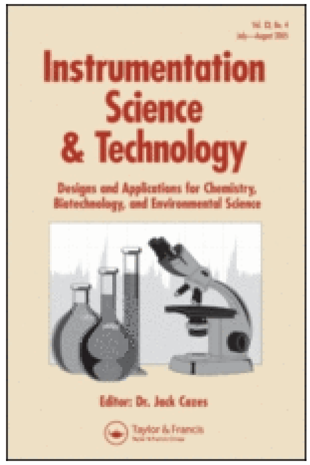

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Keywords:	Motion capture, inertial sensor, flexible sensor, hand kinematics

A flexible and attachable IMU-based motion capture system for measurement of hand kinematics: A pilot study

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A flexible and attachable IMU-based motion capture system for measurement of hand kinematics: A pilot study

This paper proposes a flexible and attachable IMU-based motion capture system for accurate measurement of hand kinematics. Twelve 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 back of the hand. Compared with traditional glove-based hand motion capture systems, the proposed system can be firmly attached to the back of the hand without any position deviation, and 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 badminton to capture hand kinematics for a pilot study. It was verified that the system is superior to traditional glove-based systems and can be used for measuring hand movements precisely and rapidly.

Keywords: Motion capture; inertial sensor; flexible sensor; hand kinematics

Introduction

Hand motions are of great significance in the fields of sports biomechanics, medical rehabilitation, gesture recognition, and VR games, etc.[1-4] Two typical types of hand motion capture approaches are non-contact 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.[5, 6] To capturing the hand kinematics precisely, contact-based systems are more practical.

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.[1-4, 7-14] Flex sensors based and IMU-based gloves are the most popular types reported in the literature.[1, 2, 7-11, 15] 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 a single degree of freedom (DOF), while the multi-DOF motion of the hand is needed to be measured. 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).[1, 2, 8] However, traditional glove-based systems have lots of disadvantages for hand motion capture. For example, the glove and the hand slide relative to each other, and the sensors on the glove will deviate from the original position during the hand movement, which leads to unreliable measuring results. Besides, 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 also lead to incorrect results.[3, 12, 13]

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. 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. Therefore, the original positions of the IMUs have no deviation even during strenuous exercise. Due to no glove used in the system, the hand can directly grip an object without external disturbance. Since badminton is a typical favorite sport by using rackets and require fine motion control of the hand,[1, 2, 12, 16, 17] the hand kinematics in badminton is studied as a pilot study to verify the performance of the proposed system.

Materials and methods

System architecture and design

As shown in Figure 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 are employed as the IMUs for measuring the hand movements in real-time. To connect the 12 IMUs to the main control chip, one chip of 16-channel multiplexer is applied to this system. The 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 with a maximum clock speed of 160

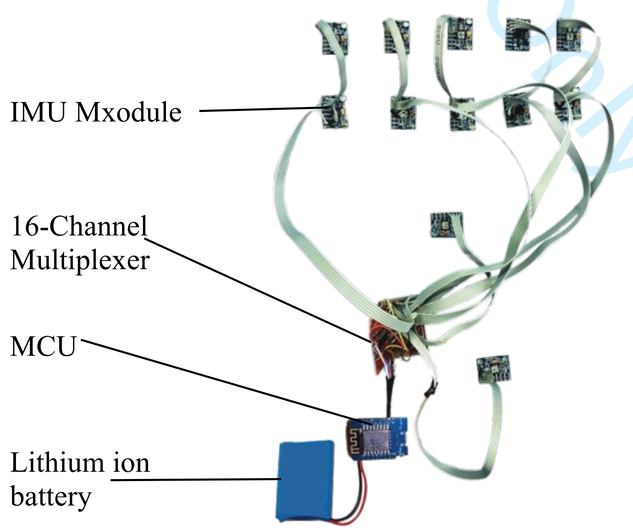
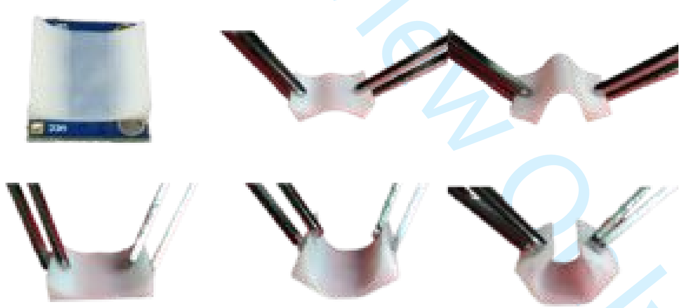


