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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.

Cover Letter

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Dear Editorial Office,

We hereby submit the manuscript entitled
"A flexible, attachable and low-cost IMU-based motion capture system for measurement of hand kinematics"
by authors
Bingcheng Hu, Tian Ding, Yuxin Peng, Mingming Zhang, Qiang Yang
to be considered for publication in *Biomedical Signal Processing and Control*.

This article describes a flexible, attachable and low-cost IMU-based motion capture system for measurement of hand kinematics. Twelve 6-axis IMUs were employed in the system and each of them was bonded to a flexible adapter. The adapter was not only attachable for precisely fixing the position of the IMU to the back of the hand, but also flexible for wearing on different sizes of hands. Compared with traditional glove-based hand motion capture systems, people could grip an object directly without any disturbance.
We believe these contents will be of interest to the readers of your journal.

We declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere. The manuscript has been read and approved by all named authors. We hope you'll find our manuscript suitable for publication, and look forward to hearing from you.

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

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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

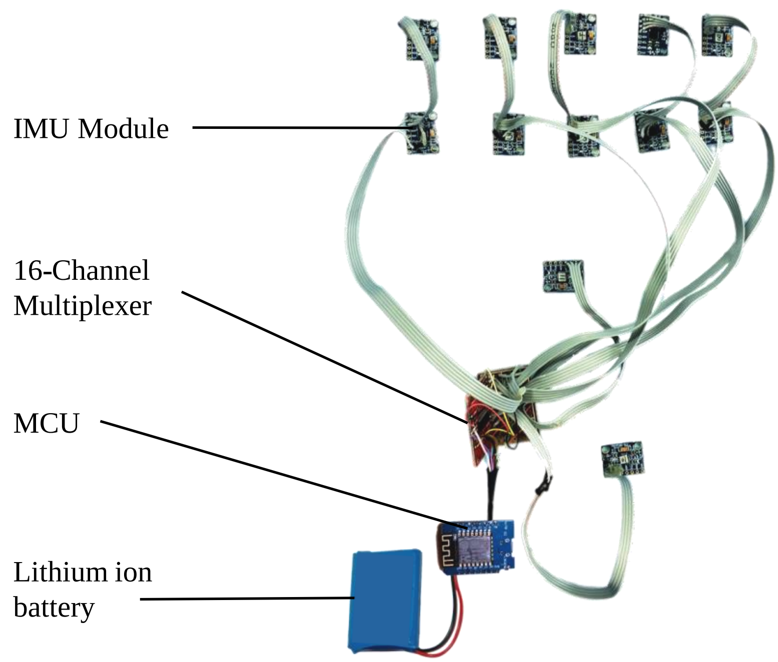


Fig 1. Structural design of the IMU-based motion capture system.

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

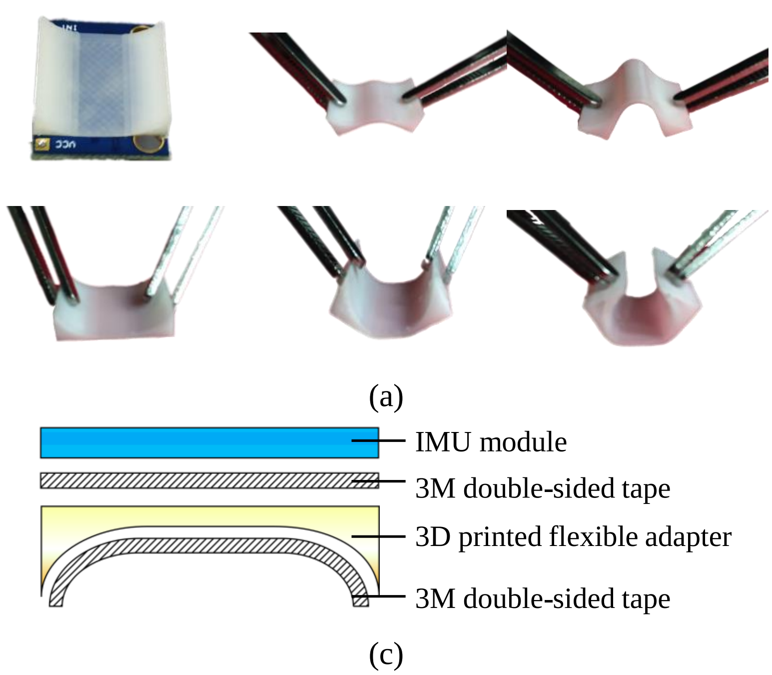


Fig 2. (a) 3D printed flexible adapter. (b) Explosion diagram of the cross-section.

