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Kinematic Analysis of Wrist and Elbow Angles in Badminton Serve Techniques Based on IMU Sensors

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ABSTRACT

Background: Motion capture technology is essential in sports biomechanics for analyzing human movement. Inertial Measurement Unit (IMU) sensors offer a practical alternative to camera-based systems, providing real-time motion analysis. While previous studies in badminton biomechanics have largely focused on stroke phases or lower-limb movements using optical systems, few have investigated the detailed angular behavior of upper-limb joint-particularly the wrist and forearm during specific serve types. Moreover, existing research rarely compares different serve techniques in terms of kinematics using wearable IMU-based methods.
Aims: This study aims to analyze angular movement patterns of the wrist and forearm during different badminton serve techniques using IMU sensor. Understanding the wrist and forearm movements is crucial, as they directly affect shuttle control, serve conssitency, and injury risk- especiaally in high-spedd, repetitive motions like the badminton serve.
Methods: Sensors were placed on the dorsum of the hand and the forearm near elbow to measure angular motion in three serves: backhand, short forehand, and long forehand.
Result: Results indicate that the centroid calculation results showed that each type of serves had a different angular distribution pattern, with varying contributions from the forearm and wrist. The forearm plays a dominant role in generating power, while the wrist contributes more to directional control and stabilization. Results indicate that forearm movement is more dominant in forehand serves, while wrist movement is more pronounced in backhand serves. These findings suggest that IMU-based motion analysis can optimize badminton techniques, prevent injuries, and enhance training programs.

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1. Introduction

Motion Capture System (MoCap) or also known as motion capture system is currently widely used in industry and study fields by providing a very important supporting tool to obtain accurate continuous data in real-time or pre-recordin of a movement and position of an object or subject (Espitia-Mora et al., 2024). In general, MoCap consists of 2 approaches, namely optical systems and non-optical systems (Reuter & Schindler, 2023). The concept of how to capture motion from these three motion capture systems has differences between one type of system and another which is then representes into motion data (Wardijono, 2013). Optical capture systems usually use special cameras and special markers to record motion from various angles (Espitia-Mora et al., 2024). Meanwhile, non-optical capture systems are divided into 3 systems including inertial systems, magnetic systems, and mechanical systems. The inertial system records the motion of the body or target object directly through acceleration sensors and gyroscopes (Espitia-Mora et al., 2024). In the magnetic systems, electromagnetic sensors connected to a computer are used to generate real-time 3D data with relatively low processing costs (Wardijono, 2013). A special suit equipped with mechanical sensors is used in mechanical motion capture systems. These sensors can capture and record motion in real-time (Wardijono, 2013).

Several previous studies have used cameras to capture and measure human movements, especially in kinematic feature analysis (Kuo et al., 2019) and (Tomita et al., 2021). The study that examines arm and body movements in overhead forehand shots used in badminton games at all skill levels using a camera and saved the recorded movements in videos, which were then analyzed on each movement. The result was that all respondents as 4 skill levels showed different patterns of arm and body movement (Wang et al., 2009). Although camera-based systems are able to translate complex human movements directly, this method is considered less efficient because it has several limitations, such as requiring high lighting, precise camera positioning, and considerable operational costs to purchase sophisticated equipment, so this method is suitable for use in the laboratory (Kuo et al., 2019). The visibility of body landmarks is a crucial factor in camera-based motion analysis, so it is necessary to synchronize measurements with multiple cameras or adjust environmental conditions to obtain optimal results (Tomita et al., 2021). Recent developments in motion capture algorihtms have enabled more accurate estimation of human motion coordinates, including joint angles and body position, providing an alternative to overcome the limitations of camera-based methods (Kuo et al., 2019). However, conventional motion capture using camera is not suitable for measuring the impact of high-acceleration, short-duration movements such as footsreps during running.

