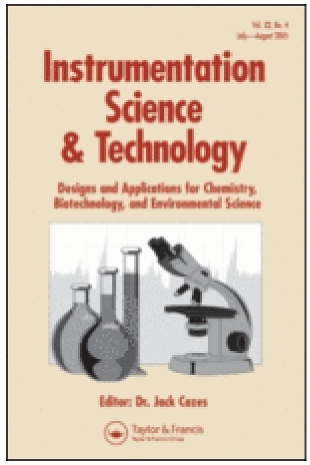


Characterization of the fine hand movement in badminton by a smart glove

Journal:	*Instrumentation Science & Technology*
Manuscript ID	LIST-2020-0037
Manuscript Type:	Original Research Paper
Date Submitted by the Author:	28-Feb-2020
Complete List of Authors:	Song, Xian; Zhejiang University, Department of Sports Science Peng, Yuxin; Zhejiang University, Department of Sports Science Hu, Bingcheng; Shanghai Jiao Tong University, University of Michigan-Shanghai Jiao Tong University Joint Institute Liu, Wenming; Zhejiang University, Department of Sports Science
Keywords:	Data glove, visualization, fine hand movement, badminton, kinematics and kinetics

Characterization of the fine hand movement in badminton by a smart glove

Xian Song [a], Yuxin Peng [a*], Bingcheng Hu [b], Wenming Liu [a]

[a]*Department of Sports Science, Zhejiang University, Hangzhou 310028, China;* [b]*University of Michigan-Shanghai Jiao Tong University Joint Institute, Shanghai Jiao Tong University, Shanghai, China*

*Corresponding author: Yuxin Peng; Address: Department of Sports Science, Zhejiang University, Hangzhou 310028, China. Tel: +86 18868118759. Email: yxpeng@zju.edu.cn.

Characterization of the fine hand movement in badminton by a smart glove

In a badminton game, dexterous fine hand movements are essential for the player to perform with extraordinary skill. Thus, this paper proposes a smart glove with proper sensing functions for finger pressures and bending angles for this sport to measure the kinematics and kinetics during the forehand grip and backhand grip. Twenty-one pressure sensors and eleven flex sensors are employed to construct the smart glove, and the measured parameters are then visualized to analyze different grip movements. An athlete and an amateur were selected for the gripping experiments and the measurements was recorded by the smart glove. During forehand gripping, although the total power generated by the amateur (33 N) was higher than for the athlete (29 N), the final shot strength was still unsatisfactory due to the disorderly arranged finger flex angle. In backhand gripping, the incorrectly laid index finger reduced the thumb power of the amateur to 3 N, which weakened the control ability and led to a distorted flying trajectory of the shuttlecock. The differences in kinematics and kinetics between the athlete and the amateur can provide a reference for the badminton learners to perform the correct technical movements. By use of this approach, the proposed system may grant trainers and trainees a better approach to analyze the grip movement.

Keywords: Data glove; visualization; fine hand movement; badminton; kinematics and kinetics

Introduction

Badminton is a sport played using racquets to hit a shuttlecock across a net and have it land in the designated court areas. It is one of the most popular sports around the world, and people of all ages play badminton for physical exercise or athletic competitions.[1],[2] Badminton is a physically demanding sport, requiring strength, endurance, muscular power, agility, speed and precision. To promote the optimum performance in badminton, specific movement patterns or sequences should be analyzed based on biomechanical principals.

Badminton is a technical sport that requires good motor coordination. It requires coordinated movements of the upper limb (hand, wrist, elbow, big arm, and shoulder), trunk, and lower limb (ankle, knee, leg, and hip). In the past few years, there have been numerous research reports to study the kinematics and kinetics of the wrist, forearm, big arm, and leg in the sport of badminton.[3]-[8] Generally, their experiments were carried out by use of a commercial measurement system, which can detect the movement or power of large joint movements.

However, due to instrumental deficiencies and limitations, there are few studies concerning the fine movement characteristics of the hand, such as the finger joint angles and pressure from fingers and palm. In a badminton game, the fine hand movement characteristics can ultimately determine the speed and trajectory of the shuttlecock, which is crucial to end the rally and win the point. Typically, one important factor that determines success is the racket grip for different types of movement, such as forehand/backhand smashes, short drops, and long clears.[9] The fine control of the badminton grip is dependent on not only the grip posture but also the grip strength of the fingers,[10] which can be characterized by the flex status of the fingers and the pressure distribution of the palm and fingers. Therefore, the measurement and visualization of the hand kinematics and kinetics can help the players and coaches precisely analyze the fine movement characteristics and improve the athletic performance.

In recent years, much research has intended to measure the fine hand movement by high-speed cameras or wearable sensors. The camera-based system can obtain joint angles and angular velocities from recorded videos, such as Qualysis, Vicon, and Kinect. With the assistant of markers, Qualysis and Vicon can acquire limb trajectory and acceleration to analyze player movements.[11]-[13] When the precision of motion capture is not a priority, markerless systems like Kinect can conduct the motion capture task without interfering with the movement of badminton players.[14]

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 limitations of the camera-based system, wearable devices have been proposed in many types of studies. Commercial motion capture systems such as Xsens and Noraxon have been employed to capture the motion of a large limb with high precision, but they are uncapable of monitoring small body parts such as fingers.[15],[16] Thus, self-developed sensors have been developed to address this limitation.

