PUBLICATIONS

B.C. Hu, T, D., Y, P., M, Z., and Q, Y. (2019). "A flexible, Attachable and Low-cost IMU-based Motion Capture System for Measurement of Hand Kinematics." Biomedical Signal Processing and Control (under review)

Y, P., X, S., L, L., B.C. Hu, and M, Z. (2019). "Hand Kinematics in Badminton Based on Smart Glove and Visualization Technology." Sensors (under review)

A flexible, attachable and low-cost IMU-based motion capture system for measurement of hand kinematics

Bingcheng Hu [a], Tian Ding [b], Yuxin Peng [c,*], Mingming Zhang [d], Qiang Yang [e]

[a]University of Michigan-Shanghai Jiao Tong University Joint Institute, Shanghai Jiao Tong University, Shanghai 200240, China

[b]Department of Ophthalmology, Chongqing Traditional Chinese Medicine Hospital, Chongqing 400021, China

[c]Department of Sports Science, Zhejiang University, Hangzhou 310028, China

[d]Department of Biomedical Engineering, Southern University of Science and Technology, Shenzhen 518055, China

[e]College of Electrical Engineering, Zhejiang University, Hangzhou 310028, China

[*]Corresponding Author. Tel.: +86-18868118759.

E-mail address: yxpeng@zju.edu.cn (Y. Peng).

ABSTRACT

This study proposed a flexible, attachable and low-cost IMU-based motion capture system for measurement of hand kinematics. Twelve low-cost 6-axis inertial measurement units (IMUs) are used in the system for capturing hand kinematics and analyzing continuous hand movements. Each IMU is bonded to a flexible adapter and then attached to the hand with double-sided tape. Compared with traditional glove-based hand motion capture systems, the proposed system can be connected to the back of the hand without any glove. Therefore, there is no effect on the user's touch sensation when gripping an object. Moreover, due to the flexible adapters used in the system, the proposed system is suitable for different sizes of hands or various hand motions. Finally, the proposed system was used in the sports of table tennis, badminton and tennis to capture the hand kinematics. It was verified that the system could be used for measuring the hand motion precisely and rapidly. Therefore, the proposed system is superior to traditional glove-based systems and is significant for capturing the motion of hands in many fields.

Keywords:

Motion capture; Flexible sensor; Inertial sensor; Hand kinematics.

1. Introduction

Hand motions are of great significance in the fields of sports biomechanics, medical rehabilitation, gesture recognition, etc. Two typical types of hand motion capture approaches are non-contact systems and contact systems. Non-contact systems mainly use cameras to capture hand kinematics and are easily affected by the environment such as illumination and background color, and the measurement accuracy is also affected by the moving speed of the hand [1-3]. Therefore, contact-based systems are more practical for capturing the hand kinematics precisely.

The most popular contact-based hand motion detection devices are designed based on gloves. A data glove can be constructed based on different data acquisition technologies, such as optical fiber sensors, flex sensors, hall-effect sensors, magnetic sensors, and inertial sensors [4-8]. Flex sensors based and IMU-based gloves are the most popular types reported in the literature [8, 9]. Flex sensor-based technology embeds different types of resistive bend sensors onto a stretchable glove for hand joint measurement. However, the repeatability of a flex sensor is low, and the accuracy decreases over time. Another limitation is that the flex sensor can only measure one degree of freedom (DOF), which cannot detect multi-DOF motion of the hand. On the other hand, many IMU-based gloves have been devised for hand motion capture due to their advantages of quick response, high data rate, high accuracy, multi-DOF measurement, and more valuable parameters (such as angles, angular velocities, and accelerations) [10-12]. However, traditional glove-based systems have lots of disadvantages for hand motion capture. For example, when the hand grips an object (racket, bottle, mobile phone or something else) with gloves, subtle changes in hand movement are strictly related to touch, force, friction, etc., which may lead to incorrect results [7, 9]. Besides, the glove and the hand also slide relative to each other, and the sensors on the glove will deviate from the original position during the hand movement, which also leads to unreliable measuring results.

To overcome the drawbacks of the glove-based systems mentioned above, a flexible and attachable IMU-based motion capture system is proposed in this paper. Twelve IMUs are employed in the system to capture the joint angles of the fingers and the wrist. Each IMU is bonded to a flexible adapter, and the flexible adapter is stick to the back of the hand by double-sided tape. Therefore, no glove is used in the system, and the hand can directly grip the object without external disturbance. The original positions of the IMUs have no deviation even during strenuous exercise. The shape of the flexible adapter can change with pressure, such that when the finger is squeezed and deformed by the object, the adapter can still fit the finger tightly. Besides, because of the use of standard ESP8266 module and the IMUs (MPU-6050), the overall cost is lower than $60 (amazon.com), making the system can be handled as consumables. Table tennis, badminton, and tennis are three favorite sports by using rackets and require fine motion control of the hand [13]. Therefore, to verify the performance of the proposed system, the hand kinematics of the three sports are studied by using the proposed hand motion capture system.

2. Methods and materials

2.1. System architecture and design

As shown in Fig. 1, the motion capture system consists of a main control unit (MCU), 12 IMUs, a 16-channel multiplexer, and a rechargeable battery. The MPU-6050 modules on the GY-521 breakout boards are employed as the IMUs for measuring the hand movements in real-time. One MPU-6050 contains “a 3-axis gyroscope and a 3-axis

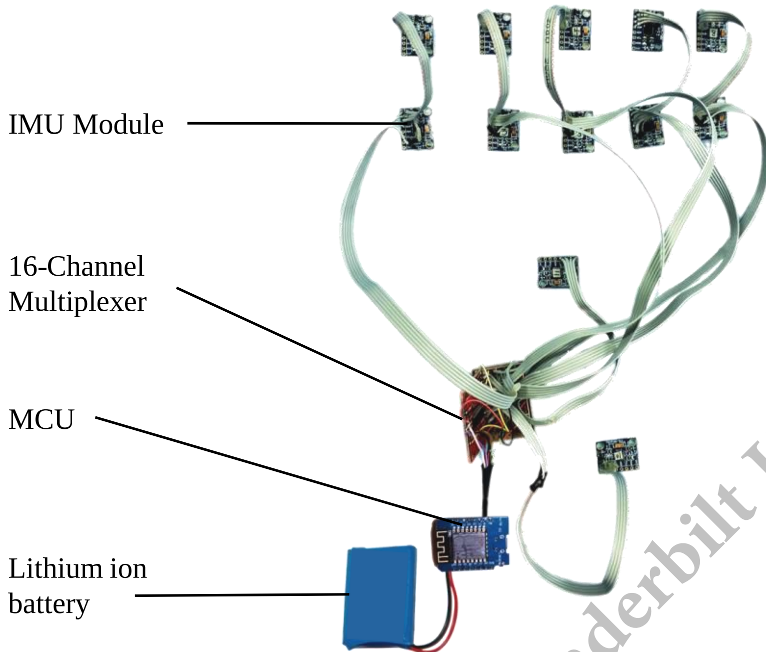


Fig 1. Structural design of the IMU-based motion capture system.

accelerometer, together with an onboard Digital Motion Processor™ (DMP™)". With the onboard DMP, the angles and angular accelerations of each axis can be computed without complex algorithm in MCU. To connect the 12 IMUs to the main control chip, one chip of 16-channel multiplexer is applied to this system. Typical switch-off signal feedthrough of this chip is almost zero when the frequency is less than 10^5 Hz, which is much higher than the maximum read speed of the hand motion capture system. An ESP8266 module is utilized as the MCU. Its maximum clock speed is 160 MHz, and it can launch a hotspot or be connected to WiFi. Therefore, the experimental data of the IMUs of the proposed system is transmitted to the computer through WiFi.

For the measurement of hand kinematics, the positions of the IMUs should be stable, and the whole system should be well-adapted to different hands or different hand motions. Therefore, a U-shaped flexible adapter is designed for connection of the IMUs to the fingers. The adapter is fabricated by 3D printing with flexible materials, Thermoplastic polyurethanes (TPU). It not only has excellent mechanical properties and structural versatility but also has the advantages of chemical resistance and abrasion [14]. As shown in Fig. 2, the flat side of the U-shaped adapter is bonded to the IMUs by 3M double-sided tape, and the other side is attached to the finger by 3M double-sided tape. It can be seen that the flexible adapter can produce a relatively large deformation, which can make the adapter fit the finger tightly. Therefore, the U-shaped adapter is not only attachable for fixing the position of the IMUs but also flexible for wearing on different sizes of hands. Moreover, it can be applied to different hand motions due to its flexibility. For example, the fingers are widened when gripping objects as they are squeezed. At this time, if rigid materials are used, people will feel uncomfortable, and the adapters may fall off from the fingers due to excessive force. The flexible materials fit snugly against the fingers and can prevent people from feeling obstructed. Also, with the attachable flexible adapters, people

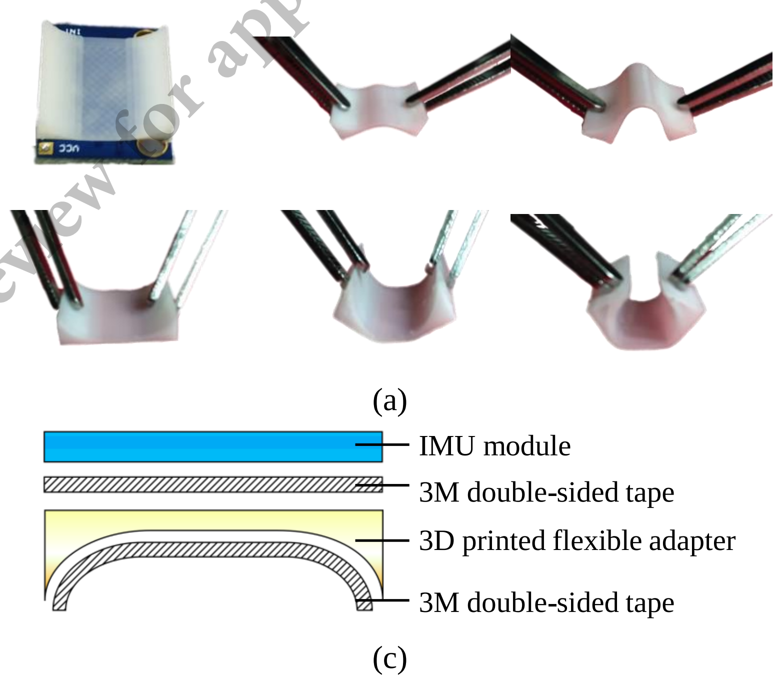


Fig 2. (a) 3D printed flexible adapter. (b) Explosion diagram of the cross-section.

can grip objects directly by hand and avoid external disturbance by using gloves. Therefore, data obtained by IMUs can be more accurate and closer to the actual situation.

The wearing appearance of the proposed system is shown in Fig. 3. Each finger is attached with two IMUs for measuring joint motions of the finger, which are connected by a flexible silicone wire. One IMU is attached to the back of the hand for capturing the motion of the wrist, and one IMU is attached to the back of the forearm as a reference. The multiplexer, MCU and the rechargeable battery are housed in a 3D printed case. The case is attached to the forearm by 3M double-sided tape and tied by an elastic band.

2.2. Algorithm and evaluation

2.2.1. Static calibration of IMUs

In the experiments for static calibration of IMUs, each IMU was calibrated in two different static situations. The Roll, Pitch, and Yaw axes of the IMU were defined as in Fig.