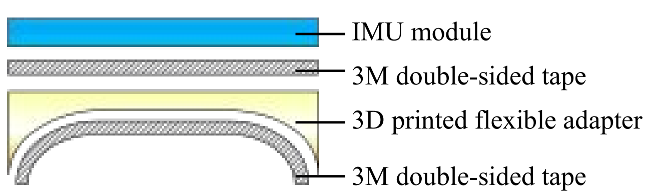
Figure 1. Structural design of the IMU-based motion capture system.

MHz is utilized as the MCU, which can launch a hotspot. The experimental data of the IMUs is transmitted to the computer through WiFi, which allows fast and stable communication for multiple devices at the same time.

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 the 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.[18] As shown in Figure 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. The flexible adapter can produce a relatively large deformation, which can make the adapter fit the



(a)



(b)

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

finger tightly and firmly fix the position of the IMUs. Besides, the U-shaped adapter is also flexible for wearing on different sizes of hands 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. In contrast, the flexible materials fit snugly against the fingers and can prevent people from feeling obstructed, and it can help people 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 Figure 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 the last 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.

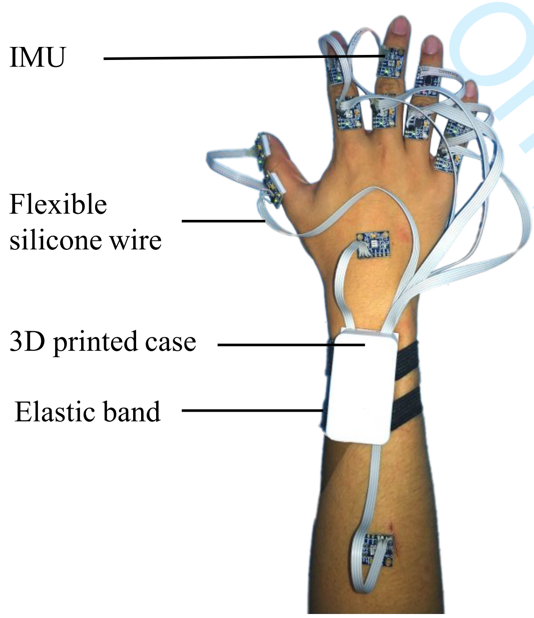


Figure 3. The appearance of the IMU-based motion capture system.

Algorithm and evaluation

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 Figure 4a. In the first static situation, the Roll axis was put vertically, and the rotation around the Pitch axis was measured. After processing 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, the 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