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.

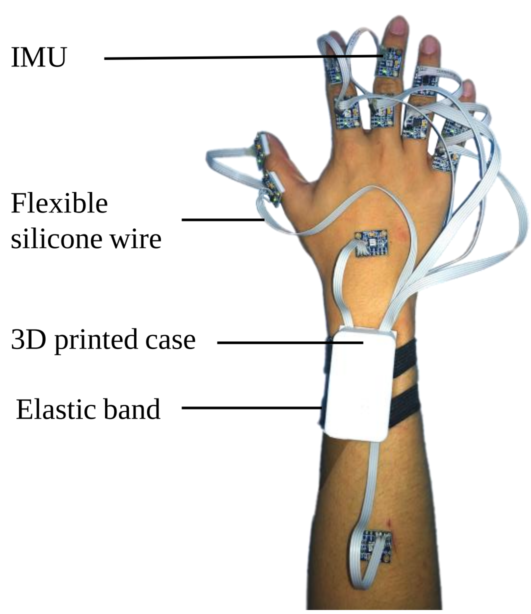
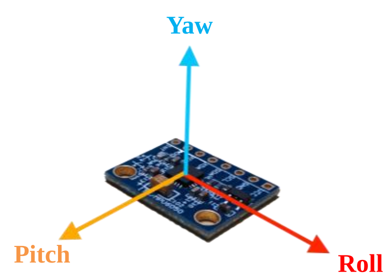
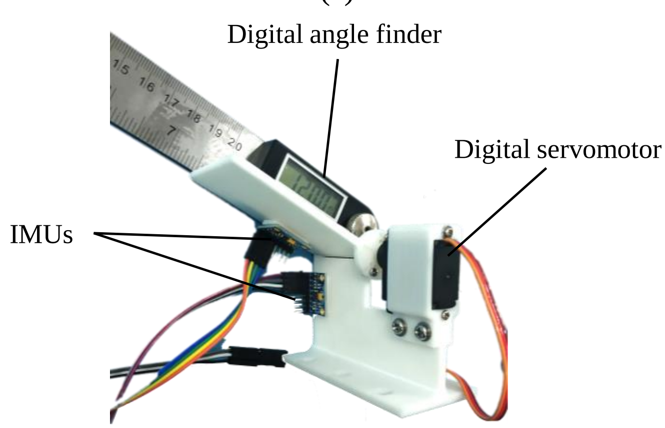


Fig 3. The appearance of the IMU-based motion capture system.

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.



(a)



(c)

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

2.2.2. Dynamic calibration

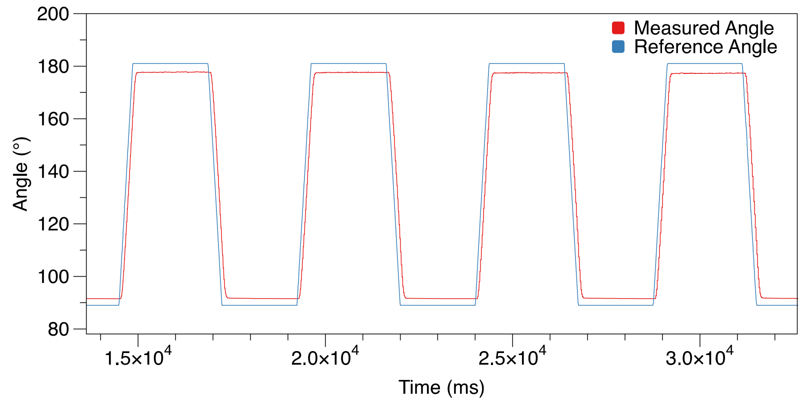
To verify the IMU performance during hand movement, dynamic angle calibration was also conducted, and a corresponding calibration device was designed as shown in Fig. 4b. An LX-16A Serial bus digital servomotor was employed to generate bending motions repeatedly to the device. There was a built-in angle 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.