There are not many research studies that have focused upon finger movement. A recent study established a so-called Opal sensor to monitor the acceleration and angular velocity of the upper limb during the smashing movement.[17] Moreover, a mobile measuring device for capturing the human finger movement was developed by the use of five flex sensors.[18] Apart from sports applications, the motion capture system based on wearable sensors is also of great interest in scientific fields such as rehabilitation, surgery, human-machine interaction, remote monitoring, and injury evaluation.[19]- [21]

Nevertheless, not only the grip posture but also the grip strength can affect the speed and trajectory of the shuttlecock. Although the above-mentioned wearable sensors may partially record hand kinematics, 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. In practice, it is impossible to discriminate different grip strength with the same grip posture or different grip postures with the same grip strength.

Moreover, the visualization of the grasping operations has not been mentioned in badminton, which makes it hard to understand the grip posture and grip strength from the abstract results acquired by the fine motion measurement systems. Therefore, the development of a detection and visualization system with comprehensive analysis ability for both grip posture and grip strength is crucial and necessary.

To solve these 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 the human hand, which 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. On the other hand, to visualize the hand kinematics and kinetics in badminton, a visualization system based on Unity and ANSYS is also proposed. Finally, in order to verify the feasibility of the measurement and visualization approaches, two typical badminton grip types have been characterized and reported in this paper.

Methodology

The analysis of the complex and unpredictable hand movements requires a well-established system based on state of art technologies. As shown in Figure 1, the overall system in this paper is divided into three sections: the data acquisition module, the data processing module, and the data visualization module. In the data acquisition module, flex sensors and pressure sensors are employed to convert the status of the hand movement into a voltage signal as the angle and pressure measurements, respectively. The acquired data are subsequently sent to an Arduino platform data processing module for analog-to-digital conversion. Next, the converted data are transmitted to a personal

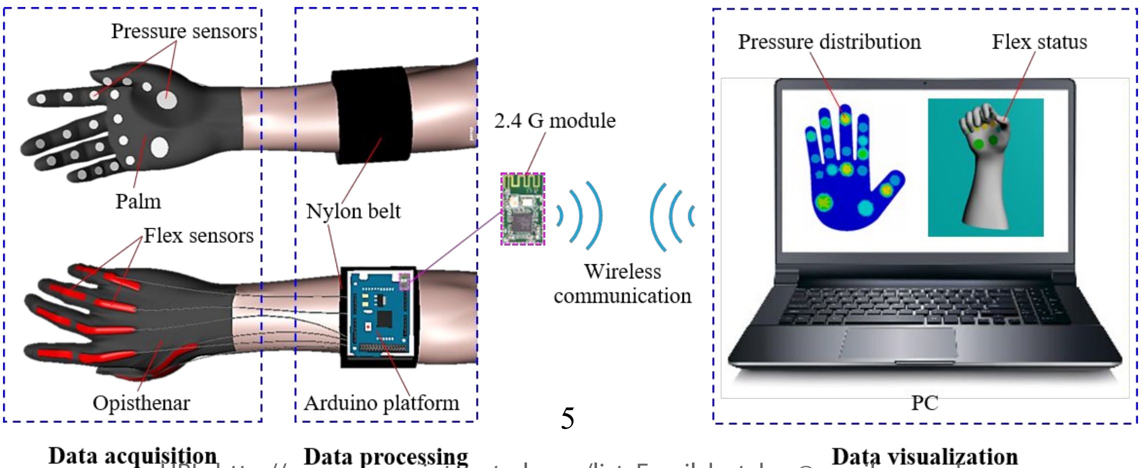


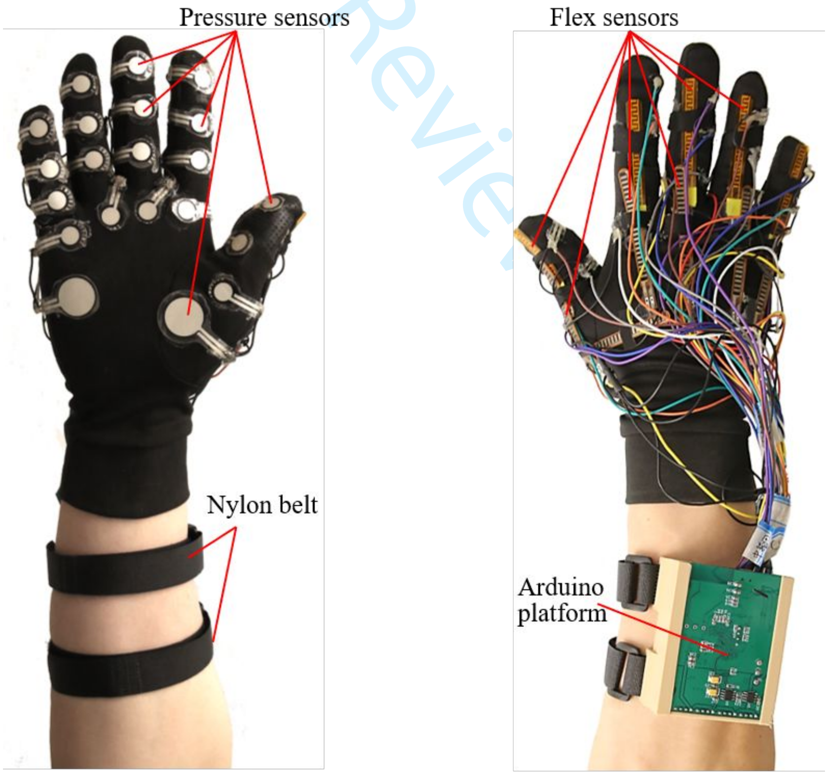
Figure 1. System architecture for the characterization of the fine hand movements in badminton by the use of a smart glove.

computer (PC) through wireless serial communication. Lastly, the measurements are visualized in the PC via the computer graphing and finite element processes in order to generate illustrations for the flex status and the pressure distribution.