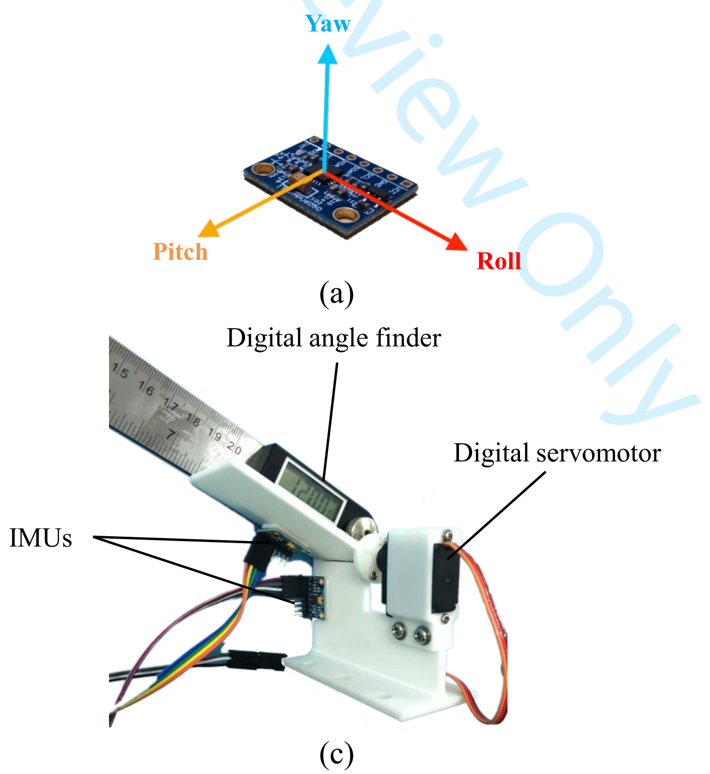


Figure 4. (a) Pitch, Roll and Yaw axis of the IMU. (b) Dynamic calibration for the IMUs.

Roll angle is that the gravity calibration needs to be adjusted according to the local gravity of the earth. The error of the angles was minimized after calibration of the sensor fusion algorithms and calibration procedures of the MPU-6050.

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 Figure 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 outputs of the servo and the IMUs were collected by an MCU simultaneously.

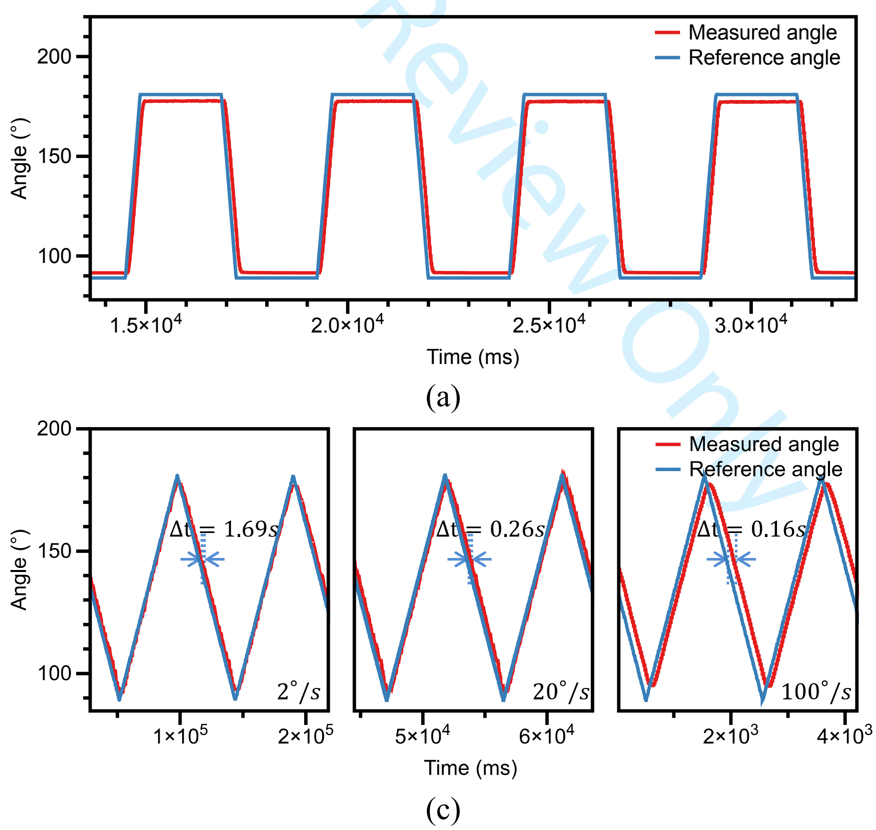


Figure 5. The measured angle between the IMUs is compared with the actual angle of the servo output at (a) square wave with a swift swing (400 °/s) and (b) triangular wave with different speeds (2 °/s, 20 °/s, 100 °/s).