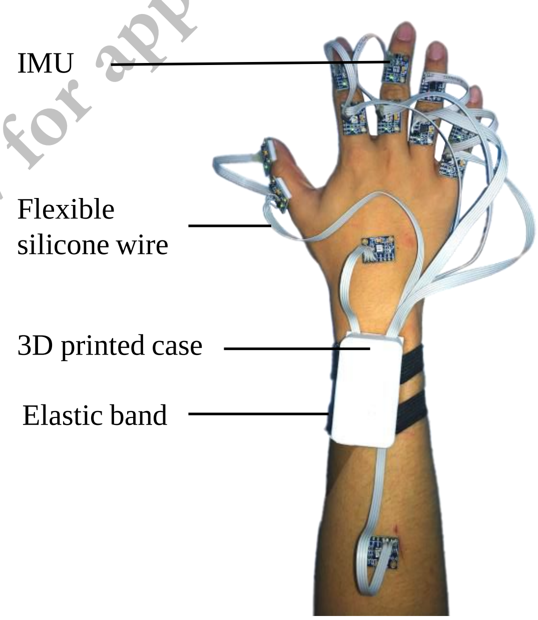


Fig 3. The appearance of the IMU-based motion capture system.

4a. In the first static situation, the Roll axis was put vertically, and the rotation around the Pitch axis was measured. After processing of the MPU-6050 calibration procedures, it was found that the rotation angle remained at around 90° and the root-mean-square deviation (RMSD) was 0.13. In the second static situation, Yaw axis was put vertically, and then its rotation error was measured. After processed by the MPU-6050 calibration firmware, the static state angle in the Yaw axis was maintained at around 0° with little fluctuation, and the RMSD was 0.14. The change in the Yaw angle is because the IMU does not have a magnetic sensing unit and cannot be automatically calibrated. The change in the Pitch angle and the Roll angle is that the gravity calibration needs to be adjusted according to the local gravity of earth. It was verified that the error was minimized after calibration of the sensor fusion algorithms and calibration procedures of the MPU-6050.

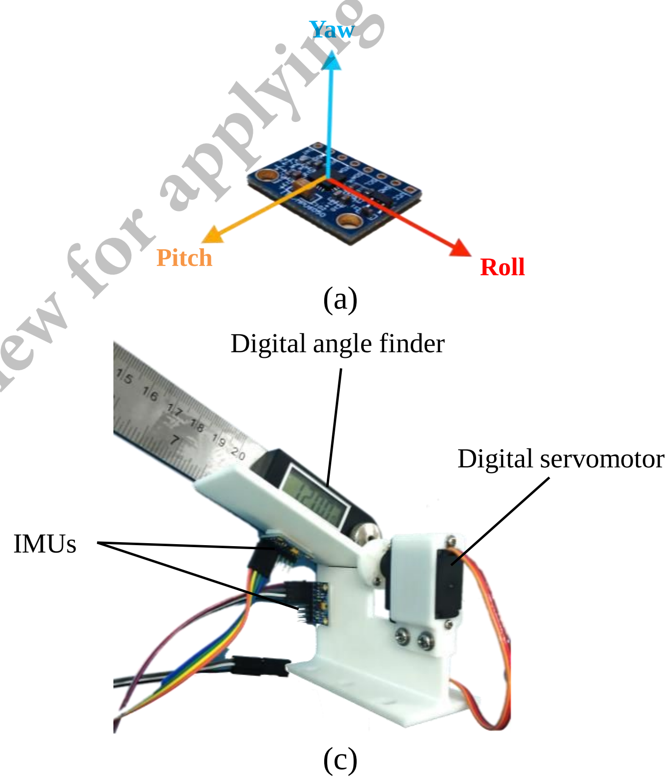


Fig 4. (a) Pitch, Roll and Yaw axis of the IMU. (b) Dynamic calibration for the IMUs.

2.2.2. Dynamic calibration

To verify the IMU performance during hand movement, dynamic angle calibration was also conducted, and a corresponding calibration device was designed as shown in Fig. 4b. An LX-16A Serial bus digital servomotor was employed to generate bending motions repeatedly to the device. There was a built-in angle sensor in the servo for outputting instant angle information, and the accuracy of the servo motor was 0.24°. Therefore, the angular output of the servo and the IMUs was collected by an MCU simultaneously.

To measure the actual angular range of the device during swift motion, the servo in this experiment was required to swing quickly to simulate the swing motion of the human hand. The servo swung from 90° to 180° with its maximum speed of 400°/sec. As shown in Fig. 5a, the angle data obtained by the IMUs at high speed could not meet the actual value, and the error was about 3°. The RMSDs at 90° and 180° were 2.56° and 3.26°, respectively.

To measure the delay of the IMUs, the servo motor was driven from 90° to 180° repeatedly at three different angular velocities of 2°/sec, 20°/sec, and 100°/sec, respectively. Fig. 5b shows the angular output of the IMUs and the servo at different angular velocities. The RMSDs and time shift are summarized in Table 1. It can be seen that the RMSDs increased when the angular velocity increased, which means the measurement error of measured angle increased with the increase of the angular velocity. The delay and measurement error of the IMUs could be compensated concerning the angular velocities during experiments.

Table 1
RMSDs and time shift at different angular velocities.

Sweep Speed ($^\circ/s$)	2	20	100
RMSD (°)	3.38	5.14	11.53
Time Shift (s)	1.69	0.26	0.16

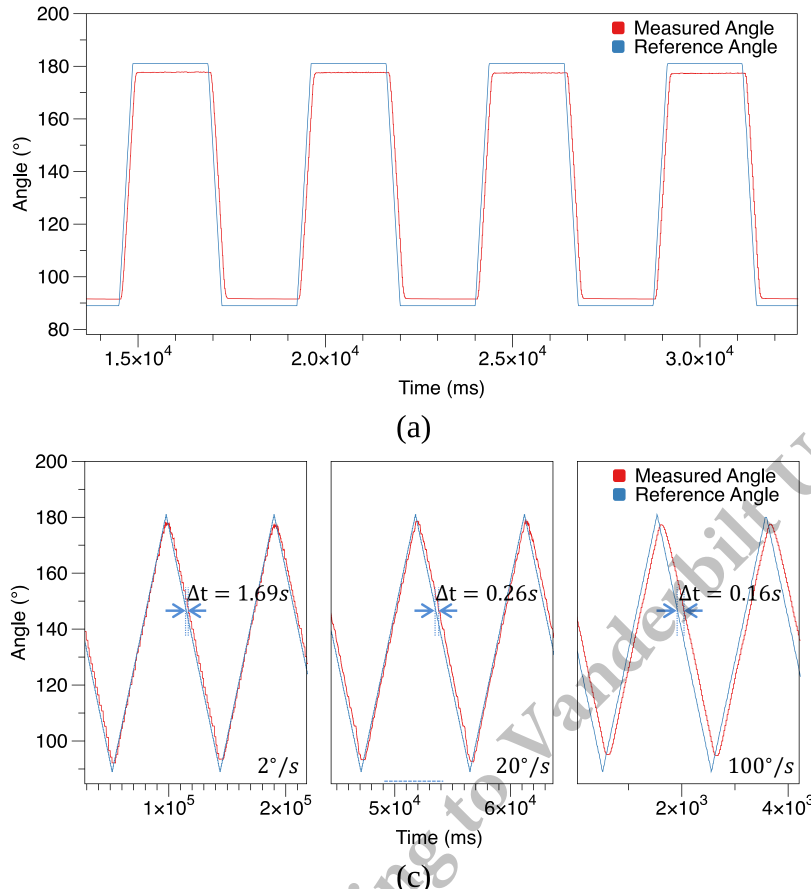


Fig 5. The measured angle between the IMUs is compared with the actual angle of the servo output at (a) square wave with swift swing (400 °/s) and (b) triangular wave with different speeds (2 °/s, 20 °/s, 100 °/s).

2.2.3. Normal anatomy of human hands

The anatomy of the human hand is shown in Fig. 6 [15]. Articulations between metacarpals and proximal phalanges are MCP joints. Interphalangeal joints can be separated as Proximal interphalangeal (PIP) joints and Distal interphalangeal (DIP) joints. The PIP joint and DIP joint of one finger always bend together so that it is no need to measure both of the angles at PIP joints and DIP joints. Carpometacarpal (CMC) joints are articulations between components of the carpus and the metacarpal bones. As shown in Fig. 7, one person can bend CMC joints to palmar (palm of the hand), dorsal (back of the hand) (Fig. 7a), radial (side of thumb) and ulnar (side of the little finger) (Fig. 7b) directions [15].

However, CMC joints cannot rotate in the direction of the arm (Fig. 7c). In other words, when the human arm bone is fixed, the palm cannot rotate along the axis of the arm's direction.

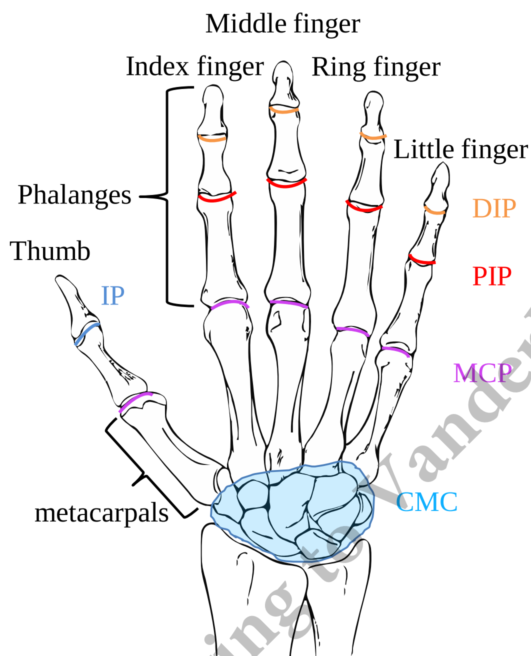


Fig 6. Terminology of the fingers and joints.

(a) (b) (c)

Fig 7. (a) Palmar flexion vs. dorsal flexion. (b) Radial abduction vs. ulnar abduction. (c) Impossible wrist rotation.

