite different from what was originally expected. As mentioned earlier, there is currently no generally accepted standard method and sensing tool for studying human hand movements. The main reason is due to the difficulty of the complexity of the problem. Even with the most advanced tools, it's still not enough to cover all situations. Under this premise, the conclusions drawn from any research are still fragmented answers. However, when more people are involved, research in this area will gradually mature. It also gets more and more answers because more people can participate with relative ease and willingness. When knowledge is accumulated to a certain level, a seemingly complex problem will lead to a better understanding of human hand movement due to more participation. This is basically the core of this research to establish this topic.

5. CONCLUSIONS

The function of the hand plays an important role in everyone's life. It is also an essential tool for each of us to survive. If a set of data collection of hand movements can be established, it can on the one hand help us understand how humans use our precious hands to complete the movements needed in daily life, and on the other hand provide people in need to understand their rehabilitation at different stages. However, human hand movements are dynamic rather than static. This means that information on finger curvature and acupressure must be collected simultaneously during the movement. More importantly for the subject, it must be non-invasive and avoid causing any discomfort. The last thing to consider is that it must be relatively economical and affordable by the general public.

Considering the above factors, this study therefore hopes to explore the hand information of eight movements in people's daily life using a low-cost homemade hand curvature and finger pressure sensing device (only a few hundred dollars). This home-made glove-sensing device, while not a high-precision instrument, helps provide simple, affordable "just-in-time sensing" information to patients in need. This research direction hopes to lead more scholars to invest in understanding the mysteries of human hand activity through affordable self-test tools.

There are two future research directions. The first is to continuously increase the repertoire of sensory data to establish healthy human hand activity norms. In addition to the 8 activities of daily living used in this study, this study recommends more data collection on other hand movements. The second direction is to allow patients to compare rehabilitation outcomes at different stages under the guidance of clinicians. In this way, we can see whether he (she) has been improving clinically through the data provided by this system, that is, whether the patient's hand function is improving. This is a more objective analysis, which is its real practical application. Finally, in the future, we hope to collect enough data on the use of this technology to integrate AI systems into this field of research and to further capture the specific biological characteristics of individuals.

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REFERENCES

1. Feix, T.; Romero, J.; Schmiedmayer, H.-B.; Dollar, A. M.; Kragic, D. The grasp taxonomy of human grasp types. IEEE Trans. Human-mach. Syst. 2015, 46(1), 66-77.
2. Orbai, A.M.; Smith, K.C.; Bartlett, S.J.; de Leon, E.; Bingham, C.O. 'Stiffness has different meanings, I think, to everyone': Examining stiffness from the perspective of people living with Rheumatoid Arthritis. Arthritis Care Res. 2014, 66, 1662–1672.
3. Ghosh, S. Capturing Human Hand Kinematics for Object Grasping and Manipulation; Texas A&M University: College Station, TX, USA, 2013.
4. Lee, K.S.; Jung, M.C. Ergonomic evaluation of biomechanical hand function. Saf. Health Work 2015, 6, 9–17.
5. Dipietro, L.; Sabatini, A.M.; Dario, P. Evaluation of an instrumented glove for hand-movement acquisition. J. Rehabil. Res. Dev. 2003, 40, 179–189.
6. Davarzani, S.; Pajouh, M.A.A. Design and Fabrication of Sensing System for Rehabilitation of Finger. In Proceedings of the 2020 28th Iranian Conference on Electrical Engineering (ICEE), Tabriz, Iran, 4–6 August 2020.
7. Abbas, S.; Condell, J.; Gardiner, P.; McCann, M.; Todd, S.; Connolly, J. Can multiple wearable sensors be used to detect the early onset of Parkinson's Disease? In In Proceedings of the 2020 31st Irish Signals and Systems Conference (ISSC), Letterkenny, Ireland, 11–12 June 2020.
8. Lin, B.S.; Lee, I.J.; Yang, S.Y.; Lo, Y.C.; Lee, J.; Chen, J.L. Design of an Inertial-Sensor-Based Data Glove for Hand Function Evaluation. Sensors 2018, 18, 1545.
9. O'Flynn, B.; Sachez-Torres, J.; Tedesco, S.; Downes, B.; Connolly, J.; Condell, J.; Curran, K. Novel Smart Glove Technology as a Biomechanical Monitoring Tool. Sens. Transducers 2015, 193, 23–32.
10. Lin, B.S.; Lee, I.J.; Chiang, P.Y.; Huang, S.Y.; Peng, C.W. A Modular Data Glove System for Finger and Hand Motion Capture Based on Inertial Sensors. J. Med. Biol. Eng. 2019, 39, 532–540.
11. Connolly, J.; Condell, J.; O'Flynn, B.; Sanchez, J.T.; Gardiner, P. IMU Sensor-Based Electronic Goniometric Glove for Clinical Finger Movement Analysis. IEEE Sens. J. 2018, 18, 1273–1281.
12. Lin, B.S.; Lee, I.J.; Chen, J.L. Novel Assembled Sensorized Glove Platform for Comprehensive Hand Function Assessment by Using Inertial Sensors and Force Sensing Resistors. IEEE Sens. J. 2020, 20, 3379–3389.
13. Pham, T.; Pathirana, P.N.; Trinh, H.; Fay, P. A non-contact measurement system for the range of motion of the hand. Sensors 2015, 15, 18315–18333.
14. Sundaram, S.; Kellnhofer, P.; Li, Y.; Zhu, J.-Y.; Torralba, A.; Matusik, W. Learning the signatures of the human grasp using a scalable tactile glov. Nature 2019, 569, 7758, 698-702.
15. Manus. Manus Prime 2 Xsens. 2020. Available online: https://manus-vr.com/xsens-gloves (accessed on 24 December 2020).
16. Cyber Glove System. Cyberglove III. 2020. Available online: http://www.cyberglovesystems.com/cyberglove-iii/ (accessed on 12 January 2021).