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

To measure the actual angular range of the device during swift motion, the servo swung 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 Figure 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. Figure 5b shows the angular output of the IMUs and the servo at different angular velocities. The RMSDs and time shifts are summarized in Table 1. The RMSDs increased when the angular velocity increased, which means the measurement error of the 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.

Normal anatomy of human hands

The anatomy of the human hand is shown in Figure 6.[19] 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 Figure 7, one person can bend CMC joints to palmar (palm of the hand), dorsal (back of the hand) (Figure

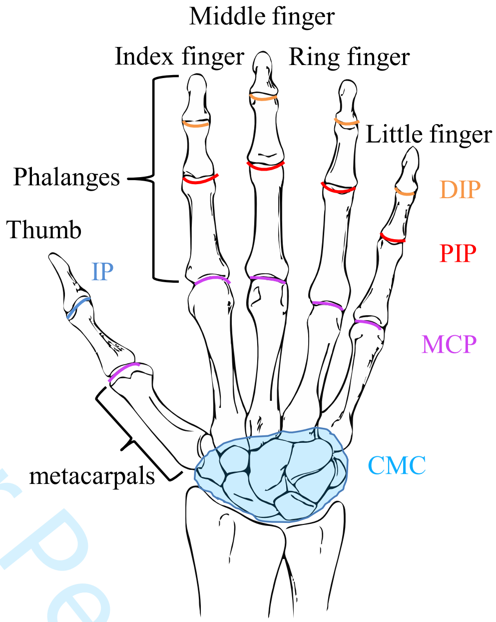


Figure 6. Terminology of the fingers and joints.

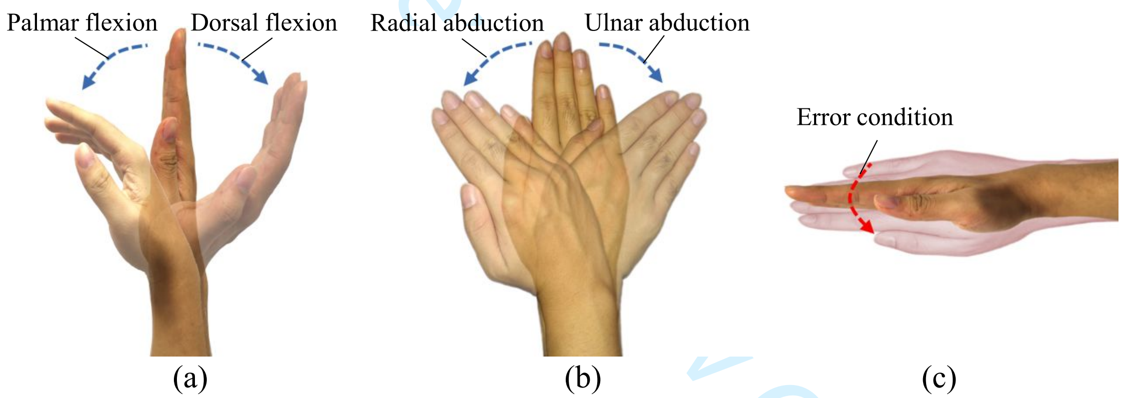


Figure 7. (a) Palmar flexion vs. dorsal flexion. (b) Radial abduction vs. ulnar abduction. (c) Impossible wrist rotation.

7a), radial (side of the thumb) and ulnar (side of the little finger) (Figure 7b) directions.[19] However, CMC joints cannot rotate in the direction of the arm (Figure 7c). In other words, when the human arm bone is fixed, the palm cannot rotate along the axis of the arm's direction.

Angle orientation

As can be seen from Figure 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 Figure 8a), five MCP joints (F to J in Figure 8a) and five PIP joints (IP joint for the thumb, A to E in Figure 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 and 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 though there were 13 angles calculated, only 12 of them could be put into valid discussion. The positive direction of the finger and hand movement is shown in Figure 8b. To calculate these angles, one particular axis on each IMU was defined to be the direction axis as in Figure 8c. Then, the quaternion was converted to 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.