The Arduino platform is capable of collecting measurements with 12-digit resolution at a maximum 10,000 sampling frequency, which is sufficient for monitoring human movements. Therefore, with the proposed measurement and visualization system, the fine hand movement differences between professionals and trainees may be discriminated.

Smart glove based on flex sensors and pressure sensors

The fine hand movements in badminton include hand kinetics and kinematics, which are primarily characterized by the finger joint angles and the pressure generated by the fingers and palm, respectively. Therefore, to capture the fine hand movement



(a) **(b)**

Figure 2. Prototype of the smart glove: (a) front view and (b) back view.

characteristics, flex sensors and pressure sensors were employed to construct the smart glove system.

According to the kinetic model of the human hand,[22] different gripping postures lead to different power generation points of the fingers and palm. Thus, to capture the pressure distribution of all the main power generation points of the human hand, twenty-one pressure sensors are attached to the smart glove as shown in Figure 2a. On the other hand, according to the hand kinematic model,[23] the human hand skeleton includes phalanges, carpals, and metacarpals with 19 links and 24 degrees of freedom (DOFs).

The thumb can be regarded as a kinematic chain that contains 3 links and 4 degrees of freedom whereas the index, middle, ring and little fingers are defined by 4 links and 5 DOFs. In these fingers, due to the reduced kinematic contribution of the distal interphalangeal joints during the grip movement, the proximal interphalangeal (PIP) together with the distal interphalangeal (DIP) are regarded to have 1 degree of freedom in this paper, and the metacarpophalangeal joint (MCP) is modelled by a single degree of freedom universal joint

As shown in Figure 2b, no flex sensor is placed on the distal interphalangeal joints, and two flex sensors are deployed at the metacarpophalangeal joints and the proximal interphalangeal joints on each finger, including the thumb. It should be noted that the thumb movements are much more complex because the movements involve the metacarpal bone. Therefore, the trapeziometacarpal (TMC) thumb joint is defined by a 2 degree of freedom universal joint, and an additional flex sensor is deployed at the trapeziometacarpal thumb joint.

The information of the finger joint angles and the pressure is stored and analyzed in the Arduino platform. The Arduino platform is attached to the forearm of the participant by nylon belts and connected to the sensors with expanded analog-to-digital conversion ports. This deployment can eliminate its influence on human movements during the badminton game.

In this study, the gripping measurements did not involve high-intensity exercise as only static gripping postures were studied in the experiments. Therefore, the device failure caused by sweating or large-scale movement could be neglected under this scenario. In our future work, waterproof and attachable materials will be used in the system to prevent the influence of sweat in high-intensity exercise.

All of the measurements obtained by the Arduino platform were transmitted to the PC through a 2.4 G communication module installed on the Arduino board. Lastly, the visualization is processed based on the measurements of the finger joint angles and pressure.

Visualization system

Since numerous multi-dimensional and complex hand movements are involved in badminton, the parameters only displayed by the data table may not be readily understood for coaches or players. Thus, the ANSYS and Unity tools are employed for the data visualization of hand movements.

Ansys is a finite element simulation software that may be employed to reveal the complex object responses under certain external conditions. The three-dimensional hand model was built by the Solidworks software in advance. To obtain an excellent visualization, the hand model was flattened before it was imported into Ansys.

The hand material was selected to be latex because its elastic module, shearing module, and density is similar to human muscle tissues. The power generation points of the hand model corresponded to the position of the pressure sensors of the smart glove. After the hand model was imported into Ansys, the boundary conditions and loads should be applied first.

In the hand model, a fixed support was employed at the back of the hand. Next, the pressure results from the smart glove was directly input into Ansys and applied to the power generation points at the corresponding areas. Please note that this simulation is only for the visualization of pressure distribution and therefore no specific mechanical equation was adopted in this procedure.

On the other hand, Unity is a tool for establishing computer graphs, which can conveniently illustrate the flex status that is extracted by the flex sensors located at the back of the human hand. Moreover, to investigate the correlation information between the flex status and the pressure distribution, the detected pressures may be also merged in the Unity model. The visualized hand model was created by the Maya software.

The pressure distribution was implemented by different colors displayed on the skin of the hand. Since the model to analyze kinematics and kinetics is required to be driven by Unity3D, the skeleton and skin were bonded together. The skeleton was controlled by a C# script. By this approach, when the Arduino platform transferred the measurements from the smart glove to the PC, the data packets were analyzed by the Unity3D engine. The fingers in the model were bent subject to the sensor measurements in real-time.

With the assistance of Ansys and Unity, the real grip status of the player may be reconstructed and displayed on the screen based on the flex and pressure values measured by the smart glove. It should be noted that the measured results may be synchronized with the values from commercial measurement systems for large joint movements, including the movement and power from the wrist, forearm, arm, and leg. This feature allows the reconstruction the human movements of the whole body in the future by the combination of the reported system and commercial measurement devices.

Experimental

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 born by the human fingers.