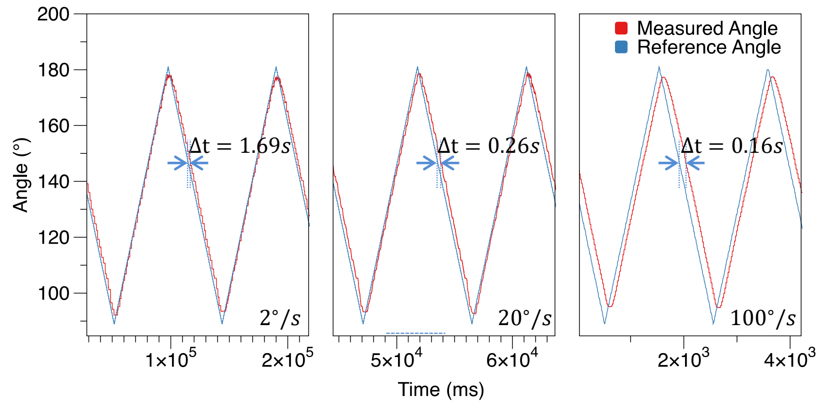
To measure the delay of the IMUs, the servo motor was driven from 90° to 180° repeatedly at three different angular velocities of 2°/sec, 20°/sec, and 100°/sec, respectively. Fig. 5b shows the angular output of the IMUs and the servo at different angular velocities. The RMSDs and time shift are summarized 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



(a)



(c)

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.

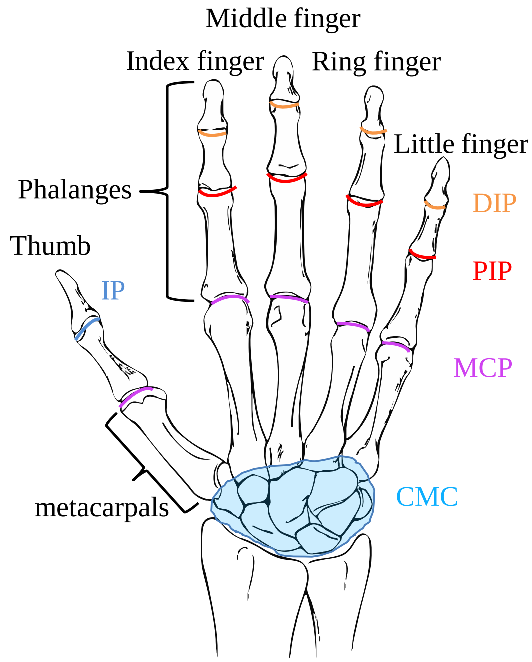
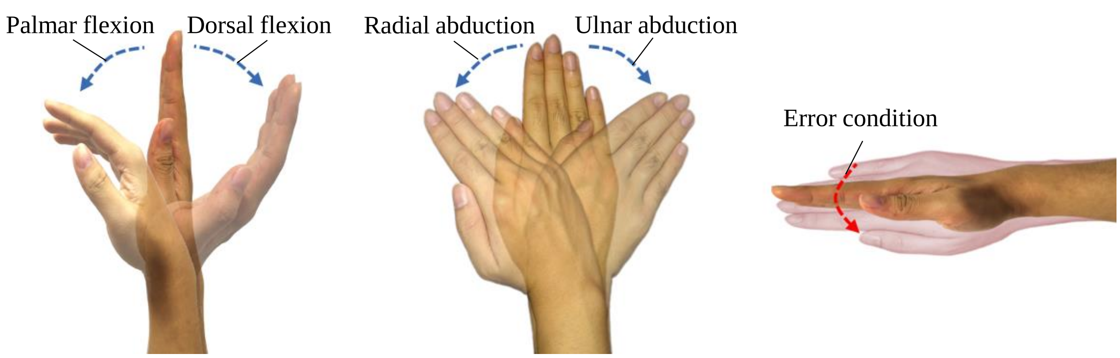


Fig 6. Terminology of the fingers and joints.