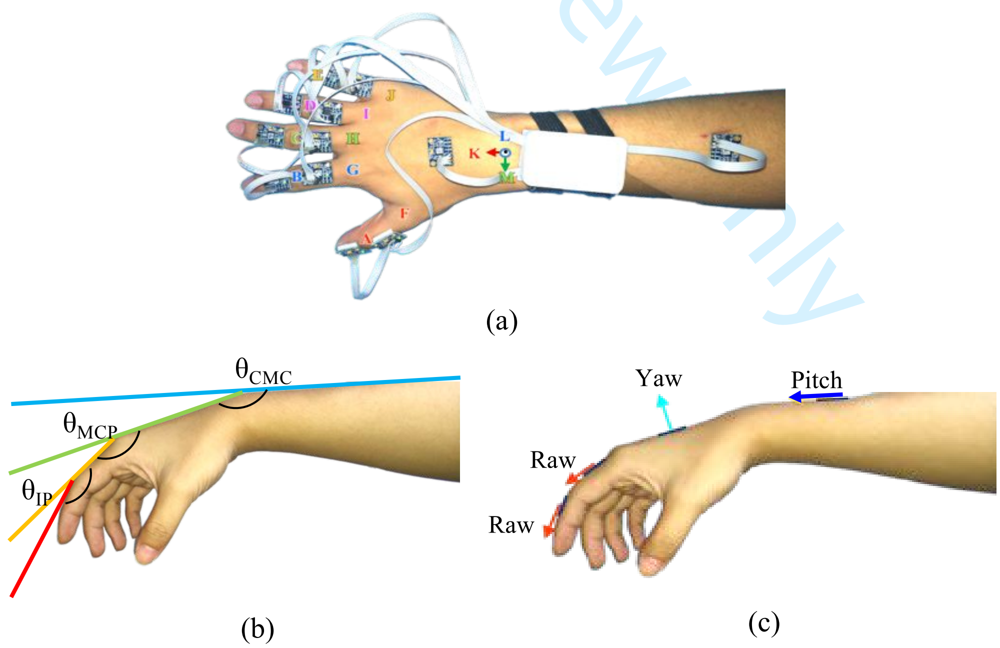


Figure 8. (a) The numbering method of the joints. (b) Joint angles for hand movements. (c) One particular axis on each IMU that's selected in this study.

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 in the 3D space is calculated as shown in Eq. (2).[20]

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

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

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:

$$\theta = a\cos\left(\frac{v \cdot w}{|v| \cdot |w|}\right) \tag{4}$$

Results and discussion

Comparison of the proposed system and the glove-based system

To verify the measurement performance superiority of the flexible and attachable IMU-based motion capture system, comparison experiments were carried out by the proposed system and a glove-based motion capture system. To eliminate the influence of the electric components on the experiments, the same electronic apparatus of the proposed system without flexible adapters was fixed to the back of a cotton glove to construct the glove-based system. As shown in Figure 9, three experiments were carried out for verification of the motion capture systems. In the first experiment, the IMUs were connected to the finger directly through flexible adapters of the proposed system (Figure 9 (a)). The second experiment is shown in Figure 9 (b), the IMUs were fixed to the glove to construct a glove-based motion capture system. In consideration of the slippage and rotation between the hand and the glove which may be caused by gripping an object, one IMU of the glove-based system was rotated by 20° in advance for the last experiment (Figure 9 (c)). In this