To overcome these problems, there is a new technology that has been developing in recent years, which consists of wearable sensors to measure human movement and dynamics and can record data flexibly and in real-time. The technology is the Inertial Measurement Unit (IMU) (Jacob et al., 2016). IMUs are considered more reliable, miniaturized, and can store large amounts of continuous data in real-time (Bastiaansen et al., 2020). Other advantages of IMU are lower cost, light weight, user-centered, and portable so that it is easier to use in the field (Guignard et al., 2021). IMU technology consists of accelerometers, gyroscopes, and magnetometers that can measure acceleration, angular velocity, and magnetic field on 3 orthogonal axes (Bastiaansen et al., 2020). In use, IMU can capture a wider range of motion without being limited by video recording equipment (Kuo et al., 2019). This is because the IMU system does not use position data to calculate its kinematic results, so this allows kinematic measurements over a wide range of performance areas (Tomita et al., 2021). Kinematic analysis with IMUs does not require digitization of body landmarks, allowing real-time display of kinematic features, such as angular velocity, joint acceleration and angle, and body segments (Tomita et al., 2021). When the IMU is placed on adjacent body segments, it can be used to measure angles between segments using euler angle rotation (Brice et al., 2019).

IMU technology has recently been widely used in kinematic data collection in several fields, such as sporting events. IMU sensors in sports science research to identify the type of movement and its intensity by using motion analysis to collect larger data. Thus, the development of methods that use sensors to identify key movements (such as walking, running, and jumping) and the intensity of those movements will make research in sports science easier (Lee et al., 2015). In the field of sports, IMU has a wide range of applications that can help athletes, coaces, and researchers in improving performance, preventing injuries, and analyzing movements. Pedro compared the concurrent validity of an IMU with an optical motion capture system to measure upper and lower limb kinematic during the acceleration phase of a tennis forehand drive. The results of this study presented important advances in the use of IMU that need to be used more frequently in tennis and other sports (Pedro et al., 2021). Aschenbrenner conducted a study to compare 3 types of turns in telemark skiing, through biomechanical description of each skiing technique using 18 wireless IMU sensors mounted on the bodies of 7 professional skiers. For each skier, each of the 3 turn techniques was recorded in 5 runs. The result of this analysis was that there were no significant differences in torso rotation angles (Aschenbrenner et al., 2023). Click or tap here to enter text.

Badminton is one of the racket sports that involves dynamic speed in every movement. Therefore, players need to be careful about strategy and energy usage in order to play the game well (Jacob et al., 2016). Players are required to do regular training to maintain and improve physical abilities to meet the physical demands of sports games. The serve movement is the most important basic badminton technique that must be mastered by a badminton player because if a player cannot serve properly and correctly, he will not get points or scores (Hardwis & Williyanto, 2023). In general, the serve stroke technique in badminton is divided into 2, namely forehand and backhand serves (Aksan, 2012). The steps in performing a short forehand serve are as follows: 1) The player stands near the center line, 2) Positions both feet parallel, 3) Holds the shuttlecock in one hand at a height below the waist, 4) Positions the elbow in a bent state, then hold the racket and place the racket head behind the ball head, 5) Determine the service target, pay attention to the shuttlecock and hit it with a relatively short racket swing to get the right direction of the ball over the net and according to the direction (Purnama, 2010). The steps of the long forehand serve are: 1) Hold the shuttlecock at a height parallel to the waits, 2) Hold the racket from behind with the palm facing forward, 3) When swinging the racket and hitting the ball, release the shuttlecock simultaneously, 4) Hit the shuttlecock with full power so that it can go high in the air and fall straight behind the opponent's court line, 5) When hitting the shuttlecock, make sure both feet are hip-width apart and the soles of the feet remain touching the floor, 6) Observe the movement of the racket swing from back to front, make sure the shot is done correctly. Make a continuous and harmonious transition from the back foot to the front foot (Purnama, 2010). The steps in doing a good and correct backhand serve are as follows: 1) Hold the racket with a backhand grip technique, 2) Stand upright with the position of the right foot in fornt of the left foot, the tip of the right foot pointing to the desired target. Both feet are hip-width apart and the knees are slightly bent so that the body weight rests on both feet, 3) Stand close to the front line without stepping ong it, 4) Hold the shuttlecock at waist level in front of the chest, 5) The hand holding the racket is behind the ball and crossed in front of the body, 6) Bend the wrist of the hand holding the racket, 7) Strike the shuttlecock with a relatively short and slow racket swing so that the shuttlecock is only pushed with the weight shift from the back foot to the front foot, 8) Avoid using excessive wrist power when hitting the shuttlecock as it may affect the direction and accuracy of the shot (Purnama, 2010).