2.2.4. Angle orientation

As can be seen from Fig. 8a, twelve IMUs were used in this study for capturing motions of 11 joints of the hand, including the angles of one CMC joint (K, M, and L in Fig. 8a), five MCP joints (F to J in Fig. 8a) and five PIP joints (IP joint for thumb, A to E in Fig. 8a). For MCP joints and PIP joints, only palmar flexion and dorsal flexion were considered in this experiment. While for the CMC joint, it can move towards the palmar/dorsal side or

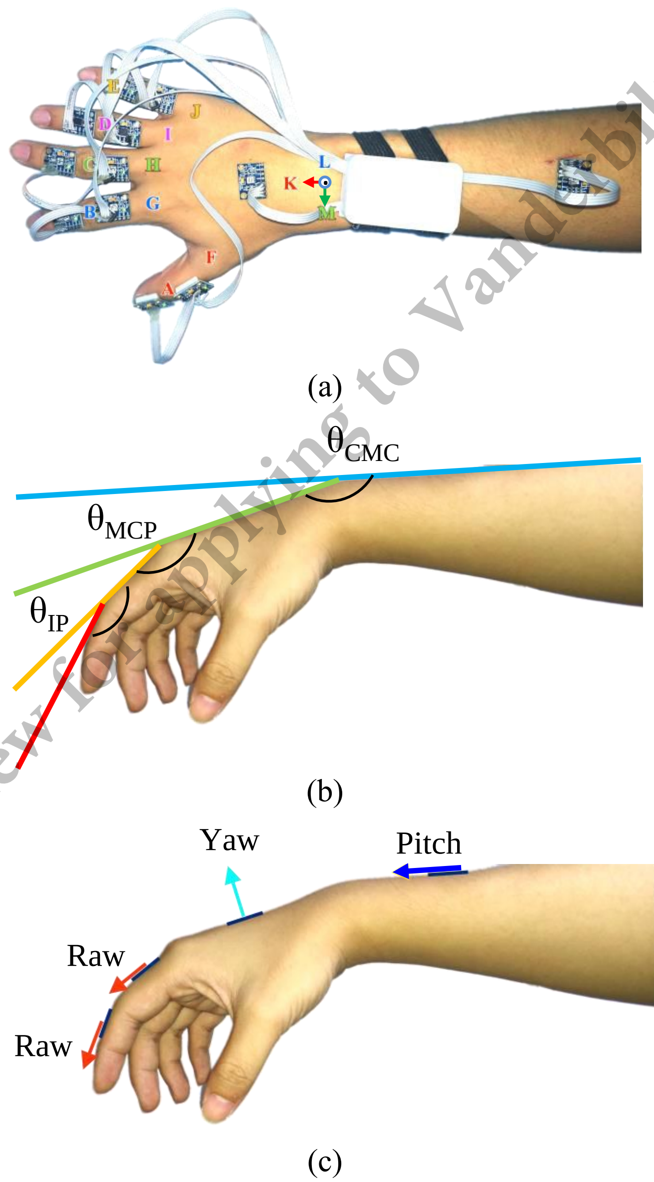


Fig 8. (a) The numbering method of the joints. (b) Joint angles for hand movement. (c) One particular axis on each IMU that's selected in this study.

the radial/ulnar side, and the palm side and radial side are considered to be the positive side. Since the palm cannot rotate along the axis of the arm's direction, which means there were 13 angles calculated, but only 12 of them could be put into valid discussion. The positive direction of the finger and hand movement is shown in Fig. 8b. To calculate these angles, one particular axis on each IMU was defined to be the direction axis as in Fig. 8c. Then, the quaternion was converted to calculate the angle between two direction vectors. In this study, the IMUs were attached along the directions of the fingers or the arm, which were considered as their directions.

To obtain the direction vector, a unit vector was rotated with the quaternion that the hand motion capture system transmitted.

The quaternion is defined as

$$q = a + bi + cj + dk \tag{1}$$

where *a*, *b*, *c*, and *d* are real numbers, and *i*, *j*, and *k* are the quaternion units of Pitch, Roll and Yaw directions.

The rotation operator of the quaternion acting on any vector v in the 3D space is calculated as shown in Eq. (2) [16].

$$w = q \cdot v \cdot q^* \tag{2}$$

$$v = (0, x, y, z) \tag{3}$$

where q is the quaternion, and v is the vector to rotate. v is a unit vector, which means there is one variable of x, y, and z to be 1 and the others to be 0. In this way, the new vector after rotation *w* can be calculated. The formula for solving the angle between two vectors is shown as follows:

$$\theta = acos(\frac{v \cdot w}{|v| \cdot |w|}) \tag{4}$$

3. Results

Table tennis, badminton, and tennis are three of the most favorable sports by using rackets, which require fine motion control of the fingers and wrist [13]. Therefore, to verify the performance for measurement of hand kinematics, the service motion in the three sports were studied by using the proposed hand motion capture system. Three professional athletes in table tennis, tennis and badminton were invited to conduct the service motion. For table tennis, the athlete used shake hand grip, which means the position of the thumb was on the edge of the handle, and the index finger should be placed at the opposite side precisely of the thumb position (Malagoli Lanzoni et al., 2014). For badminton, the service method was backhand long serve, which used a thumb grip with the wrist bent to the radial direction. Long serve requires "speed and strength, to be able to put the shuttle high and down the center of the line and to fall vertically at the back of the court (Edwards et al., 2005)" . The athlete held the racket out in front of her with "thumbs down", so the racket was still facing roughly forwards and pointing at a downwards angle (Ladds, 2010). The tennis athlete used the flat serve and held the racquet grip with a continental grip in a semi-loose fashion (Kovacs and Ellenbecker, 2011). The characteristics of the service motion in the three sports are shown in Fig. 9. Since the strokes were always completed when the hand gripped the rackets tightly, a vertical line near the minimum joint angles was used to analyze the service motion. Before the time of t0he vertical line, the athletes could finish the swing and stroke of the service motion.

Fig. 9a shows the joint angles of the hand in the service motion of the table tennis. The motion range of the IP joints was less than 20°, while the MCP joints changed 40° to 45°, which means the MCP joints played a significant role in the service motion. It can be found

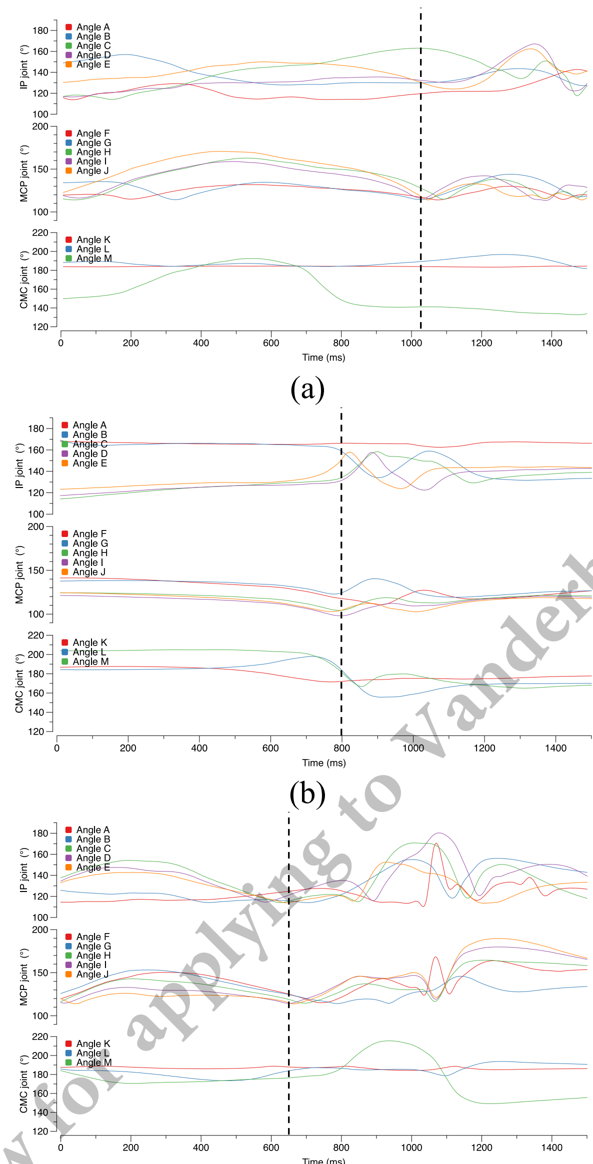


Fig 9. Angles of hand joints for (a) table tennis, (b) badminton and (c) tennis.

that the MCP joint angles of H, I and J increased at first, and then decreased, which indicates that joints relaxed to accumulate strength and then gripped tightly to hit the ball. However, there was a much smaller change for the MCP joints of the thumb and index finger (F and G). This is because the thumb and the index finger served as a fulcrum for supporting the racket, while the other three fingers were used for accumulating and releasing strength. For the CMC joint, the motion range of the K and L was less than 10°, while the M changed more than 40°. It means that the wrist mainly rotated around the M in the service motion. Together with the increasing and decreasing of the joint angles of the H, I and J, the angle M also increased first to gather strength, and then decreased to release strength for hitting the ball. Consequently, the table tennis could get enough energy in an expected direction.

The characteristics of the badminton are shown in Fig. 9b. The IP joint of the thumb almost had no movement in the service motion, because the thumb played as a fulcrum of a lever in the backhand long serve. All the MCP joint angles decreased during the stroke process, and the angles of the thumb and the index finger were approximately 20° larger than that of the other three fingers. For the CMC joints, it can be seen that all the angles of the K, L, and M decreased, which means that the badminton's backhand service was a kind of complex spacial three-dimensional movement.

Fig. 9c shows the characteristics of the tennis. The IP joint angles of the C, D and E changed more than the other two fingers, which means they were the main joints to gather and release strength. All the MCP angles increased first and decreased subsequently. This is because the athlete should swing the racket backward to gain potential and then swing the racket forwards to transfer potential to hit the ball. It was also observed that the CMC joints angles K, M, and L changed slightly, which were less than 20°. This is because the wrist needed to be perfectly "locked" in tennis, especially in the forehand.

4. Discussion

To compare with traditional glove-based systems for measurement of hand kinematics, a rubber glove and a cloth glove were worn by the athletes. According to the feedback of athletes', the feeling of the rubber glove was the worst, because the friction between the rubber and the racket was so large that it was hard for the fingers to move or change the grip position. Whereas, the cloth glove was too soft and often slid relatively to the fingers. In addition, the athletes also felt a little obstructed or uncomfortable because of external disturbance by using gloves. When wearing the flexible and attachable motion capture system proposed in this study, and athletes said there was no effect on their motion because the sensors were attached to the back of the hand and they could grip objects directly by hand without any disturbance.

From the experiment results, it can be seen that most of the IP and MCP joint angles in the three sports increased first and decreased subsequently. This is because the athletes should gain potential with a relaxed grip of the racket and then grip tightly to release the potential to hit the ball. Moreover, the motion range in table tennis was more extensive than that in the other two sports. It means that the service motion in table tennis relied more on fine motion control of the fingers. The difference of the CMC joint angles among the three sports could also be seen from the experiments. The motion range of the angle M in table tennis was the largest because the wrist movement in table tennis played a significant role to control the direction and strength of the serve. It was also observed that all the angles K, L, and M decreased in badminton, but all the K, L, and M changed slightly in tennis. The results confirmed that the movement of the wrist in badminton was the most complex and significant for control the direction and strength of the shuttle. However, there was a slight motion of the wrist in tennis, because the wrist had to be firm and stable to hit a proper tennis forehand.

Since the MPU-6050 modules served as the IMUs, the size of the motion capture system was relatively large. In our future work, the PCB of the inertial sensors will be designed by ourselves to reduce the size of the system. The portability of the system will also be enhanced by using softer wire and lighter battery. In addition, the packet sent by the hand motion capture system contained a large amount of original IMU data. Since the transmission bandwidth was sufficient, the data sampling rate of the algorithm was limited by the computing performance of the MCU (ESP8266). In our future work, the ESP32 will be used for dual-core programming to improve the performance of the system.

5. Conclusion

A flexible, attachable and low-cost IMU-based hand motion capture system was developed in this study. Twelve 6-axis IMUs were employed in the system to capture hand kinematics. Each of the IMU was bonded to a flexible adapter and attached to the back of the hand. Compared with traditional glove-based hand motion capture systems, people could grip an object directly without any disturbance. The adapters were not only attachable for fixing the position of the IMUs precisely, but also flexible for wearing on different sizes of hands. Finally, the hand kinematics of the service motion of the table tennis, badminton and tennis was studied by using the proposed system. It was verified that the system could capture the motion of hands precisely and could be used for studying the hand kinematics in many fields.