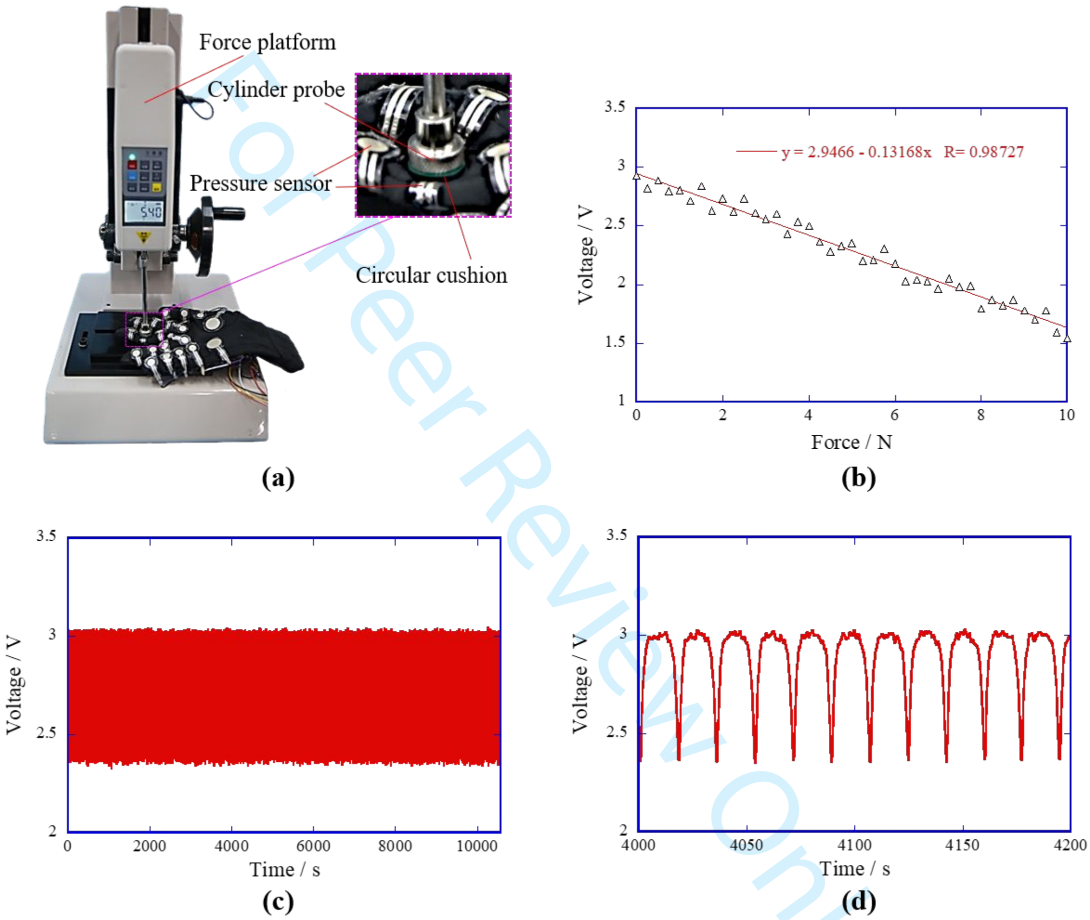


Figure 3. Calibration procedure for the pressure sensor. (a) Experimental setup. (b) Calibration result of the sensor response as a function of the applied force. (c) 600-cycle test for the pressure sensor. (d) A representative number of cycles from the 600-cycle procedure.

The calibration setup for the pressure sensor is shown in Figure 3a. A force platform (HP-50, Handpi, CHINA) was used to apply the forces to the pressure sensors (IMS009, I-Motion, China). Their tolerances between the theoretical and measured values were all within ± 5%.[24] A circular cushion was attached to the head of the force platform in order to ensure that the pressures were applied within the validated range.

As shown in Figure 3b, the pressure sensors were tuned by applying forces between 0 N and 10 N. The pressure-voltage relationship was subsequently determined by the least square method to be equal to:

$$F = 22.3905 - 7.9587U\,, \tag{1}$$

where F represents the force and U describes the voltage response of the pressure sensor. To verify the reliability of the pressure sensor, its repeatability was investigated by an electro-mechanical universal testing platform (Instron Legend 2344, USA). The measurements were repeated 600 times as in Figure 3c. A representative number of cycles performed from the complete procedure are shown in Figure 3d. The results verified the stable performance of the pressure sensor and demonstrated its reliability.

The flex sensor 2.2 (Spectra Symbol, USA) was adopted to characterize the finger angles in this study. The tolerance values of this type of sensor between measured value and ground truth were limited to ± 7.1%.[25] The calibration setup for the flex sensor is shown in Figure 4a.