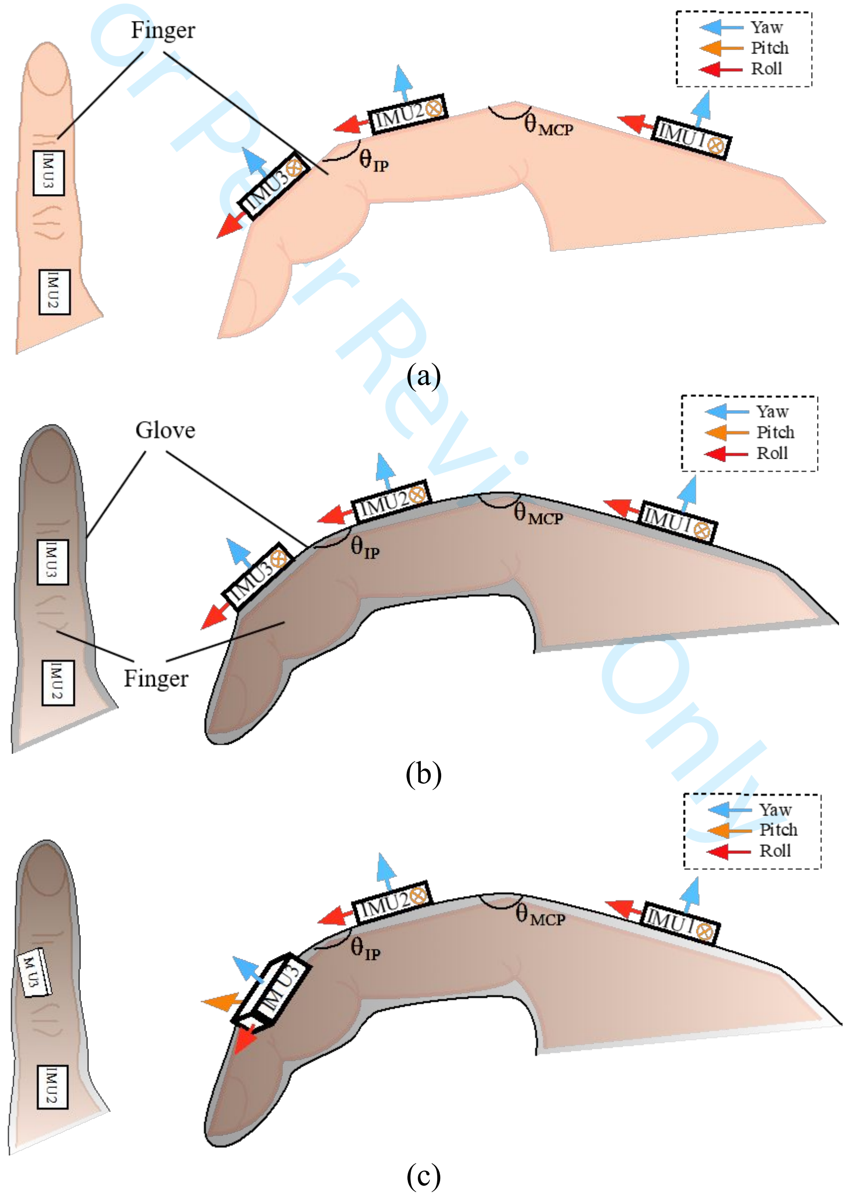


Figure 9. Experimental setups of (a) the proposed system, (b) glove-based system, and (c) glove-based system with rotation of an IMU.

study, the index finger was selected as the experimental finger and bent 15 times from 0° to 90° in each experiment.

To investigate the position deviation of the IMU, the differences of the IMU rotation error around the finger axis were compared during the three experiments. As shown in Figure 9, the IMU 1 on the back of the hand was used as a reference, and the angle between the pitch vector of the IMU 1 and that of the IMU 3 could be calculated for comparison. As shown in Table 2, the angle change can be calculated by the measured maximum and minimum rotation angle during the 15-cycle finger bending experiments. It can be seen that angle change was only 3° of the proposed system because the IMUs were firmly stick on the finger with the adapters. However, the angle change became 8° by using the glove-based system. If a pre-rotation angle existed in the glove-based system, angle change got as large as 14°. This is because the glove cannot be firmly attached to the human hand and large position deviation was caused by slippage or rotation between the hand and the glove. The results verified that the glove is a defective carrier for sensors, but the proposed system can be firmly attached to the hand without position deviation and measure the hand movement precisely.

To verify the repeatability of the proposed system and the glove-based system, the joint angle between the roll vector of the IMU 2 and that of the IMU 3 (the PIP joint angle) was measured in the experiments. As shown in Figure 10, both the proposed system and the

Table 2. The IMU rotation angle during the three experiments.