Acknowledgments

This research was supported by the Fundamental Research Funds for the Central Universities (No. 2018QNA224), Zhejiang Province Qian Jiang Talent Program of 2018 (No. QJC1802009), Zhejiang Province Natural Science Foundation of China (No. Q19C100004), MOE (Ministry of Education in China) Project of Humanities and Social Sciences (No. 19YJCZH126), and the "Double First-Class" Construction Fund of Zhejiang University.

Reference

[1] T. Rhee, U. Neumann, J.P. Lewis, Human hand modeling from surface anatomy, Proceedings of the 2006 symposium on Interactive 3D graphics and games, ACM, 2006, pp. 27-34.

[2] C.-W. Chang, C.-H. Chang, A two-hand multi-point gesture recognition system based on adaptive skin color model, Consumer Electronics, Communications and Networks (CECNet), 2011 International Conference on, IEEE, 2011, pp. 2901-2904.

[3] L. Dipietro, A.M. Sabatini, P.J.I.T.S. Dario, Man,, P.C. Cybernetics, A survey of glove-based systems and their applications, 38 (2008) 461-482.

[4] M. Nishiyama, K.J.I.T.o.I. Watanabe, Measurement, Wearable sensing glove with embedded hetero-core fiber-optic nerves for unconstrained hand motion capture, 58 (2009) 3995.

[5] S. Jacobsen, E. Iversen, D. Knutti, R. Johnson, K. Biggers, Design of the Utah/MIT dextrous hand, Robotics and Automation. Proceedings. 1986 IEEE International Conference on, IEEE, 1986, pp. 1520-1532.

[6] J. Lenz, S.J.I.S.j. Edelstein, Magnetic sensors and their applications, 6 (2006) 631-649.

[7] B.-S. Lin, I. Lee, S.-Y. Yang, Y.-C. Lo, J. Lee, J.-L.J.S. Chen, Design of an Inertial-Sensor-Based Data Glove for Hand Function Evaluation, 18 (2018) 1545.

[8] Z. Shen, J. Yi, X. Li, M.H.P. Lo, M.Z. Chen, Y. Hu, Z.J.R. Wang, biomimetics, A soft stretchable bending sensor and data glove applications, 3 (2016) 22.

[9] A. Jacob, W. Zakaria, W. Nurshazwani, M. Tomari, M. Razali, Implementation of bluetooth communication in developing a mobile measuring device to measure human finger movement, (2015).

[10] M. Georgi, C. Amma, T. Schultz, Recognizing Hand and Finger Gestures with IMU based Motion and EMG based Muscle Activity Sensing, Biosignals, 2015, pp. 99-108.

[11] Y. Jing, C. Eun-Seok, C. Wook, B. Won-Chul, C. Sung-Jung, O. Jong-Koo, C. Joon-Kee, K. Dong-Yoon, A novel hand gesture input device based on inertial sensing technique, 30th Annual Conference of IEEE Industrial Electronics Society, 2004. IECON 2004, 2004, pp. 2786-2791 Vol. 2783.

[12] J. Lopes, M. Simão, N. Mendes, M. Safeea, J. Afonso, P.J.P.M. Neto, Hand/arm gesture segmentation by motion using IMU and EMG sensing, 11 (2017) 107-113.

[13] A.J.J.o.s.s. Lees, Science and the major racket sports: a review, 21 (2003) 707-732.

[14] A. Pattanayak, S.C.J.P. Jana, Properties of bulk-polymerized thermoplastic polyurethane nanocomposites, 46 (2005) 3394-3406.

[15] R.J. Schwarz, C.J.A.l. Taylor, The anatomy and mechanics of the human hand, 2 (1955) 22-35.

[16] R. Mukundan, Quaternions: From classical mechanics to computer graphics, and beyond, Proceedings of the 7th Asian Technology conference in Mathematics, 2002, pp. 97-105.

Conflict of Interest Statement

The authors declare no conflict of interest.

sensors

MDPI

Article

Measurement and Visualization of Hand Kinematics and Kinetics in Badminton based on Data Glove

Yuxin Peng [1], Xian Song [1], Li Liu [2,*], Bingcheng Hu [3], Mingming Zhang [4].

[1] Department of Sports Science, Zhejiang University, Hangzhou 310028, China; yxpeng@zju.edu.cn (Y.P.); sx1993@zju.edu.cn (X.S.)
[2] School of Big Data & Software Engineering, Chongqing University, Chongqing 400044, PR China; dcsliuli@cqu.edu.cn
[3] University of Michigan-Shanghai Jiao Tong University Joint Institute, Shanghai Jiao Tong University, Shanghai 200240, China; bingcheng@sjtu.edu.cn
[4] Department of Biomedical Engineering, Southern University of Science and Technology, Shenzhen 518055, China; zhangmm@sustech.edu.cn
* Correspondence: dcsliuli@cqu.edu.cn

Received: date; Accepted: date; Published: date

Abstract: Hand movements are typical human body fine movements, which can help people accomplish complex jobs like grabbing objects and operating tools. It is mainly characterized by the flex and pressure applied by its fingers. In a badminton game, dexterity hand movements are essential for the player to conduct extraordinary skills. As a result, such game is chosen to analyze typical hand kinematics and kinetics. However, only rely on bare eye observation cannot recognize and record such movements. Thus, a more accurate smart glove with sensing functions for finger pressure and flex is employed in this case to measure the finger bending and force situation during the forehand grip and backhand grip. An athlete and an amateur are chosen to conduct the grip movement in the static states, and the data is recorded by the smart glove. The measured parameters are then visualized to analyze different grip movement, which can provide a reference for the badminton learners to perform a correct technical movement.

Keywords: badminton; hand fine movement; smart detection; visualization analysis

1. Introduction

Hand movement for a specific task is conducted by small muscle groups on fingers and palms, and the proficient control of such movements is the most important ability for human beings. The most typical actions of this motion is characterized by the movement of fingers and wrists, which are mainly reflected in the pressure and flex angle changes, for example, in badminton, table tennis, tennis or daily grasping operations. Thus, measurement and visualization of the grasping operations can help people precisely determine the human hand kinematics and kinetics.

Badminton is one of the most popular sports around the world [1], which can enhance both the physical and the spiritual function of the human body. One factor that determine the success of a badminton game is the racket grip for different types of movement, such as forehand/backhand smashes, short drops, and long clears [2]. A correct grip type can increase the power and accuracy of the stroke and result in optimal performance. However, using only the wrist to control the badminton racket does not allow very many grip variations. The badminton grip variation of the racket is mainly controlled finely through the fingers. Fine finger control of the badminton grip is dependent on not only the grip posture, but also the grip strength of the fingers [3], which is very hard to be observed during the badminton game. In traditional teaching approaches, the grip pattern of trainees can only be indirectly observed from the flying trajectories and dropping points during conducting specific movements, which may lead to an incorrect training path due to the inaccurate observation [4].

Therefore, measurement and visualization of the badminton grip types can help the players and coaches precisely evaluate the hand kinematics and kinetics in different strokes and improve the training efficiency. Moreover, it is also of great significance in other areas, for example, hand gesture recognition with biomedical analysis [5], rehabilitation process monitoring [6], and remote control for robots and unmanned aerial vehicles [7].

In recent years, most of the fine motion measurement has been conducted based on high-speed cameras [8] or wearable sensors [9] like flex sensors or accelerators. The camera-based system can obtain the joint angles and angular velocities from pre-recorded videos. MS Salim et al. [10] adopted four Oqus cameras to detect the arm trajectory and acceleration to analyze the motion difference between male and female players. A markerless motion capture system was developed by Cheryl D. Metcalf et al. for measurement of hand kinematics by using a commercially available gaming system (Microsoft Kinect) [11]. However, the camera-based systems are easily affected by light conditions, and their resolution is inadequate to capture the fine motion of the fingers. To avoid the demerits of the camera-based system, the wearable devices have been proposed in many researches. Chew Zhen Shan et al. [12] established a so-called Opal sensor to monitor the acceleration and angular velocity of the upper limb during the smashing movement. Alvin Jacob et al. [13,14] developed a mobile measuring device for capturing human finger movement by using five flex sensors. Apart from sport applications, the smart glove based on wearable sensors are also a hot spot in the fields such as rehabilitation [15], surgery [16], human-machine interaction [17], and injury evaluation [18]. It is a popular application scenario for novel sensing materials like carbon textile [19], graphene [20], and carbon nanotube as well [21].

Nevertheless, although the above-mentioned wearable sensors could record hand kinematics accurately, such as acceleration or angular velocity, they were not able to detect the kinetics such as the grip strength of the fingers in different strokes. Some of the smart gloves employed in the rehabilitation area focused on the strength evaluation, but they have not fuse motion sensors to explore the correlation of strength and motion status [15]. Therefore, it is impossible to discriminate different grip strength with the same grip posture or different grip postures with the same grip strength. In addition, the visualization of the grasping operations was not mentioned in badminton, which makes it hard to understand the grip posture and grip strength from the abstract data acquired by the fine motion measurement systems.

Not only the grip posture but also the grip strength can affect the velocity or the route of the shuttle. Therefore, exploiting a detection system with comprehensive analysis ability for both grip posture and grip strength is crucial and necessary. To solve the problems, this paper proposes a smart glove with the sensor array of flex sensors and pressure sensors based on the kinetic and anatomy principles of human hands. On the other hand, visualization can not only reveal the relationship between the grip posture and grip strength, but also demonstrate hand kinematics and kinetics caused by their combined action. To visualize the grip posture and grip strength of a badminton grip type, a hand movement visualization system based on Unity and ANSYS is proposed. Finally, to verify the feasibility of the measurement and visualization approaches, two typical badminton grip types are studied in this paper.

2. Methodology

Conducting the analysis for the complex and unpredictable hand movement requires a well-established system based on state of art technologies. As shown in Figure 1, the overall system in this paper is divided in three sections: the data acquisition module, the data processing module, and the data visualization module. In the data acquisition section, the flex sensors and pressure sensors convert the status of hand movement into voltage form as angle data and pressure data, respectively. The acquired data are send to the Arduino platform (data processing module) for analog-digital conversion. Then, the converted data are transmitted to the personal computer (PC) through serial communication. The visualization procedure will be conducted in PC via computer graph process and finite element process to generate illustrations for flex status and pressure distribution. The Arduino platform can collect data with 12-digit resolution and maximally 10 k sampling frequency, which is sufficient for monitoring human movement. With this system, the differences of movements conducted by both professionals and trainees can be discriminated from the aspect of quantified section pressures and bending angles of human hand.

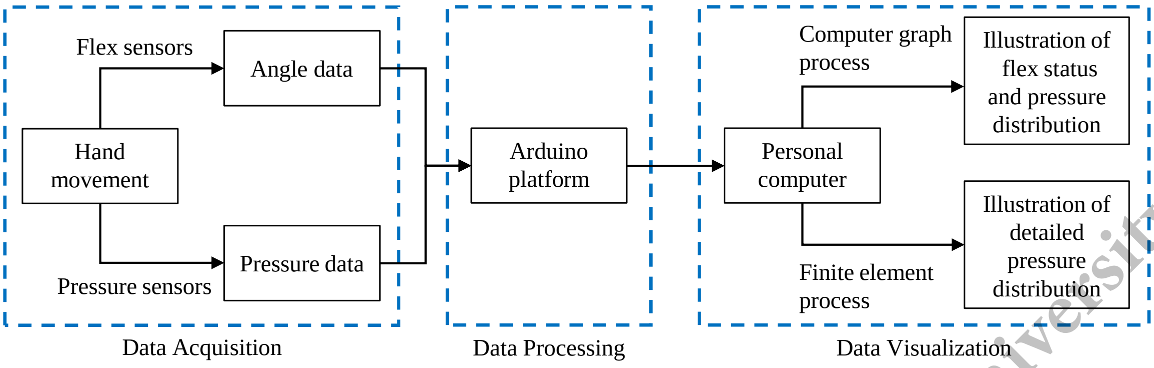


Figure 1. The flow chart for the whole system.