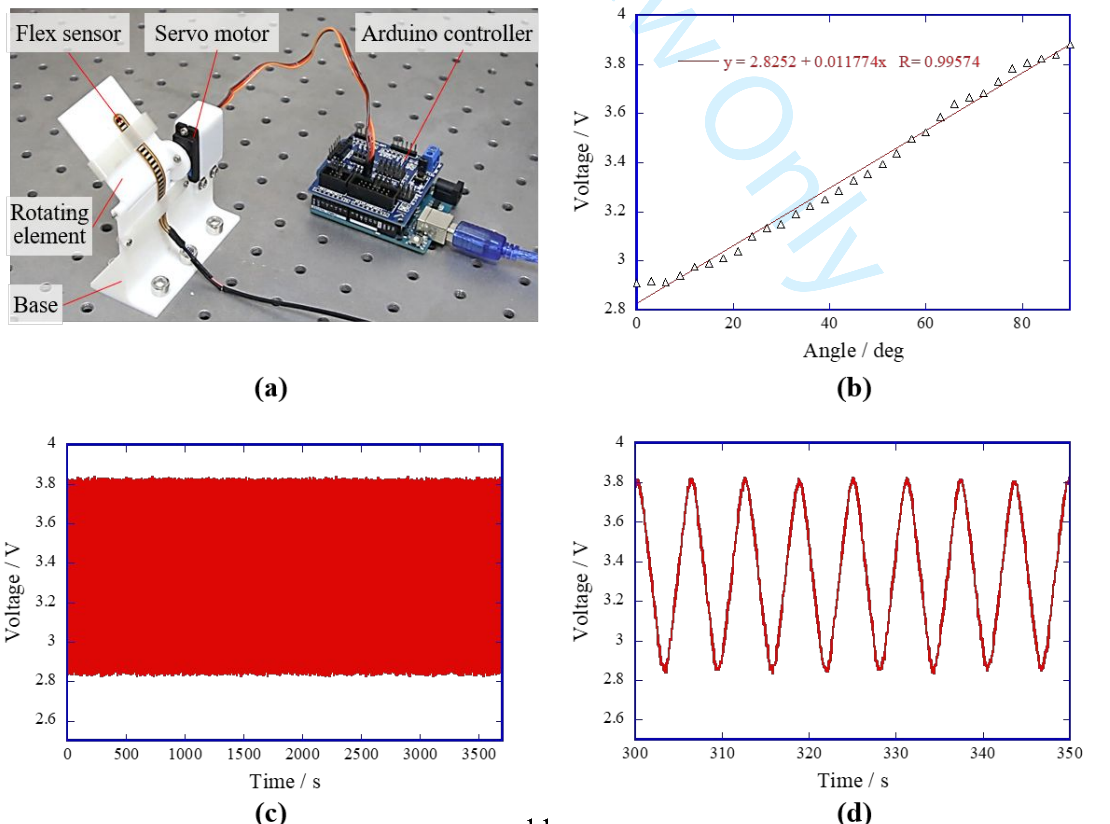


Figure 4. Calibration of the flex sensor. (a) Experimental setup. (b) Calibration results of sensor as a function of the applied bending angle. (c) 600-Cycle test for the flex sensor. (d) Representative number cycles from the 600-cycle procedure.

A rotating element was driven from 0 ° to 90 ° by a servo motor, and the actual angle was obtained from the servo motor by an Arduino controller. In addition, the voltage response of the flex sensor was recorded by the Arduino controller to compare with the actual angle. The calibration result is shown in Figure 4b.

The angle was evaluated by the method of least squares to be equal to:

$$D = 84.9329U - 239.9524 \tag{2}$$

where D indicates the rotation angle and U represents the voltage response of the flex sensor.

The repeatability of the flex sensor was also characterized by bending it 600 times on the rotating element. The results are shown in Figure 4c. In the more detailed view shown in Figure 4d, the flex sensor was shown to operate without distortion, which indicates stable system performance. Notice that the overshoots and oscillations of the Servo motor controlled by Arduino could not be avoided during continuous rotation. Thus, some errors in the repeatability measurements for the flex sensor may have been caused by the servo.

Measurement of the kinematics and kinetics

A correct badminton grip is fundamental for playing badminton. Gripping the racket incorrectly decreases the accuracy and power of the strokes. The correct grip on the badminton racket has been demonstrated to reduce injuries, increase the accuracy of shots, and produces more efficient contact. The basic types of grip in badminton generally include the forehand and backhand grip. Therefore, these two grips were investigated in the following experiments to characterize the differences between professionals and amateurs.

The measurement and visualization of the grip were conducted based on the measurements obtained using the flex sensors and pressure sensors of the smart glove.

The test procedure was accomplished by a professional badminton athlete and an amateur. Each movement was conducted 15 times, and the average value of these measurements was recorded as the result.

It should be noted that the goal of this work is to develop and verify the smart glove and the visualization method for coaches and trainees in order to provide a novel approach for analyzing the hand kinematics and kinetics in badminton. Therefore, in this type of work focused on equipment and devices, two participants in the experiment stage are sufficient to verify its feasibility.[26] In further work, an in-depth investigation of badminton biomechanics will be carried out by the use of the proposed method, and additional measurements from athletes and amateurs will be sampled and analyzed to further reveal the hand kinematics and kinetics in badminton.

Results and discussion

The forehand grip is used to hit shots that are on the forehand side of your body and around the head. The badminton racket handle has two wide parts that are in line with the face of the racket. The index finger should be pressed over one of the wider surfaces, and the bottom three fingers hold the racket handle. The thumb can be adjusted comfortably anywhere near the wider surfaces to create a V-shape between the thumb and the index finger, which enables the player to switch grip quickly. It should be noted that the index finger should be in control in a forehand stroke. In other words, the index finger is used to push the racket forward when performing a forehand stroke.

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

The forehand grip was studied first and the measurement and visualization of the grip movements conducted by both athlete and amateur are shown in Figure 5. The results in Figures 5b and 5g show that the professional player generated 29 N in total while the amateur generated 33 N. The main power generation points of professional players in the forehand grip are the root of each finger and the edges of the palm, which may reach 3 to 6 N, while other parts of the hand played subordinate roles. This pressure distribution allowed the player to firmly hold the racket and continuum to generate momentum for a shot.