17. 5th Dimension Technologies, 5DT. 2020. Available online: https://5dt.com/5dt-data-glove-ultra/ (accessed on 25 December 2020).
18. Rashid, A.; Hasan, O. Wearable technologies for hand joints monitoring for rehabilitation: A survey. Microelectron. J. 2019, 88, 173–183.
19. Tyndall National Institute. Tyndall IMU version 2. Tyndall National Institute. 2015. Available online: https://www.tyndall.ie/biomechanics-and-motion-monitoring (accessed on 12 January 2021).
20. Tyndall National Institute. VR Glove. Tyndall National Institute. 2017. Available online: https://www.tyndall.ie/funded-programmes/vr-glove/ (accessed on 20 November 2020).
21. Condell, J.; Connolly, J.; Young, W. Action Sense. 2020. Available online: https://www.actionsense.org/ (accessed on 1 November 2020).
22. Neofect. Rapael smart glove. 2020. Available online: https://www.neofect.com/us/blog/stroke-rehabilitation-is-now-fun-thanks-to-rapael-smart-glove (accessed on 12 December 2020).
23. Rashid, A.; Hasan, O. Wearable technologies for hand joints monitoring for rehabilitation: A survey. Microelectron. J. 2019, 88, 173–183.
24. de Pasquale, G. Glove-based systems for medical applications: Review of recent advancements. J. Text. Eng. Fash. Technol. 2018, 4, 286–295.
25. Henderson, J.; Condell, J.; Connolly, J.; Kelly, D.; Curran, K. Review of Wearable Sensor-Based Health Monitoring Glove Devices for Rheumatoid Arthritis. Sensors 2021, 21, 1576. https://doi.org/10.3390/ s21051576.
26. Cotugno, G; Althoefer, K.; Nanayakkara, T. The role of the thumb: study of finger motion in grasping and reachability space in human and robotic Hands. IEEE Trans. on Syst Man Cyber, vol. 47, pp. 1061-1070, 2017, doi: 10.1109/TSMC.2016.2531679.
27. Fahn, C.-S., & Sun, H. Development of a Dataglove With Reducing Sensors Based on Magnetic Induction, IEEE Transactions On Industrial Electronics, 2005. Vol. 52, No. 2, 585-594.
28. Fahn, C.-S., & Sun, H. Development of a fingertip glove equipped with magnetic tracking sensors. Sensors 2010, 10, 1119-1140; doi:10.3390/s100201119.
29. Kim, D. H.; Lee, S.W.; Park, H.-S. Improving kinematic accuracy of soft wearable data gloves by optimizing sensor locations. Sensors 2016,16(6), 766.