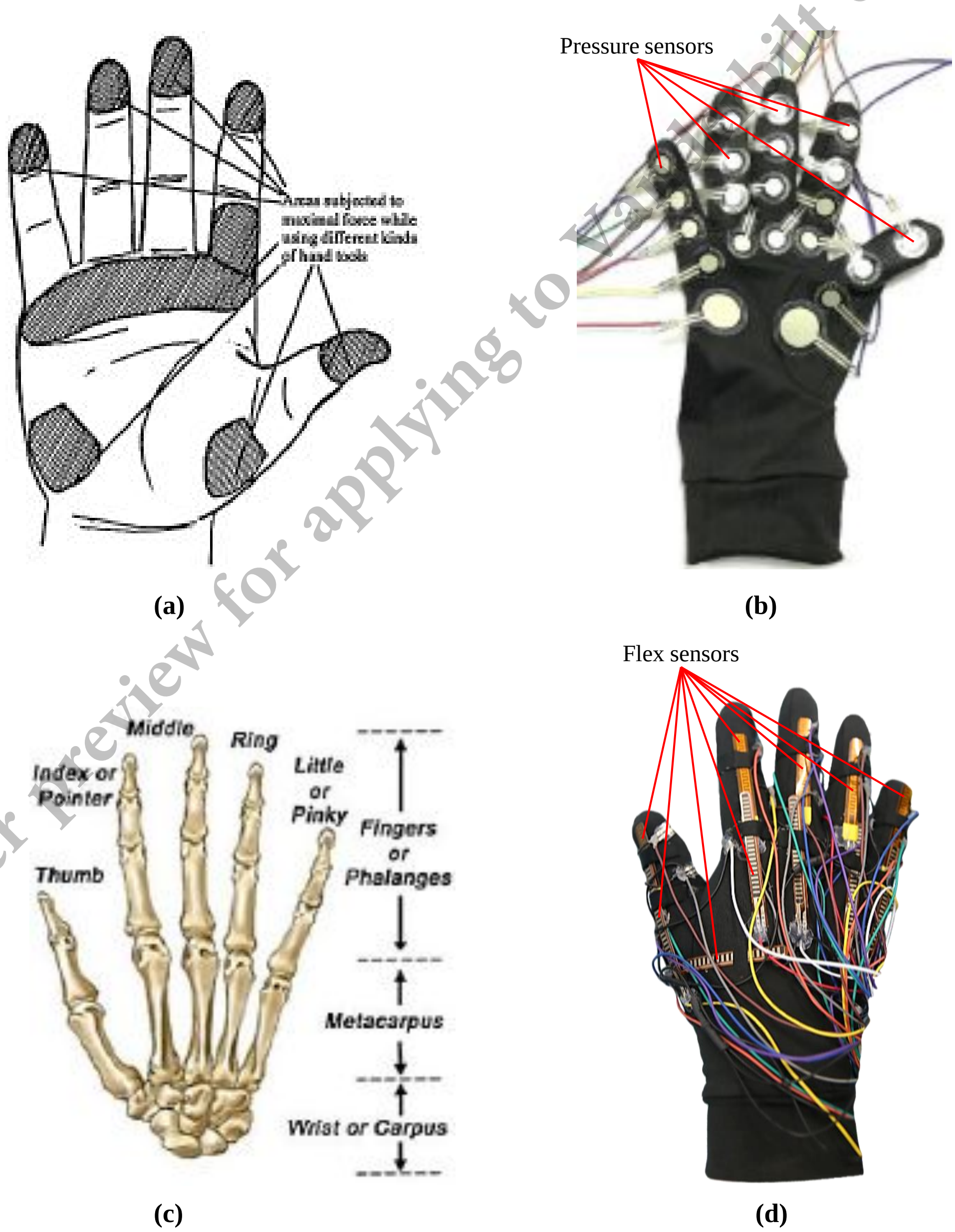


Figure 2. The overview of the smart glove: (a) pressure distribution under a type of griping; (b) front view (c) hand skeleton in the kinematic model; (d) back view.

2.1 Smart glove based on flex sensors and pressure sensors

The main fine movement characteristics of the human hand are the finger joint angles as well as the pressure generated by fingers and the palm. To capture the hand kinematics of finger joint angles as well as the pressure generated by fingers and the palm, flex sensors and pressure sensors are employed to construct a smart glove system.

According to the kinetic model, different gripping postures correspond to different power generation points of human hand, and an example of the pressure distribution under gripping gesture is shown in Figure 2(a) [22]. When playing badminton, different power generation points are involved due to various gripping postures. Thus, in order to capture the pressure distribution of all the main power generation points of the human hand, twenty-one pressure sensors [23] are arranged at sections that have direct contact with the racket, which is shown in Figure 2(b). The detailed tissue deformation requires a large amount of works in biomechanics analysis, and it is not the key focus of the provided job during the development of this equipment. Thus, these promising factors will be added in our further study.

From the kinematic model, the human hand skeleton includes phalanges, metacarpus and wrist with 19 links and 24 degree of freedoms (DOFs), which is shown in Figure 2(c) [24]. Each finger except the thumb can be regarded as a kinematic chain that contains 4 links and 5 DOFs. Due to the less contribution of the distal interphalangeal joint during the grip movement, this paper only employs one flex sensor for the upper two joints. As shown in Figure 2(d), ten flex sensors [25] are deployed at the metacarpophalangeal joints and the proximal interphalangeal joints on each finger including the thumb.

Figure 3 shows the working principles of the smart glove. The information of the finger joint angles as well as the pressure acquired by the glove is stored and analyzed in the Arduino system. The Arduino system is attached on the forearm of the participant by nylon belts and connected to the sensors with expanded ADC ports. This deployment will eliminate its influence on human movement during the badminton game. All the data will be then transmitted to the PC through the 2.4G communication equipment installed on the Arduino board. Visualization will be processed based on the data of the finger joint angles and pressure.

2.2 Visualization system

Since the human hand conducts multi-dimensional and complex movement, the parameters displayed only by data table may confuse researchers. Thus, the ANSYS and Unity tools are employed for the data visualization of hand movement.

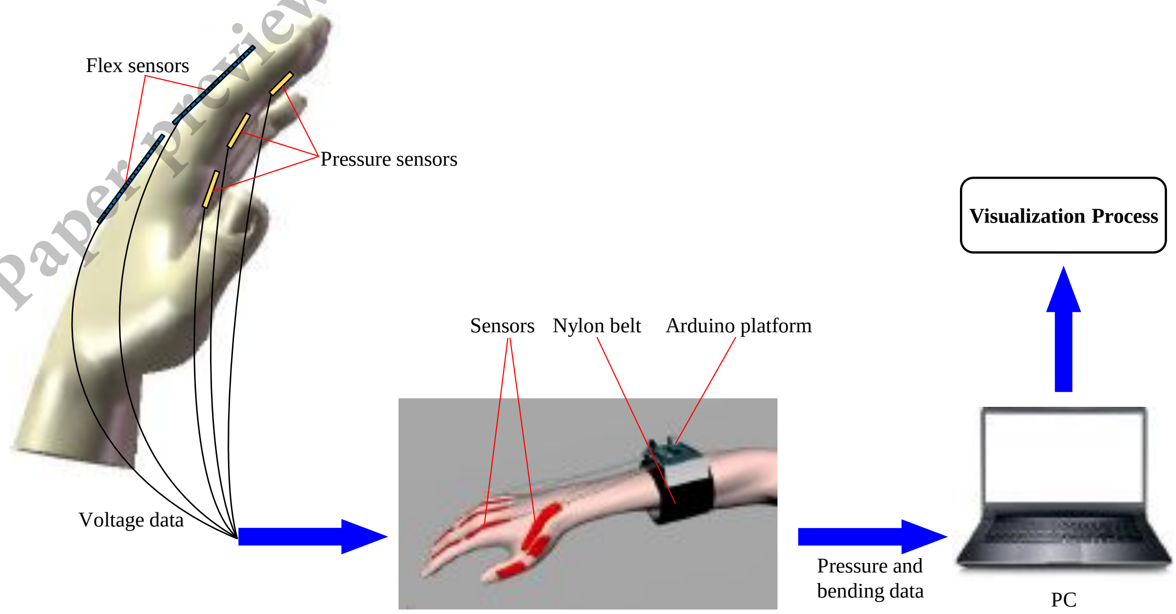


Figure 3. Working principle of the smart glove.

ANSYS [26] is a finite element simulation software that can reveal the complex object responses under certain external conditions. The data of pressure distribution is accessed by circular pressure sensors of the smart glove. Therefore, in the ANSYS module of statics analysis, the illustration of pressure distribution can be displayed by exerting the detected pressure values on the corresponding areas successively, where the hand model is stabled by a fixed support during the simulation.

Unity [27] is a tool for establishing computer graph (CG), which can conveniently illustrate the flex status that are extracted by bar type sensors located at the back of human hand. Moreover, to achieve the information of the correlation between the flex status and pressure distribution, the detected pressures are also merged on the Unity model. The visualized model is created by Maya software. The pressure distribution is implemented by different colors displayed on the hand skin. Since the model to analyze kinematics and kinetics requires to be driven by Unity3D, the skeleton and skin are bonded. The skeleton is controlled by C# script. When MCU transfers the data from sensors of smart gloves to PC, data packets can be analyzed by the Unity3D engine. The fingers in the model can be bended subject to the sensor data in real time.

3. Experiments

3.1 Sensor calibration

The primary step is to calibrate the flex sensors and pressure sensors installed on the smart glove, which can clarify the relationship between the voltage acquired by the Arduino platform and the actual bending angles or pressure bear by human fingers.