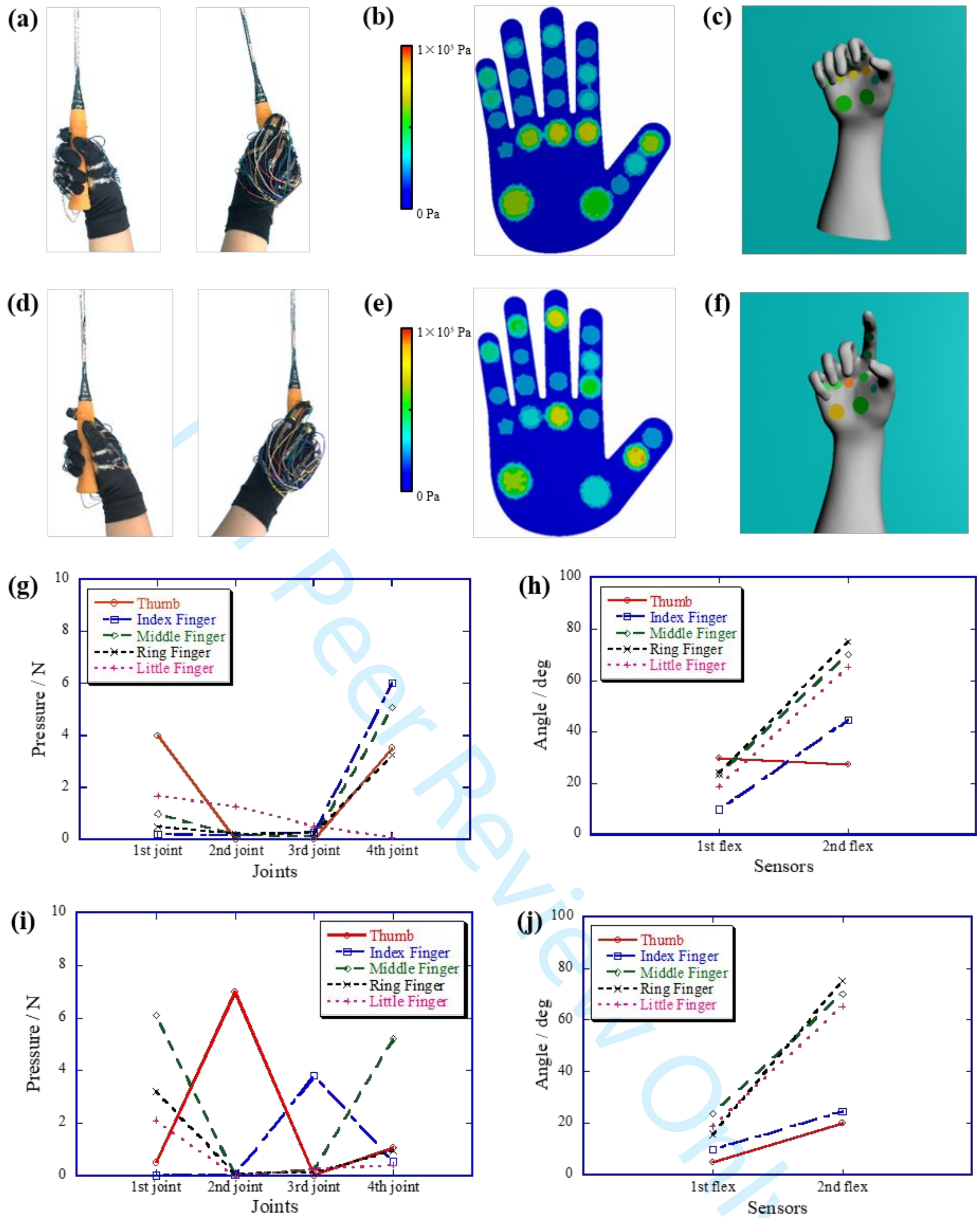


Figure 5. Measurement and visualization results of the forehand grip: (a) front and back view of the athlete, (b) hand pressure distribution of the athlete, (c) three dimensional simulation of the athlete, (d) front and back view of the amateur, (e) hand pressure distribution of the amateur, (f) three dimensional simulation of the amateur, (g) hand pressure of the athlete, (h) joint bending angles of the athlete, (i) hand pressure of the amateur, and (j) joint bending angles of the amateur.

In contrast, in Figures 5e and 5i, the pressure on the hand of an amateur was concentrated towards the medium part of the thumb, the edge of the palm, and the fingertips of the left three fingers, which was distributed in a range of 3 to 7 N. The pressure on the thumb of the amateur may delay the control effect for the racket orientation, and the absence of force upon the metacarpophalangeal joints of the index and ring finger may curtail the strength of the shuttle.

As shown in Figures 5c and 5h, for the flex characteristics, the orderly arranged four fingers may fix the purlicue of the athlete and the racket face in the same direction, which resulted in an average 60-degree bending status. However, the disorderly distributed