(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

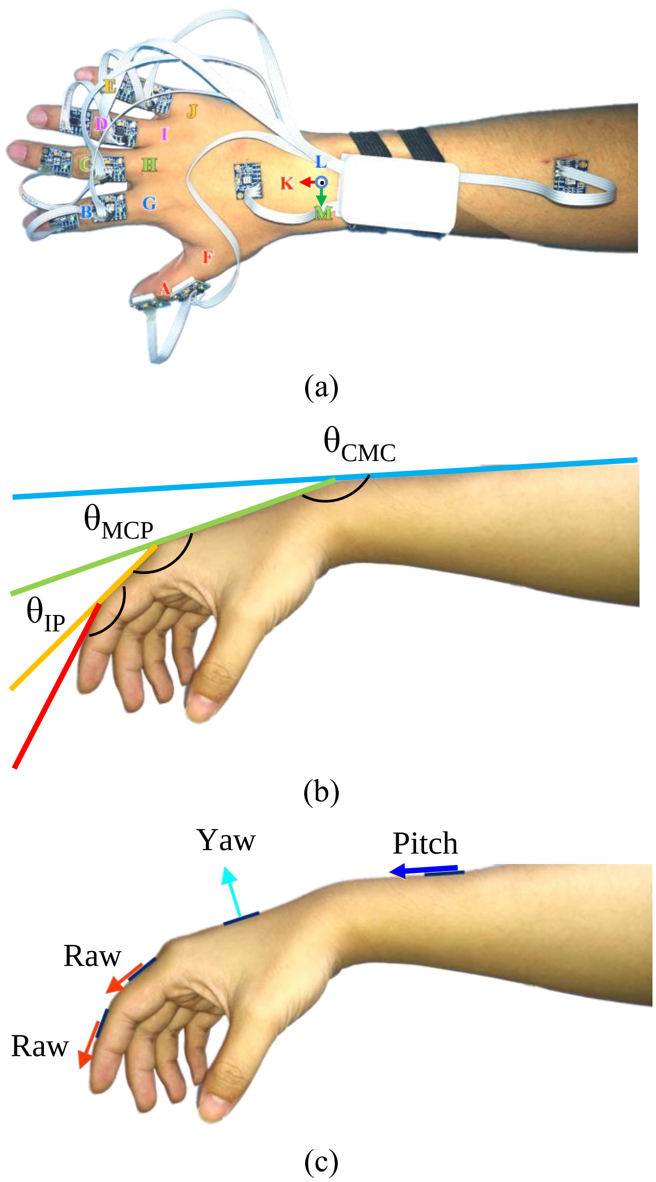


Fig 8. (a) The numbering method of the joints. (b) Joint angles for hand movement. (c) One particular axis on each IMU that’s selected in this study.

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].

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

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

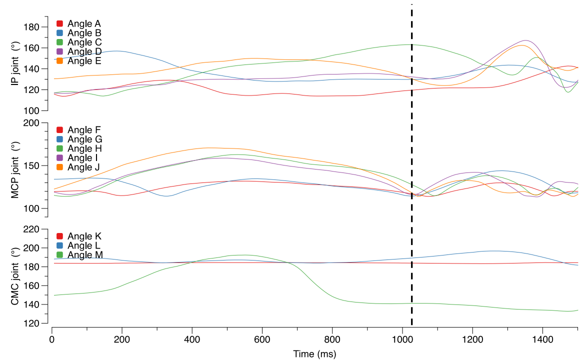
where q is the quaternion, and v is the vector to rotate. v is a unit vector, which means there is one variable of x, y, and z to be 1 and the others to be 0. In this way, the new vector after rotation w can be calculated. The formula for solving the angle between two vectors is shown as follows:

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

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



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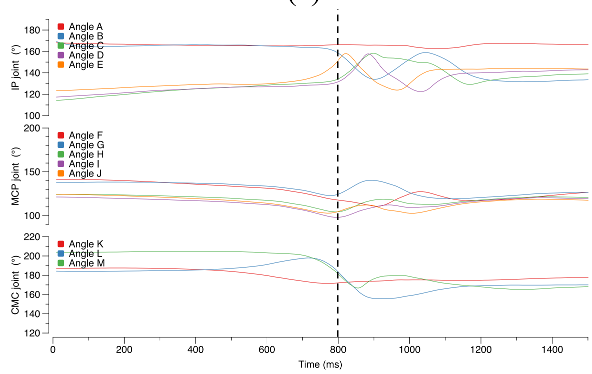

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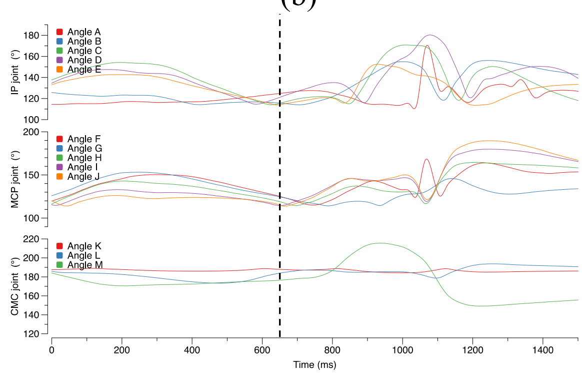

(c)

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

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Figure Legends

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

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

Fig. 3. Appearance of the IMU-based motion capture system.