The calibration experimental setup for the pressure sensor is shown in Figure 4(a). A force platform (HP-50, HANDPI, CHINA) is used to apply pressure to the pressure sensors. A circular cushion is attached to the head of the force platform for ensuring that the pressures are applied with in the validated rage. As shown in Figure 4(b), the pressure sensors are tuned by applying several

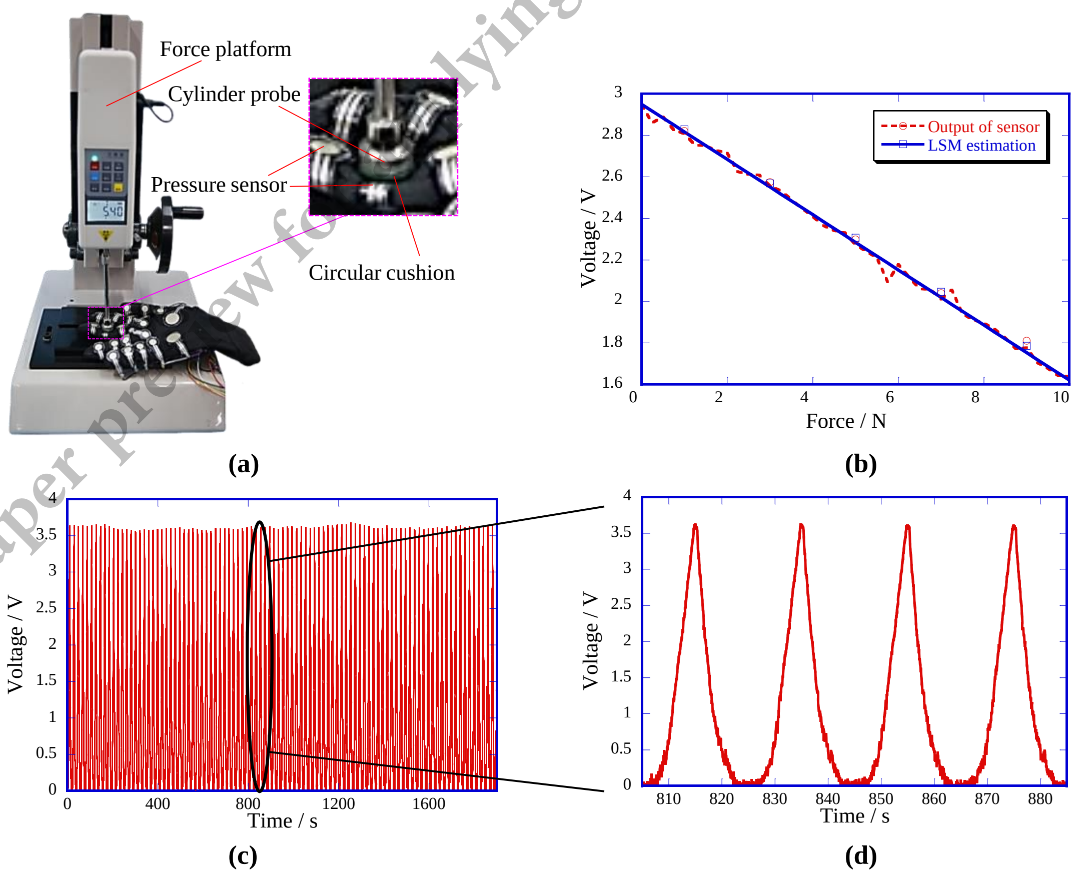


Figure 4. The calibration procedure for the pressure sensor: (a) experimental setup; (b) calibration result; (c) 120-cycle test for the robustness of the pressure sensor; (d) 4 cycles in the 120-cycle procedure.

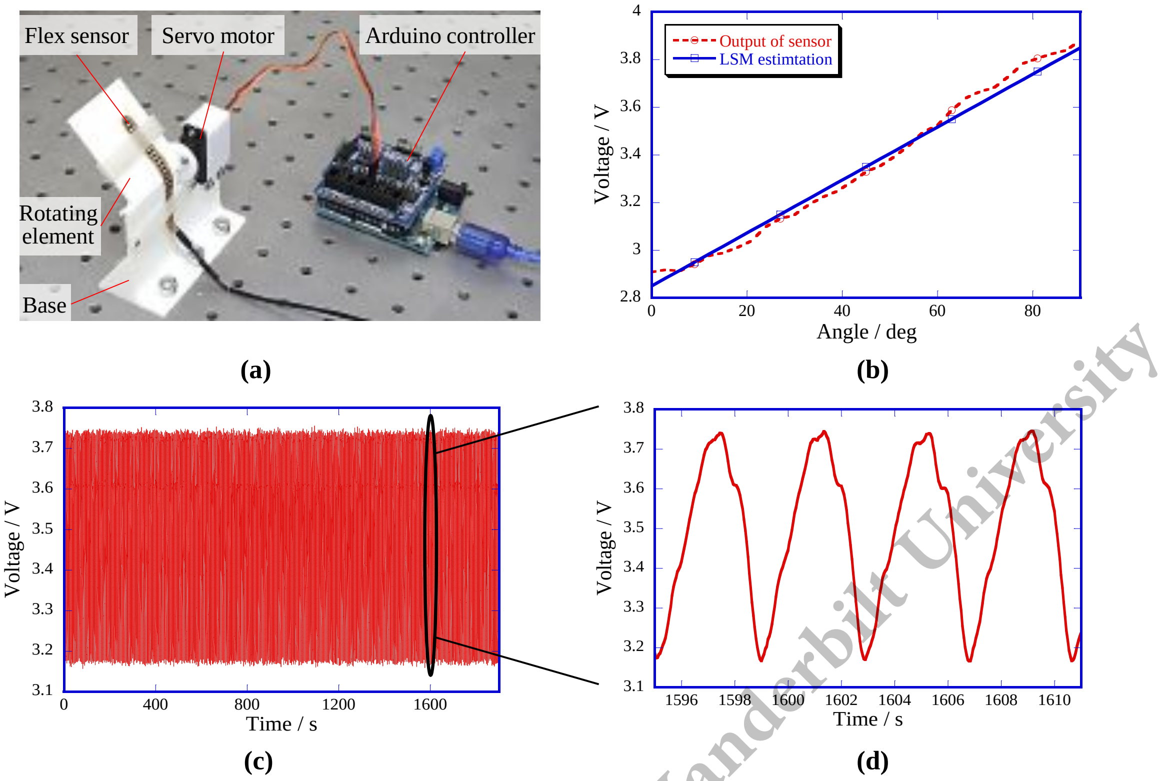


Figure 5. The calibration for the flex sensor: (a) experimental setup; (b) calibration result; (c) 480-cycle test for the robustness of the flex sensor; (d) 4 cycles in the 480-cycle procedure.

forces between 0 N and 10 N, and their characteristic functions are obtained via LSM as well. Figure 4(c) shows a 120-cycle test for the repeatability of pressure sensors on the force platform, and 4 cycles within the whole 120-cycle procedure is shown in Figure 4(d).

The calibration experimental setup for the flex sensor is shown in Figure 5(a). A rotating element is driven from 0° to 90° by a servo motor, and the actual angle can be obtained from the servo motor by an Arduino controller. Also, the output voltage of the flex sensor is recorded by the Arduino controller to compare with the actual angle. The calibration result is shown in Figure 5(b), and the characteristic function is fitted by the least square method (LSM). The repeatability of the flex sensors is tested by bending them for 480 times on the rotating element, where the data of the whole procedure is shown in Figure 5(c), and 4 cycles within the whole 480-cycle procedure is shown in Figure 5(d).

3.2 Measurement of hand kinematics and kinetics

A correct badminton grip is the foundation of playing badminton. Gripping the racket wrongly will decrease your stroke's accuracy and power. A good grip on badminton rackets can reduce injuries, increase the accuracy of shots and produces more efficient hits. The basic grip types of badminton can be generally divided into forehand grip and backhand grip. Therefore, the two grip types are studied in the experiment stage to illustrate the difference between professionals and amateurs.

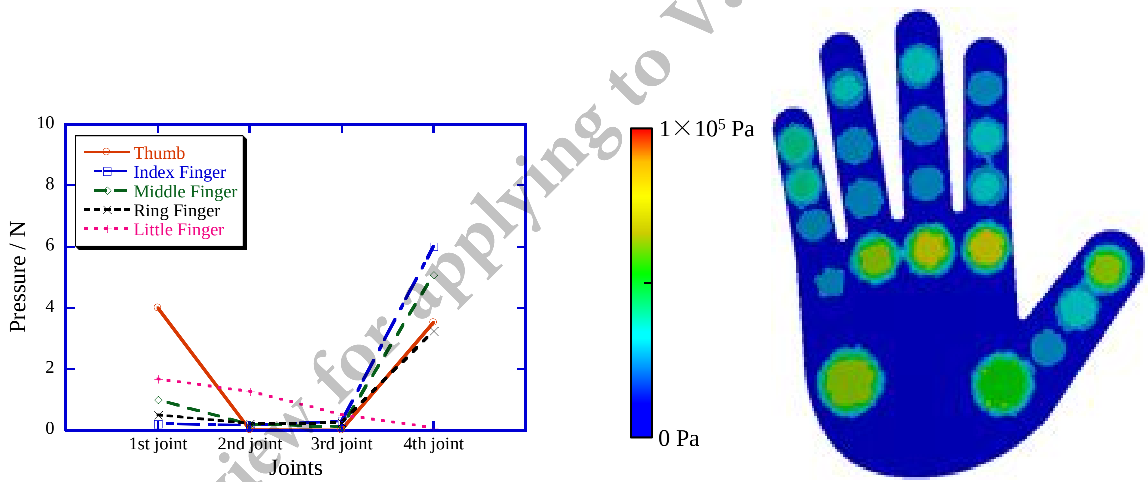
The measurement and visualization of the grip type is conducted based on the data obtained through the flex sensors and pressure sensors of the smart glove. The test procedure is accomplished by a professional badminton athlete and a badminton amateur. Each movement is conducted for 15 times and the average value of them is taken as the result. The concentration of this work is to develop the smart glove and the visualization method based on it, where the kinematic and kinetic analysis is provided to verify whether the smart glove is feasible. Thus, two participants on the experiment stage is sufficient [18, 28]. In further work, in-depth investigation will be conducted by introducing more participants.

4. Results and discussion

The forehand grip is used to hit shots that are on the forehand side of your body and around the head shots. The badminton racket handle has two wide parts that are in line with face of the racket. The index finger should be pressed over one of the wider surfaces and the bottom 3 fingers hold the racket handle. The thumb can be adjusted comfortably anywhere near the wider surfaces to create a

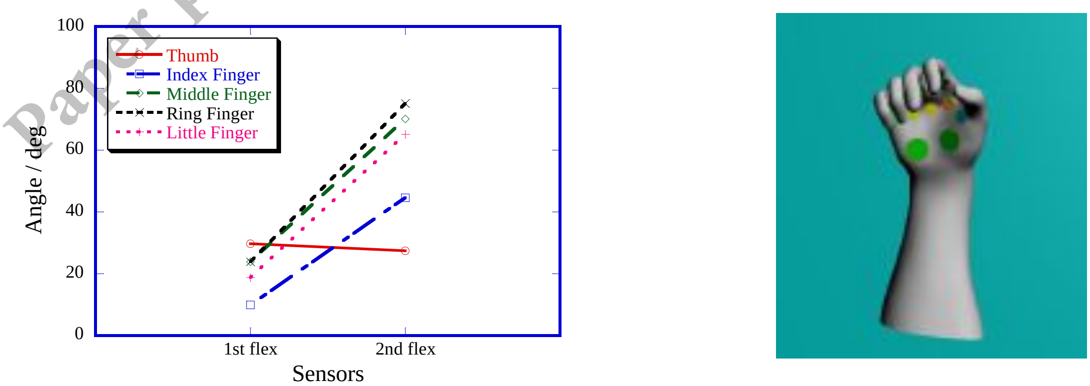
(a) (b)

Figure 6. Forehand grip of a professional athlete: (a) front view; (b) back view.



(a) (b)

Figure 7. The pressure distribution for the forehand grip of the professional athlete: (a) numerical detail; (b) 2D illustration.