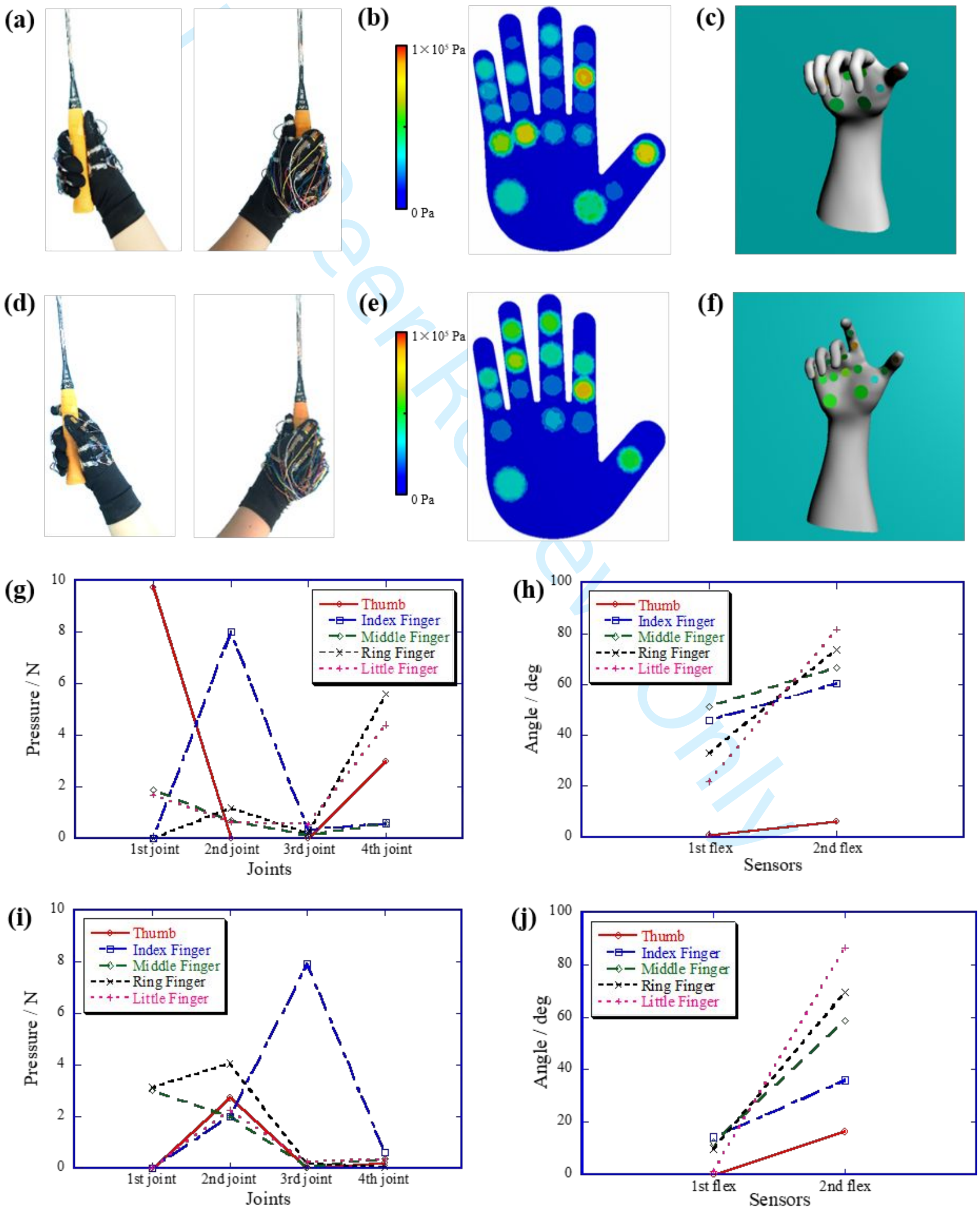


Figure 6. Measurement and visualization results of the backhand grip: (a) front and back view of the athlete, (b) hand pressure distribution of the athlete, (c) three dimensional simulation of the athlete, (d) front and back view of the amateur, (e) hand pressure distribution of the amateur, (f) three dimensional simulation of the amateur, (g) hand pressure of the athlete, (h) joint bending angles of the athlete, (i) hand pressure of the amateur, and (j) joint bending angles of the amateur.

fingers of the amateur in Figures 5f and 5j deviated 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 were approximately the same between athlete and amateur at approximately 60 degrees, the strength of the professional came from fourth joints of these fingers and the amateur used his weak fingertips. Using this gripping approach, although the total power generated by the amateur was higher than the athlete, the final shot strength would be unsatisfactory. This parameter cannot be solely obtained from gloves with single pressure or flex sensing ability.

The flowing experiment for the characterization of the backhand grip and the measurement and visualization results for both the athlete and the amateur are shown in Figure 6. Figures 6b and 6g show the pressure distribution of the hand for the backhand grip of the professional athlete. The roots of ring finger and little finger (4 to 5 N), the fingertip of the thumb (10 N), and the middle section of the index finger (8 N) contributed the strongest holding forces for the backhand grip in the professional movement.

Distinct from the skilled player, Figures 6e and 6i show that the amateur primarily employed his middle and top part of the middle and ring finger to hold the racket, where the four fingers tightly held the handle and blocked the thumb from exerting sufficient pressure for a successful shot. As can be seen from Figures 6c and 6f, the bending angle of each finger of the professional backhand grip was almost the same as for the forehand grip except the thumb, which provided a margin to change the grip type during the game.

However, the wrapping technique of the amateur makes it impossible to change the grip rapidly because the racket was fixed at the phalanges but not the palm which was demonstrated by the pressure distribution. The thumb was the primary power generation source during the backhand shot. However, the disorderly laid index finger withdrew the thumb power from 10 N to 3 N for the amateur, which may induce a distorted trajectory of the shuttlecock.

The glove was tested more than 60 times during the experiments and was turned on and off several times. In all cases, its performance remained intact, which demonstrates the reliability of the entire system.

In these two sets of measurements, the numerical details presented in Figures 5g, 5h, 5i, and 5j and Figures 6g, 6h, 6i, and 6j were employed to construct the above discussion due to their abstract nature. Moreover, the correlation between joint bending angle and finger distribution may provide more information than employing only one of these parameters.

Conclusions

In this paper, a smart glove with a flex sensor array and a pressure sensor array has been reported for capturing hand kinematics and kinetics. The glove is constructed of 11 flex sensors and 21 pressure sensors for measuring the joint angles and the pressure at various locations on the hand. A visualization method is also proposed in this paper.