High frequency of training can also cause a great risk of muscle injury (Bastiaansen et al., 2020). Muscle injuries can cause limitation of movement in players, even the worst thing that can happen is that players cannot play anymore and have to rest completely. Players have a 60% chance of a lower extremity injury with the most common injuries being knee and ankle injuries (Guignard et al., 2021). Li et al. (2024), performed 3D knee and hip angle estimation with a minimized IMU sensor set during yoga, golf, swimming, badminton, and dance movements. The result of Li's research was the maximum improvement in estimation accuracy (RMSE) achieved by transfer learning of 23,6° for knee flexion/ extension and 22,2° for hip flexion/extension movements compared to no transfer learning. Rusydi et al. (2016), proposed a new method to determine arm movement patterns for forehand and backhand shots in badminton based on the local euler angle gradient signatures of 4 points of the right arm segment (backhand, wrist, elbow, and shoulder) using IMU sensors. The results showed that local euler angles can be used to recognize arm movement patterns, where professional players have a higher similarity pattern with the coach's pattern compared to the amateur player's pattern with the coach. Rusydi et al. (2015), examined local euler angle patterns for smash and backhand in badminton based on arm position using IMU sensors positioned at 4 points of the right arm segment (backhand, wrist, elbow, and shoulder). The result of his research is that smash and backhand movements have different local euler angle gradient directions. This study aims to analyze angular movement patterns of the wrist and forearm during different badminton serve techniques using IMU sensor.

2. Methods

2.1 Participants

Eight beginner-level badminton players participated in this study. Novice badminton players are categorized by the age of each player, not based on the length of playing experience. All respondents in this study have fulfilled several requirements. These requirements include: 1) Have competed in city or provincial badminton championships, 2) Not suffering from moderate to severe diseases at the moment and in a right-handed dominant condition (not left-handed), 3) Not using drugs that interfere with the musculoskeletal response or experiencing pain that makes the muscles hurt. The moderate to severe diseases are health conditions that can interfere with daily activites or interfere with body movement functions that can cause fatal effects if not treated immediately. Respondents expressed their willingness by signing the respondent's consent form and filling out a questionnaire sheet containing question points including training patterns, championship history, injury history, and serve movements. The questions on the questionnaire form were made based on predetermined requirements. The questionnaire form was used to ensure that all respondents who expressed their willingness had met the predetermined requirements.

The Declaration of Helsinki was developed by the World Media Association (WMTA) as a set of moral guidelines for researchers and clinicians working on medical projects involving human participants. Any experiment involving human subjects needs to be throughly described in an experimental protocol, which is then sent for review, comment, direction, and, if appropriate, approval by a committee (Association, 2013). This research has been approved with the ethics code number "2.483/X/HREC/2024" after being submitted to the Ethics Committee of Dr. Moewardi Hospital in accordance with the guidelines outlined in the Declaration of Helsinki. The location of data collection in this study at GOR PB. PMS Surakarta.

2.2 Experimental Setup

The angle measurement in this research uses the WT9011DCL-BT5.0 IMU module. The WT9011DCL-BT5.0 module is a multisensor device that can detect acceleration, angular velocity, angle, and magnetic field. The WT9011DCL module has 9 Degree of Freedom, which combines a high-precision gyroscope, accelerometer, and geomagnetic field sensor. The data output frequency selected in this research is 10 Hz. The construction of the WT9011DCL-BT5.0 IMU module uses stamp hole gold layer technology that can be embedded in PCB boards and is supported by the presence of Bluetooth 5.0. An important thing that must be done before the data collection process is the preparation of research respondents. The first step in this preparation process is to give directions to the respondent to be in the serve position.

The second step is to ensure that the respondent’s forearm is dry, if the arm is sweaty, it must be dried first using a tissue or cloth. The third step is to place the IMU module on the dorsum of the hand and forearm near the elbow of the respondent. The IMU module on the dorsum of the hand is labeled “1” while the IMU module on the forearm near the elbow is labeled “2”.