(a) (b)

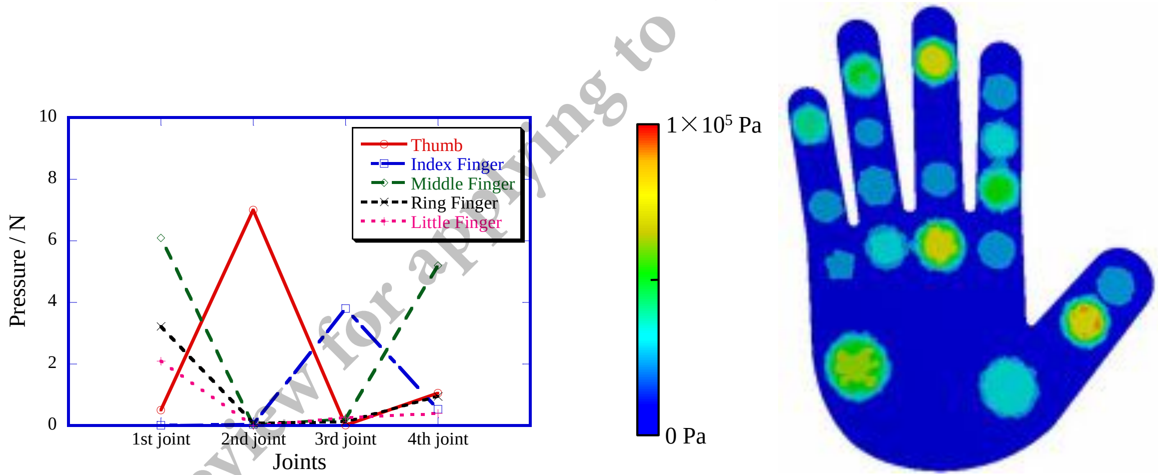
Figure 8. The kinematic and kinetic status for the forehand grip of the professional athlete: (a) numerical detail; (b) 3D illustration.

V-shape between the thumb and the index finger, which enable the players to switch grip quickly. It should be noted that the index finger should be the one "in control" in a forehand stroke. It means the index finger is used to push the racket forward when doing a forehand stroke.

The backhand grip is used for all shots on your backhand side which is just the opposite side to your forehand side. While playing a backhand shot, the thumb should be placed on one of the wider surfaces of the handle and the index finger should be relaxed and moved closer to the middle finger.

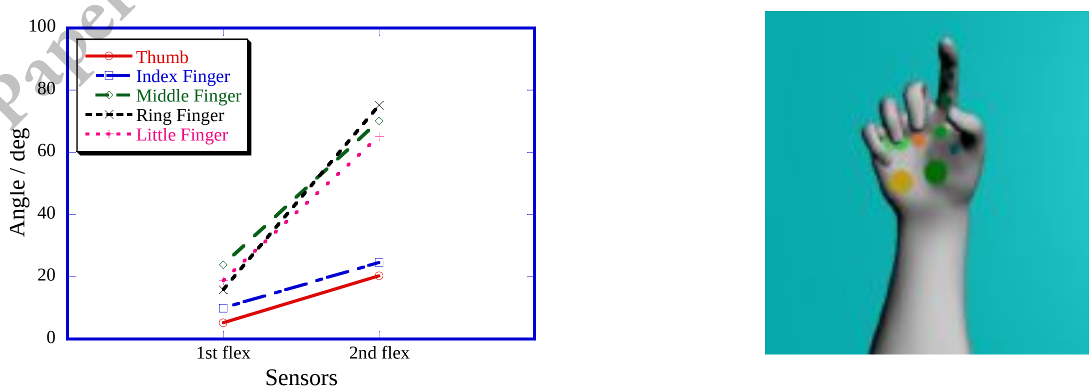
(a) **(b)**

Figure 9. Forehand grip of an amateur: (a) front view; (b) back view.



(a) **(b)**

Figure 10. The pressure distribution for the forehand grip of the amateur: (a) numerical detail; (b) 2D illustration.



(a) **(b)**

Figure 11. The kinematic and kinetic status for the forehand grip of the amateur: (a) numerical detail; (b) 3D illustration.

The backhand grip resembles a 'thumbs up' action, and the power of a backhand shot comes from the push of the thumb.

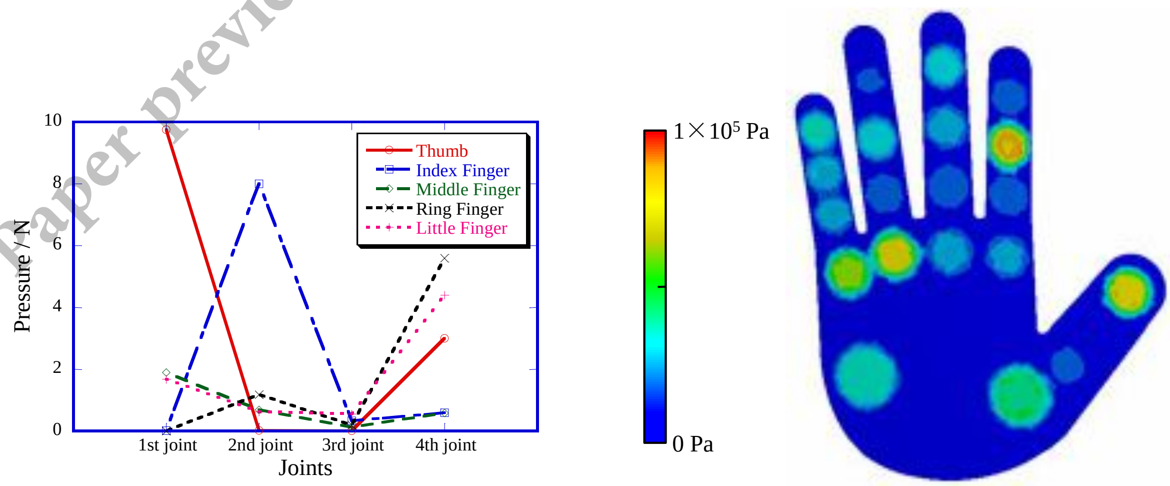
The forehand grip is studied in the first place, where Figures 6-8 illustrate the detail of a professional grip type and Figures 9-11 show the amateur one. Figures 6 and 9 show the grip posture of the athlete and the amateur, respectively.

From Figure 7(b), it can be seen that the main power generation points of professional players in the forehand grip are the root of each finger and the edges of the palm, where other parts of the hand play subordinate roles. By contrast, in Figure 10(b), it can be observed that the pressure on the hand of an amateur concentrate towards the medium part of the thumb, the edge of the palm, and the fingertips of the left three fingers. The pressure on the thumb of the amateur will delay the control effect for the racket orientation, and the lack of force on the metacarpophalangeal joints of the index and ring finger will curtail the strength of the shuttle.

As shown in Figure 8 (b), for the flex characteristics, the orderly arranged 4 fingers can fix the purlicue of the athlete and the racket face be on the same direction. Yet the disorderly distributed fingers of the amateur in Figure 11 (b) deviate the purlicue from the racket face, which may decrease the accuracy and power of the shot. Moreover, although the joint angles of the middle finger, ring finger and little finger are approximately the same between athlete and amateur, the strength of the professional comes from 4th joints of these fingers, yet the amateur uses his weak finger tips, which

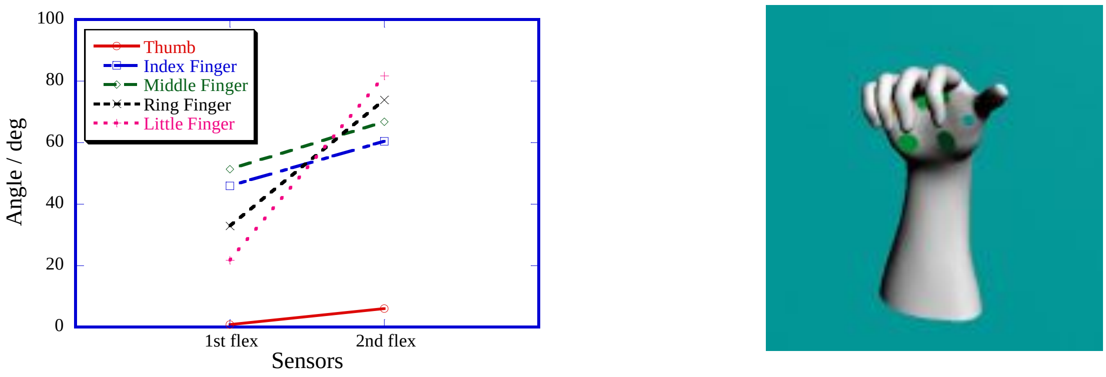
(a) **(b)**

Figure 12. Backhand grip of a professional athlete: (a) front view; (b) back view.



(a) **(b)**

Figure 13. The pressure distribution for the backhand grip of the professional athlete: (a) numerical detail; (b) 2D illustration.



(a) **(b)**

Figure 14. The kinematic and kinetic status for the backhand grip of the professional athlete: (a) numerical detail; (b) 3D illustration.

is the main reason for an unsatisfied shot. This cannot be solely concluded from gloves with single pressure or flex sensing ability.

The flowing experiment is about the backhand grip, and the illustrations are shown in Figures 12-17. Figures 12 and 15 show the grip posture of the athlete and the amateur, respectively.

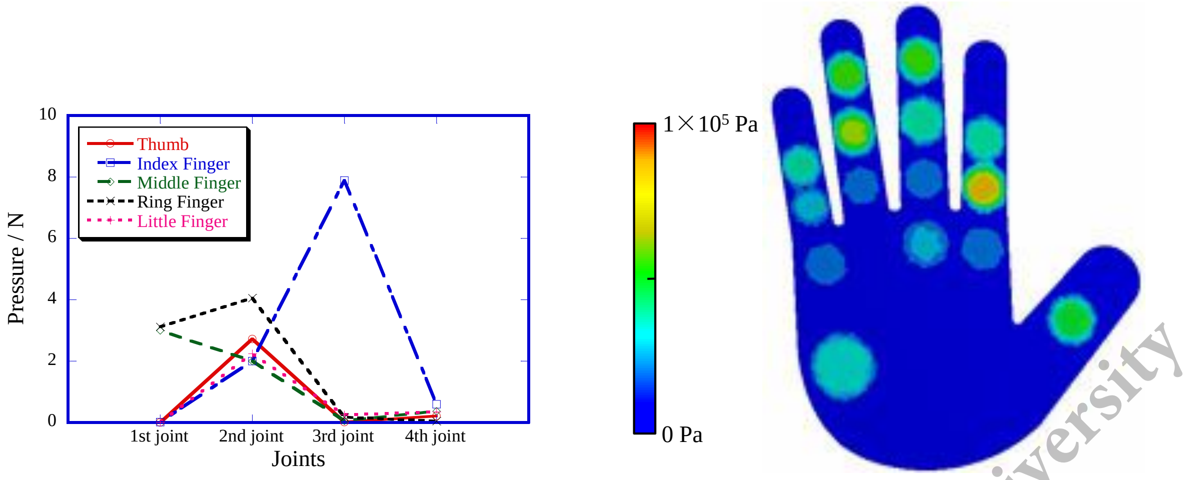
From Figure 13(b), it can be seen the pressure distribution of the hand for the backhand grip of the professional athlete. The root of each finger, the fingertip of the thumb, and the middle section of the index finger contribute the strongest holding forces for the backhand grip in the professional movement. Differ from the skilled ones, in Figure 16(b), the amateur mainly employs his middle and top part of the middle and ring finger to hold the racket, where the four fingers tightly hold the handle and block the thumb from exerting sufficient pressure for a success hit.

As can be seen from Figures 14 and 17, the bending angle of each finger of the professional backhand grip is almost the same as the forehand grip except the thumb, which makes him easy to change the grip type during the game. However, the wrapping way of the amateur makes it unable to change the grip type rapidly. Moreover, the disorderly laid index finger withdrew the holding power of it, which degrades the strength exerted for the backhand movement and will lead to distorted flying trajectory of the ball.