The hand kinematics and kinetics of two badminton grip types were investigated to verify the measurement and visualization of the smart glove. The results revealed the differences in the joint bending angles and finger pressure between an athlete and an amateur, which may provide more help for the coaches and trainees than traditional data analysis methods.

In the future, a more compatible structural design will be carried out to improve the smart glove. In addition, more participants will be included for more in-depth hand biomechanical research involving badminton.

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.

Disclosure of Interest

The authors declare no conflicts of interest.

References

[1] Faude, O.; Meyer, T.; Rosenberger, F.; Fries, M.; Huber, G.; Kindermann, W. Physiological characteristics of badminton match play. *Eur. J. Appl. Physiol*. **2007**, 100, 479-485.

[2] Manrique, D.; Gonzalez-Badillo, J. Analysis of the characteristics of competitive badminton. *Br. J. Sports Med*. **2003**, 37, 62-66.

[3] Lam, W. K.; Ding, R.; Qu, Y. Ground reaction forces and knee kinetics during single and repeated badminton lunges. *J. Sports Sci*. **2017**, 35, 587-592.

[4] Sasaki, S.; Nagano, Y.; Ichikawa, H. Loading differences in single-leg landing in the forehand-and backhand-side courts after an overhead stroke in badminton: A novel tri-axial accelerometer research. *J. Sports Sci.* **2018**, 36, 2794-2801.

[5] Teu, K. K.; Kim, W.; Tan, J.; Fuss, G. K. Using dual Euler angles for the analysis of arm movement during the badminton smash. *Sports Eng*. **2005**, 8, 171-178.

[6] Huang, B.; Li, M.; Mei, T.; McCoul, D.; Qinm S.; Zhao, Z.; Zhao, J. Wearable stretch sensors for motion measurement of the wrist joint based on dielectric elastomers. *Sensors*. **2017**, 17(2708), 1-12.

[7] Waddell, D. B.; Gowitzke, B. A. Biomechanical principles applied to badminton power strokes. *ISBS-Conference Proceedings Archive*. **2000**, 1-6.

[8] Henricson, A.; Larsson, A.; Olsson, E.; Westlin, N. The effect of stretching on the range of motion of the ankle joint in badminton players. *J. Orthop. Sports Phys. Ther.* **1983**, 5, 74-77.

[9] 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. Sport*. **2013**, 13, 860-871.

[10] 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.

[11] Salim, M. S.; Lim, H. N.; Salim, M. M.; Baharuddin, M. Y. Motion analysis of arm movement during badminton smash. *IEEE EMBS Conference on Biomedical Engineering and Sciences*. **2010**, 111-114.

[12] Shuhei, N.; Urabe, Y.; Tekeuchi, T.; Sasadai, J.; Maeda, N. 179-analysis of dynamic knee motion during lateral and posterolateral jump landing in female badminton players. *Gait Posture*. **2018**, 65, 537-539.

[13] Mei, Q.; Gu, Y.; Fu, F.; Fernandez, J. A biomechanical investigation of right-forward lunging step among badminton players. *J. Sports Sci.* **2017**, 35, 457-462.

[14] 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 Trans. Biomed. Eng*. **2013**, 60, 2184-2192.

[15] Mehdizadeh, S. A robust method to estimate the largest lyapunov exponent of noisy signals: a revision to the rosenstein's algorithm. *J. Biomech*. 2019, 85, 84-91.

[16] Karatsidis, A., Bellusci, G.; Schepers, H. M.; De Z, M.; Andersen, M. S.; Veltink, P. H. Estimation of ground reaction forces and moments during gait using only inertial motion capture. *Sensors*. **2017**, 17(75), 1-22.

[17] Shan, C. Z.; Ming, E. L.; Rahman, H. A.; Fai, Y. C. Investigation of upper limb movement during badminton smash. Tenth Asian Control Conference. **2015**, 1-6.

[18] Jacob, A.; Zakaria, W. N. W.; Tomari, M. R. B. M. Quantitative analysis of hand movement in Badminton. *Prog. Adv. Comput. Intell. Eng*. **2016**, 439-448.

[19] Santos, L.; Carbonaro, N.; Tognetti, A.; Luis, G. J.; Fuente, E.; Carlos, F. J.; Perez, T. J. Dynamic Gesture Recognition Using a Smart Glove in Hand-Assisted Laparoscopic Surgery. *Technologies*. **2018**, 6, 1-14.

[20] Pezzuoli, F.; Corona, D.; Corradini, M. L. Improvements in a Wearable Device for Sign Language Translation. *International Conference on Applied Human Factors and Ergonomics*. **2019**, 973, 70-81.

[21] Li, K.; Chen, I. M.; Yeo, S. H.; Lim, C. K. Development of finger-motion capturing device based on optical linear encoder. *J. Rehabil. Res. Dev*. **2011**, 48, 69-82.

[22] Muralidhar, A.; Bishu, R. R.; Hallbeck, M. S. The development and evaluation of an ergonomic glove. *Appl. Ergon*. **1999**, 30, 555-563.

[23] Cobos, S.; Ferre, M.; Uran, M. S.; Ortego. J.; Pena. C. Efficient human hand kinematics for manipulation tasks. *IEEE/RSJ International Conference on Intelligent Robots and Systems*. **2008**, 2246-2251.

[24] I-Motion, I-Motion Sensors. http://www.imsensorhub.com/sensor.html (accessed on 02/02/2020).

[25] Shen, Z.; Yi, J.; Li, X.; Lo, M. H. P.; Chen, M. Z.; Hu, Y.; Wang, Z. A soft stretchable bending sensor and data glove applications. *Robotics Biomim.* **2016**, 3, 22.

[26] 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.