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

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).

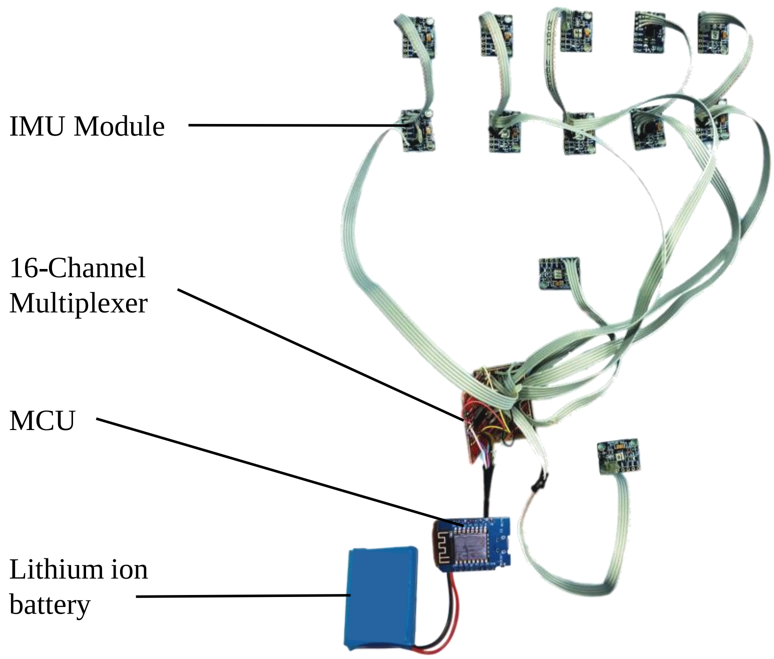
Fig. 6. Terminology of the fingers and joints.

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

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.

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

Figure



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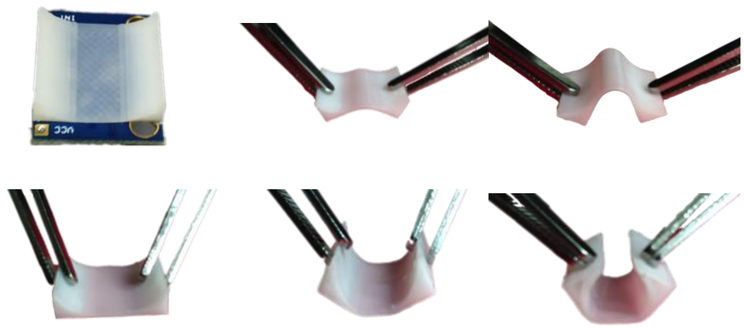

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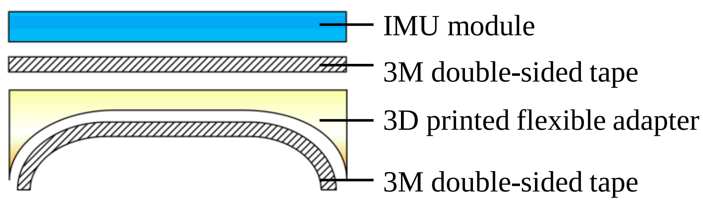

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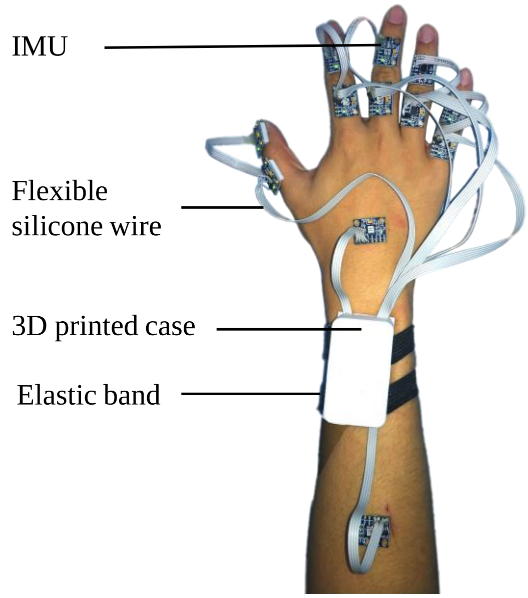