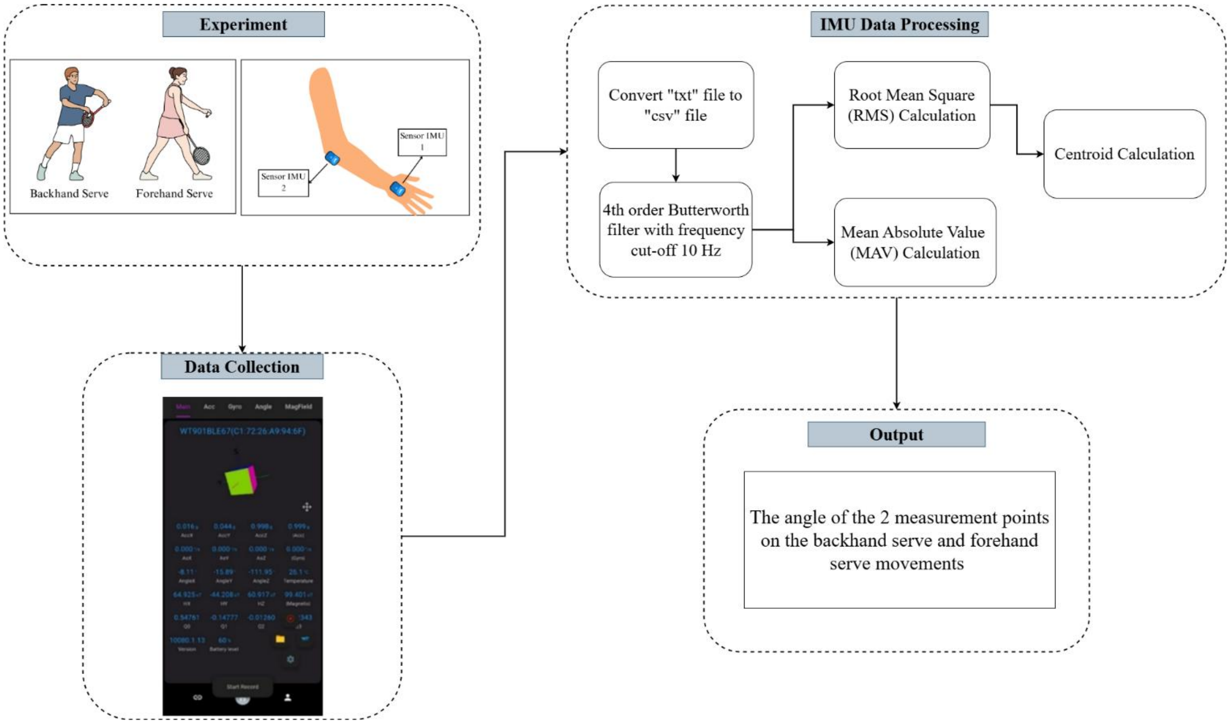

Figure 1. Experimental setup

2.3 Data Collection Procedure

All respondents were instructed to perform serve movements in sequence, starting from short backhand serves, short forehand serves, and long forehand serves. The serving rule used was the serving motion for singles play, where a long serve would earn a point if it reached the back boundary line. One type of serve movement constitutes 1 data collection cycle, which consists of 5 repetitions of the serve movement, where between 1 movement and the next movement there is a break of 10 seconds. During the rest period, the player’s hand is in the stand-by position or the first position when going to serve. The distance between each serve movement is a rest pause of 300 seconds, this condition aims to restore muscles to prevent muscle injury and maintain the respondent’s performance level to remain stable during the data collection process. Local angle measurement with the WT9011DCL-BT5.0 module is by recording the angle output results generated during backhand or forehand serve movements through the WitMotion application. Each movement is monitored for angle changes in detail.