	Proposed system	Glove-based system	Glove-based system with rotation of an IMU
Maximum angle (°)	4	3	-19
Minimum angle (°)	1	-5	-5
Angle change (°)	3	8	-14

glove-based system show relatively good performance and the joint angles changed little during the 15-cycle finger bending experiments. However, if a pre-rotation angle existed in the glove-based system, the measured joint angle decreased approximately 15°. It means that the glove-based system is not applicable to the griping motion which slippage or rotation between the hand and the glove occurs. While using the proposed system, the repeatability error can be much small at any time.

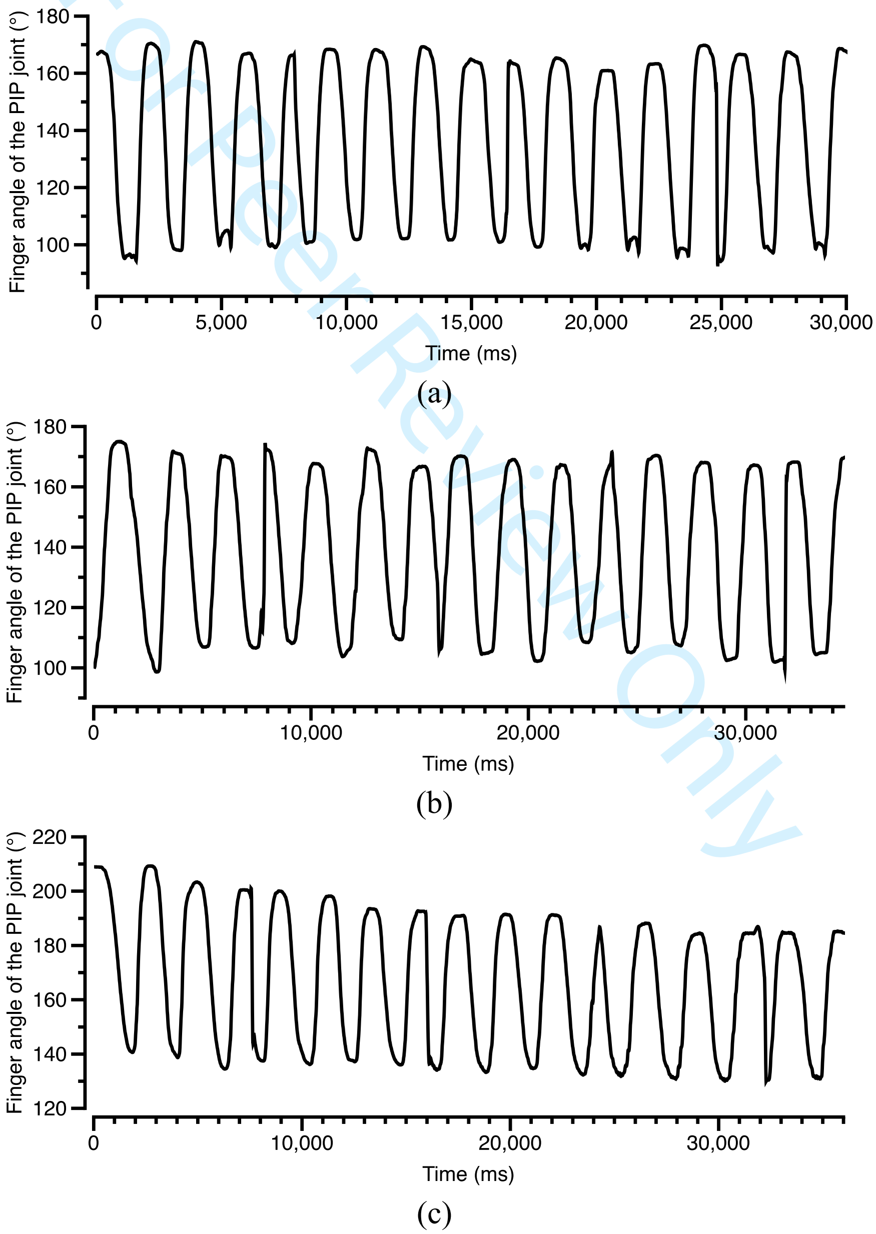


Figure 10. Finger angle of the PIP joint for (a) the proposed system, (b) glove-based system, and (c) glove-based system with rotation of an IMU.