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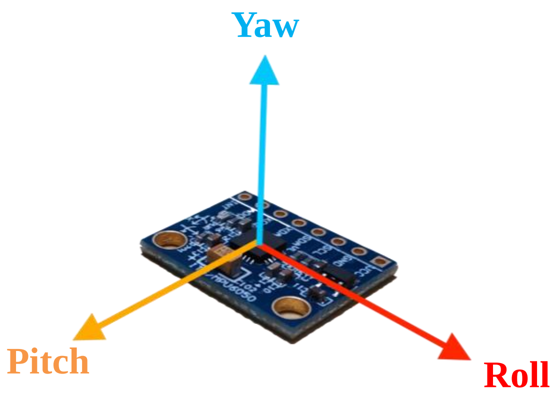

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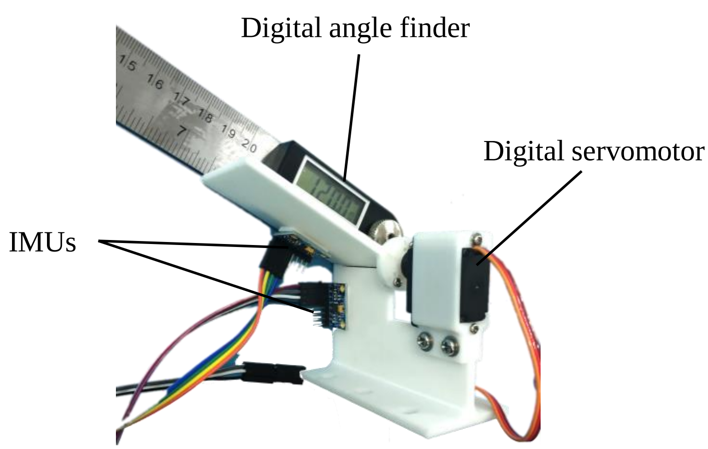

(b)

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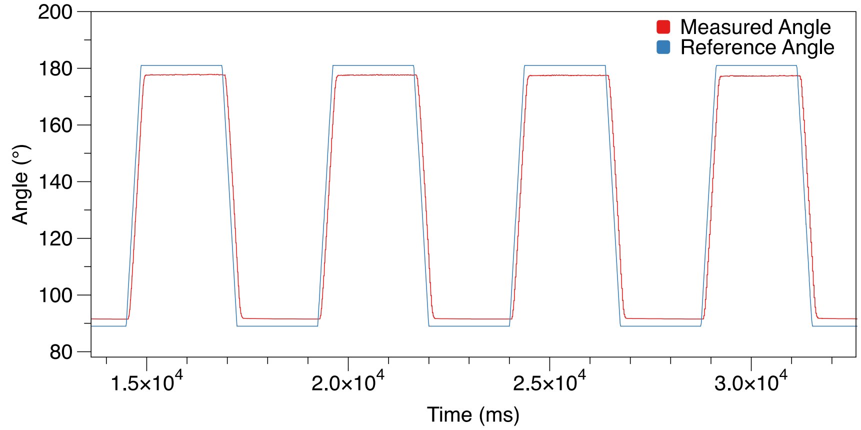

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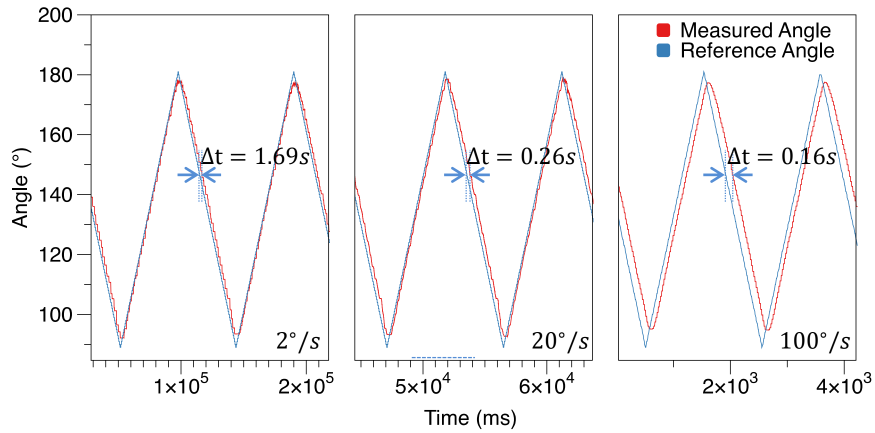