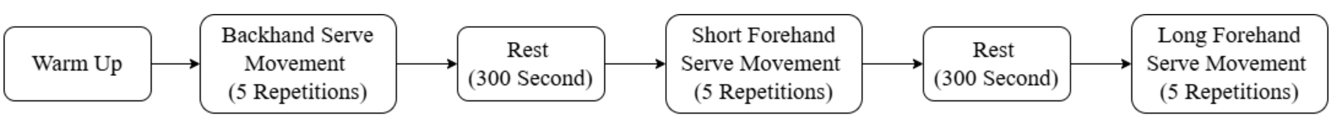

Figure 2. Data collection procedure

2.4 Data Analysis

The angular data recording results are stored in the form of “txt” files, then converted into “.csv” form for further processing using the MATLAB application. The first stage of angle data processing is filtering which aims to remove noise so that a cleaner data signal is obtained. The filtering process in this study uses a 4th order butterworth filter with a cut-off frequency of 10 Hz. Angular feature extraction is a method used to get more information from the data by removing unwanted parts of the data (Phinyomark et al., 2012). In this research, the type of feature extraction used is time-domain. Time-domain features are widely used in real-time applications because they produce motion classification accuracy in simple calculation systems. This feature is calculated based on the amplitude of the data. The types of time-domain signal extraction features used in this study are Root Mean Square (RMS) and Mean Absolute Value (MAV). After that, the final step in the angular data processing is to find the centroid point of the RMS value. The formulas of RMS and MAV can be seen in the equation below (Rechy-Ramirez & Hu, 2015) :

$$RMS_k = \sqrt{\frac{1}{N}\sum_{i=1}^{N} {x_i}^2}$$

$$MAV_k = \frac{1}{N}\sum_{i=1}^{N} |x_i|$$

with N is the length of the segment and x_i is the value of each part of the segment k.

3. Results and Dicussion

Some findings from previous studies that use IMU sensors in researching sports, especially badminton, such as the use of IMU sensors to measure acceleration and angular velocity on rackets (Van Herbruggen et al., 2024), develop and evaluate binary classification models to detect physical fatigue in badminton athletes using IMU sensors (Liu et al., 2025). Other findings from previous research include determining arm movement patterns for badminton strokes based on local euler angle gradient signs using IMU sensors. From the research that has been done by Rusydi et al. (2016) and Rusydi et al. (2015), the author adopts an angle measurement instrument on the surface of the back of the hand and elbow using an IMU sensor, what distinguishes previous research from current research is the selection of the IMU module used, the movements analyzed and the placement of the module.

3.1 Results of Angle Analysis on Backhand Serve Movements

The raw data processing is done through 2 main stages. The first stage is filtering the data using a 4th order Butterworth filter with a cut-off frequency of 10 Hz. The second stafe of the data processing process for the angle of the backhand serve movement is feature extraction from the filtered data. The feature extraction process is done by calculating the Root Mean Square (RMS) and Mean Absolute Value (MAV) values. The results of the angle data processing process can be seen in Figure 3 for the IMU sensor on the dorsum of the hand and Figure 4 for the IMU sensor on the forearm near the elbow.