Measurement of hand kinematics in badminton

Badminton is one of the most favorable sports by using rackets, which require fine motion control of the fingers and wrist.[12] Therefore, to verify the performance for the measurement of hand kinematics, the service motion in badminton was studied by using the proposed hand motion capture system. A professional athlete in badminton was invited to conduct the service motion as a pilot study. The service method for badminton 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".[21] 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.[16] Figure 11 shows the hand kinematics characteristics of the service motion. The angles A-M in Figure 11 are marked in Figure 8 (a). Since the hand should grip the racket tightly for stroking, the MCP joint angles should be minimum when the racket hit the shuttlecock. Therefore, a vertical dashed line near the minimum MCP joint angle was drawn to divide the change in hand movements to help analyze the service motion. Before the time of the vertical line, the athletes could finish the

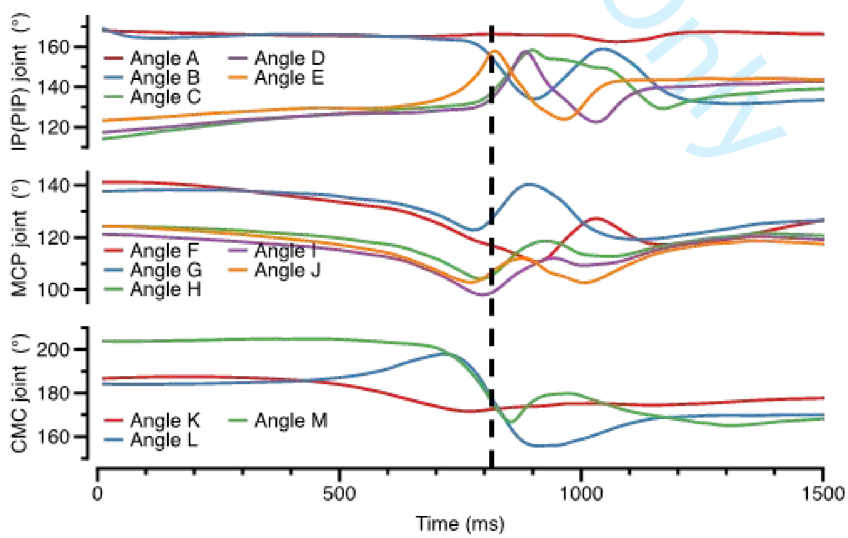


Figure 11. Hand joint angles of the service motion in badminton.

swing and stroke of the service motion.

As shown in Figure 11, the IP joint of the thumb almost had no movement because the thumb played as a fulcrum of a lever in the backhand long serve, which demonstrates that the backhand long serve used a firm "thumb grip" with little angle change of the IP joint. All the MCP joint angles decreased during the stroke process, and the angles of the thumb and index fingers were approximately 20° larger than that of the other three fingers. The decrease of the MCP joint angles indicates that the hand gripped the racket tightly for stroking. For the CMC joints, it can be seen that the angle K changed very little, which proves the illustration in Figure 7(c). On the other hand, the angles of the L and M decreased obviously, which demonstrates that the badminton's backhand service is a kind of complex special three-dimensional wrist-bending movement. The results verified that the hand kinematics in badminton can be precisely studied by the proposed system.

Conclusions

In conclusion, this pilot study designed and evaluated a flexible and attachable IMU-based hand motion capture system. 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 position deviation or external 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 in badminton was studied by using the proposed system. It was verified that the system could capture the motion of hands precisely and had promising potentials for studying the hand kinematics in many fields.

Acknowledgments

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Disclosure of Interest

The authors declare no conflict of interest.

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