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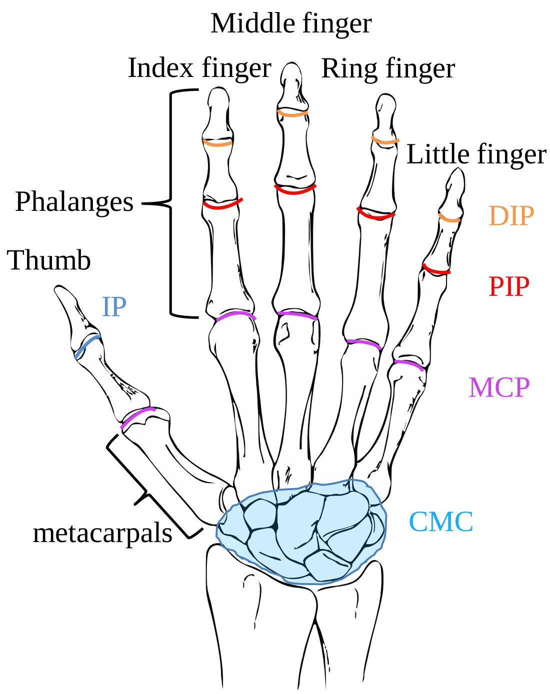

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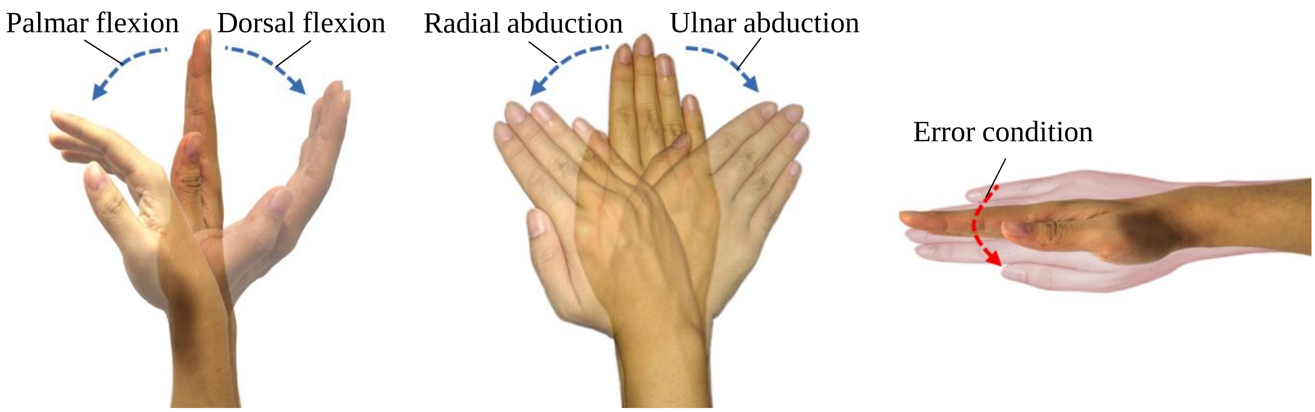

(a) (b) (c)

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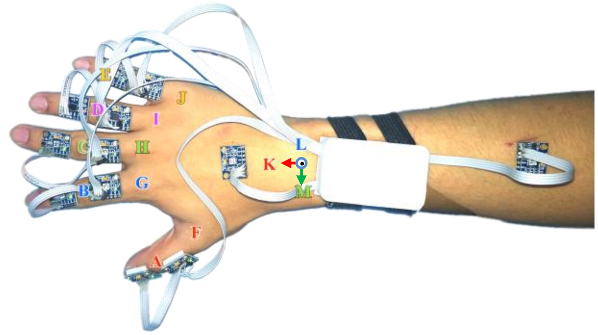