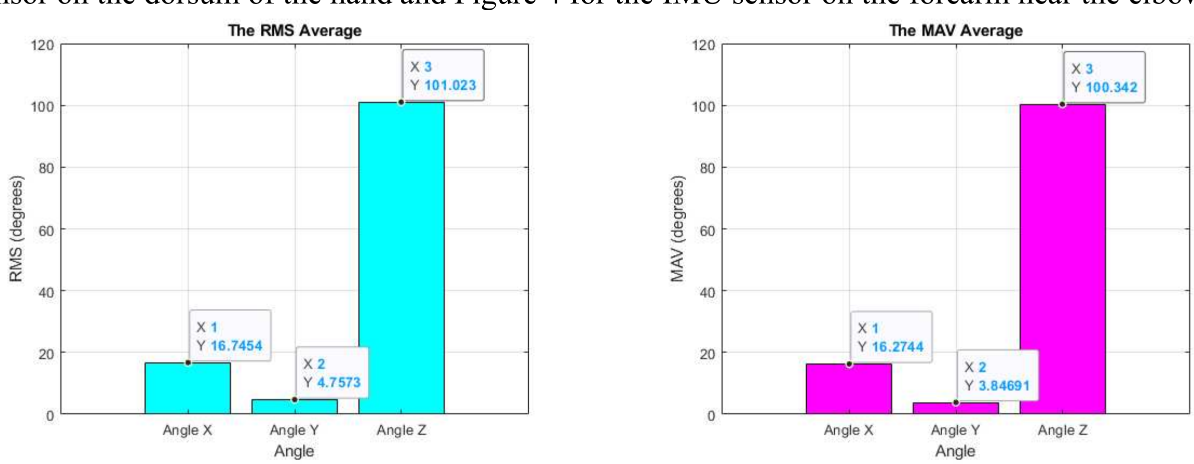

Figure 3. The angle at the dorsum of the hand for a backhand serve

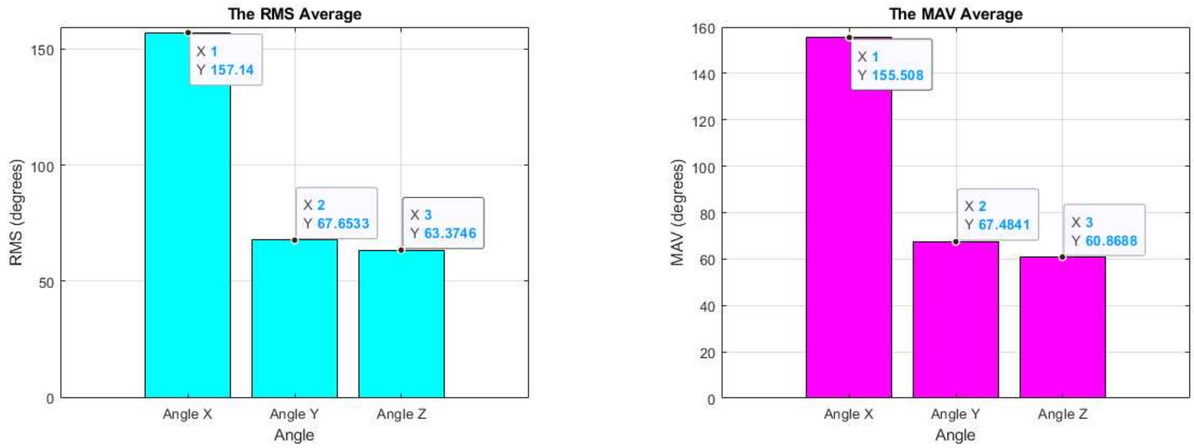

Figure 4. The angle at the forearm near the elbow for a backhand serve

After calculating the RMS and MAV values, the next step is to find the centroid value of the RMS value of each corner point. centroid is the center point of an object or area in multidimensional space (Windarto, 2017). The results of the centroid calculation can be seen in Figure 5.

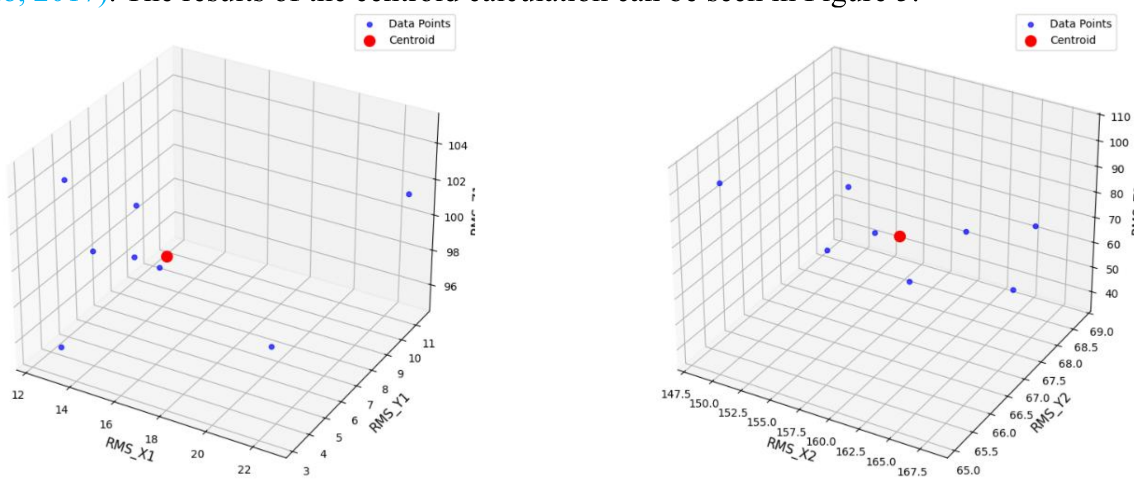

Figure 5. Centroid value of 2 corner points in backhand serve.