During the experiment, the glove is tested for more than 60 times during the experiment, and have been put on/off for several times. Yet the performance of it remains intact, which demonstrates the anti-interfere ability of the whole system.

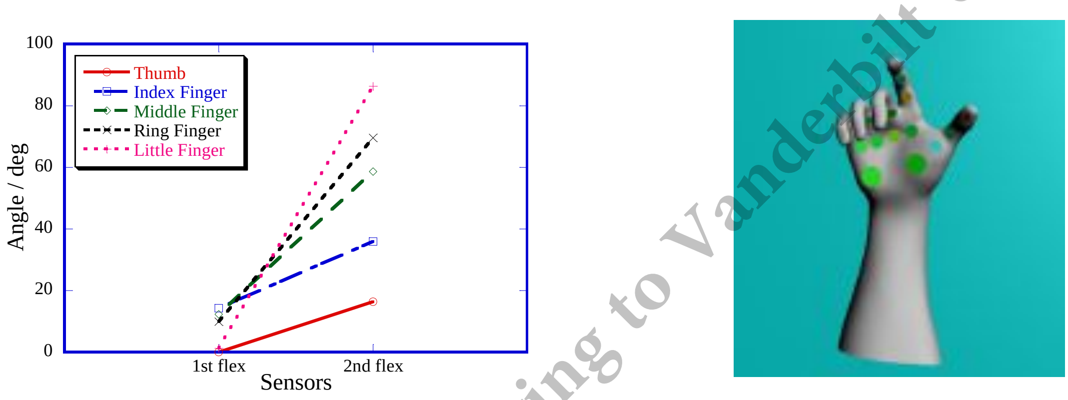
(a) **(b)**

Figure 15. Backhand grip of an amateur: (a) front view; (b) back view.



(a) **(b)**

Figure 16. The pressure distribution for the backhand grip of the amateur: (a) numerical detail; (b) 2D illustration.



(a) **(b)**

Figure 17. The kinematic and kinetic status for the backhand grip of the amateur: (a) numerical detail; (b) 3D illustration.

5. Conclusions

In this paper, a smart glove with flex sensor array and pressure sensor array is proposed for capturing the hand kinematics and kinetics. The glove is constructed by 10 flex sensors and 21 pressure sensor for measuring the joint angles and pressure of the hand. A visualization method is also proposed in this paper. The hand kinematics and kinetics of two badminton grip type are investigated to verify the measurement and visualization of the smart glove. Results revealed the difference of the joint bending angles and finger pressure between an athlete and an amateur, which can provide great help for the couches and trainees in the badminton lesson. Moreover, combining the pressure distribution with the flex status can assist the user to identify the main cause of the movement distortion.

Author Contributions: Conceptualization, Y.P. and L.L.; Methodology, Y.P. and L.L.; Software, X.S. and B.H..; Validation, M.Z; Formal analysis, M.Z.; Investigation, Y.P. and B.H.; Writing—original draft preparation, Y.P. and X.S.; Writing—review and editing, Y.P. and L.L.; Supervision, L.L.; Project administration, Y.P. and L.L.; Funding acquisition, Y.P. and L.L..

Funding: This research was supported by the Fundamental Research Funds for the Central Universities (No. 2018QNA224, X20190213), Zhejiang Province Qian Jiang Talent Program of 2018 (No. QJC1802009), Zhejiang Province Natural Science Foundation of China (No. Q19C100004), the National Natural Science Foundation of China (No. 61977012), MOE (Ministry of Education in China) Project of Humanities and Social Sciences (No. 19YJCZH126), the Fundamental Research Funds for the Key Research Program of Chongqing Science & Technology Commission (grant nos. cstc2017rgzn-zdyf0064), and the “Double First-Class” Construction Fund of Zhejiang University.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Phomsoupha, M.; Laffaye, G. The Science of Badminton: Game Characteristics, Anthropometry, Physiology, Visual Fitness and Biomechanics. *Sports Med* **2015**, 45, 473-495, doi:10.1007/s40279-014-0287-2.
2. Gawin, W.; Beyer, C.; Hasse, H.; Busch, D. How to attack the service: an empirical contribution to rally opening in world-class badminton doubles. *Int J Perf Anal Spor* **2013,** 13, 860-871.
3. Sakurai, S.; Ohtsuki, T. Muscle activity and accuracy of performance of the smash stroke in badminton with reference to skill and practice. *J Sport Sci* **2000**, 18, 901-914, doi: 10.1080/026404100750017832.
4. Badminton Gripping The Racket. Available online: https://www.teachpe.com/sports-coaching/badminton/badminton-skills-techniques/badminton-gripping-the-racket (accessed on 02 August 2019).
5. Dong, K.; Deng, J.; Ding, W.; Wang, A.C.; Wang, P.; Cheng, C.; Wang, Y.-C.; Jin, L.; Gu, B.; Sun, B., et al. Versatile Core-Sheath Yarn for Sustainable Biomechanical Energy Harvesting and Real-Time Human-Interactive Sensing. *Advanced Energy Materials* **2018**, 8, doi:10.1002/aenm.201801114.
6. Koseoglu, M.; Celik, O.M.; Pektas, O.; Ieee. Design of a smart glove for monitoring finger injury rehabilitation process via MQTT server; 2018 2nd International Symposium on Multidisciplinary Studies and Innovative Technologies **2018**; pp. 620-625.
7. Mendes, J.J.A., Jr.; Marinho Vieira, M.E.; Pires, M.B.; Stevan, S.L., Jr. Sensor Fusion and Smart Sensor in Sports and Biomedical Applications. *Sensors* **2016**, 16, doi:10.3390/s16101569.
8. Calderita, L.V.; Bandera, J.P.; Bustos, P.; Skiadopoulos, A. Model-Based Reinforcement of Kinect Depth Data for Human Motion Capture Applications. *Sensors-Basel* **2013**, 13, 8835-8855, doi:10.3390/s130708835.
9. Cakic, N.S.; Popovic, M.B. Battery Operated Smart Device for Human Movement Measurement Based on Android OS Platform and Bluetooth Technology. 2014 12th Symposium on Neural Network Applications in Electrical Engineering (Neurel) **2014**, 173-177.
10. Salim, M.S.; Lim, H.N.; Salim, M.S.M.; Baharuddin, M.Y. Motion analysis of arm movement during badminton smash. In Proceedings of 2010 IEEE EMBS Conference on Biomedical Engineering and Sciences (IECBES), 30 Nov.-2 Dec. **2010**; pp. 111-114.
11. Metcalf, C.D.; Robinson, R.; Malpass, A.J.; Bogle, T.P.; Dell, T.A.; Harris, C.; Demain, S.H. Markerless Motion Capture and Measurement of Hand Kinematics: Validation and Application to Home-Based Upper Limb Rehabilitation. *IEEE Transactions on Biomedical Engineering* **2013**, 60, 2184-2192, doi:10.1109/TBME.2013.2250286.
12. Shan, C.Z.; Ming, E.S.L.; Rahman, H.A.; Fai, Y.C. Investigation of upper limb movement during badminton smash. In Proceedings of 2015 10th Asian Control Conference (ASCC), 31 May-3 June **2015**; pp. 1-6.
13. Jacob, A.; Wan Zakaria, W.N.; Tomari, R. Implementation of Bluetooth communication in developing a mobile measuring device to measure human finger movement; *ARPN Journal of Engineering and Applied Sciences* **2015**; Vol. 10, pp. 8520-8524.
14. Jacob, A.; Wan Zakaria, W.N.; Tomari, R.; Tee, K.; Azwani, A. Wearable flex sensor system for multiple badminton player grip identification; American Institute of Physics Conference Series. American Institute of Physics Conference Series **2017**; Vol. 1883, pp. 020036.
15. Makableh, Y.F.; Ghabashneh, E.; Harahsheh, T.; Khwaileh, F. Smart Muscle Strength Assessment Glove for Rehabilitation Purposes; 2019 Jordan International Joint Conference on Electrical Engineering and Information Technology **2019**; pp. 648-652.
16. Santos, L.; Carbonaro, N.; Tognetti, A.; Luis Gonzalez, J.; de la Fuente, E.; Carlos Fraile, J.; Perez-Turiel, J. Dynamic Gesture Recognition Using a Smart Glove in Hand-Assisted Laparoscopic Surgery. *Technologies* **2018**, 6, doi:10.3390/technologies6010008.
17. Pezzuoli, F.; Corona, D.; Corradini, M, L. Improvements in a Wearable Device for Sign Language Translation. 2019 International Conference on Applied Human Factors and Ergonomics 2019; Vol. 973
18. Li, K.; Chen, I.M.; Yeo, S.H.; Lim, C.K. Development of finger-motion capturing device based on optical linear encoder. *Journal of rehabilitation research and development* **2011**, 48, 69-82, doi:10.1682/Jrrd.2010.02.0013.
19. Deng, J.; Zhuang, W.; Bao, L.; Wu, X.; Gao, J.; Wang, B.; Sun, X.; Peng, H. A tactile sensing textile with bending-independent pressure perception and spatial acuity. *Carbon* **2019** 149:63-70. doi: 10.1016/j.carbon.2019.04.019

20. Wang, P.; Sun, B.; Liang, Y.; Han, H.; Fan, X.; Wang, W.; Yang, Z. A stretchable and super-robust graphene superhydrophobic composite for electromechanical sensor application. *Journal of Materials Chemistry A* **2018** 6 (22):10404-10410. doi: 10.1039/c8ta01923a
21. Zuruzi, AS.; Haffiz, TM.; Affidah, D.; Amirul, A.; Norfatriah, A.; Nurmawati, MH. Towards wearable pressure sensors using multiwall carbon nanotube/polydimethylsiloxane nanocomposite foams. Materials & Design **2017** 132:449-458. doi: 10.1016/j.matdes.2017.06.059
22. Muralidhar, A.; Bishu, R, R.; Hallbeck, M, S. The development and evaluation of an ergonomic glove. *Applied ergonomics* **1999**, 30(6), 555-563, doi: 10.1016/S0003-6870(99)00005-8
23. I-MOTION SENSORS. Available online: URL: http://www.imsensorhub.com/sensor.html (accessed on 1/7/2019).
24. Virgala, I.; Kelemen, M.; Mrkva, S.: Kinematic analysis of humanoid robot hand. *Am. J. Mech. Eng* **2013**, 1(7), 443–446, doi: 10.12691/ajme-1-7-58
25. Flex Sensor 2.2". Available online: URL: https://www.sparkfun.com/products/10264 (accessed on 1/7/2019)
26. Li, J.S.; Qu, Y.G.; Hua, H.X. Hydroelastic analysis of underwater rotating elastic marine propellers by using a coupled BEM-FEM algorithm. *Ocean Eng* **2017**, 146, 178-191, doi:10.1016/j.oceaneng.2017.09.028.
27. Shin, I.-S.; Beirami, M.; Cho, S.-J.; Yu, Y.-H. Development of 3D Terrain Visualization for Navigation Simulation using a Unity 3D Development Tool; *Dermatologic Surgery* **2015**; Vol. 39, pp. 570-576, doi: 10.5916/jkosme.2015.39.5.570
28. Hsiao, P.C.; Yang, S.Y.; Lin, B.S.; Lee, I.J.; Chou, W. Data Glove Embedded with 9-Axis IMU and Force Sensing Sensors for Evaluation of Hand Function. *IEEE Eng Med Bio* 2015, 4631-4634.