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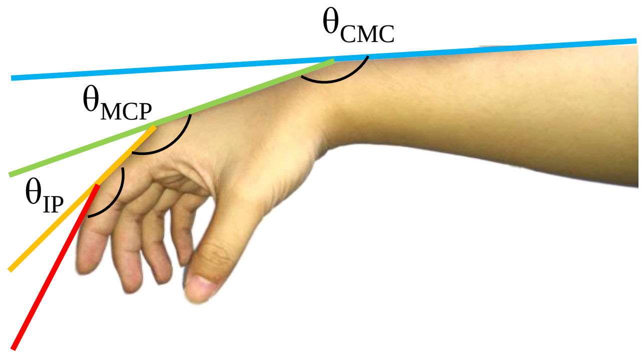

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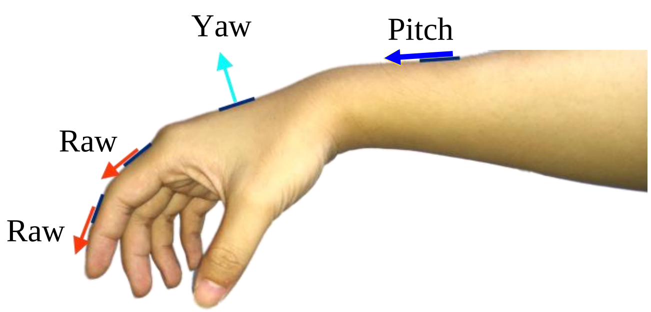

(c)

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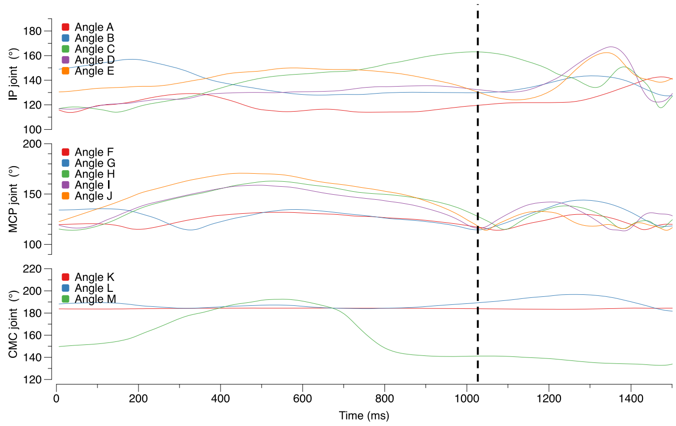

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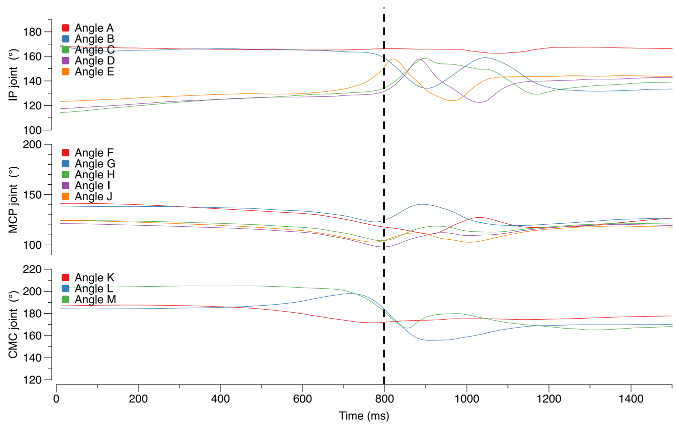

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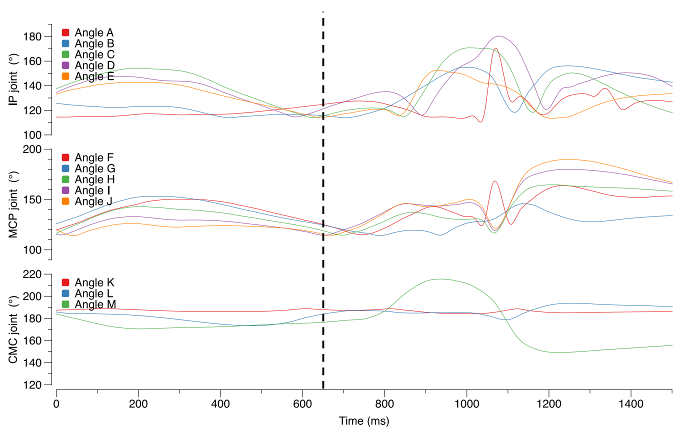

(c)

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Table 1
RMSDs and time shift at different angular velocities.

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

Conflict of Interest Statement

The authors declare no conflict of interest.