Based on the results of the calculation of the centroid value in Figure 5, it is found that the centroid point for the sensor on the dorsum of the hand is equal to 16,7454 for angle X, 4,7573 for angle Y, 101,0233 for angle Z. The centroid point for the sensor on the forearm elbow is equal to 157,1401 for angle X, 67,6533 for angle Y, 63,3746 for angle Z. The largest differences occurred in the X and Y angle, respectively, indicating that the forarm elbow experienced greater angular changes than the wrist during the execution of the backhand serve. This indicates that the main movement in the backhand serve is controlled more by the movement of the forearm, while the wrist plays a role in stabilization and setting the direction and speed of the stroke, as indicated by the centroid angle value in the Z angle, which is higher on the dorsum of the hand than the forearm elbow.

Rusydi et al. (2015) found that in the backhand stroke, the dorsum of the hand has a positive euler angle gradient in all axes (X, Y, Z), indicating the active role of the wrist in the motion. This is in line with authors finding that the wrist is dominant in the backhand serve, especially in the Z axis for directional control. Rusydi et al. (2016) showed that the dorsum of the hand had the most pattern variation in backhand shots (pattern probability 1: 0,81), indicating wrist flexibility. The authors and Rusydi's findings confirm that the wrist is a critical segment in backhand movement, both for serves (precision control) and overhead shots (flexibility and direction). The high Z angle in author's study supports the role of the backhand in Rusydi's to set the direction of the shuttlecock. For training, backhand drills should focus on wrist flexibility for beginners (based on angle) and pattern consistency for professional players (based on euler angle pattern).

3.2 Results of Angle Analysis on Short Forehand Serve Movements

The data obtained through these measurements is then further processed to improve its quality and validity. The first step in data processing is the filtering process. After the filtering process is performed, the next step is to perform feature extraction to obtain important parameters that represent the angular characteristics during motion. The types of feature extraction used are RMS and MAV. The results of the angle data processing process can be seen in Figure 6 for the IMU sensor on the dorsum of the hand and Figure 7 for the IMU sensor on the forearm near the elbow.

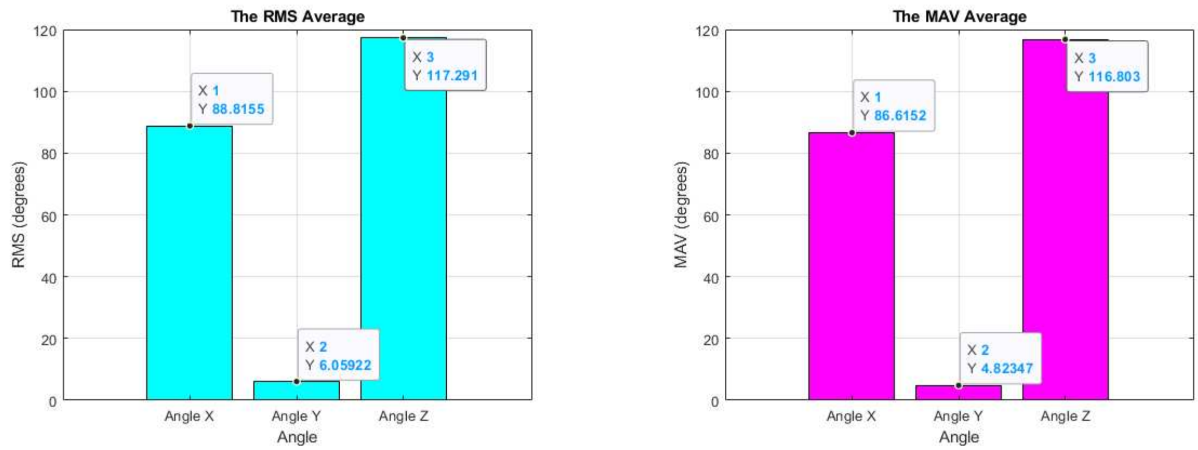

Figure 6. The angle at the dorsum of the hand for a short forehand serve

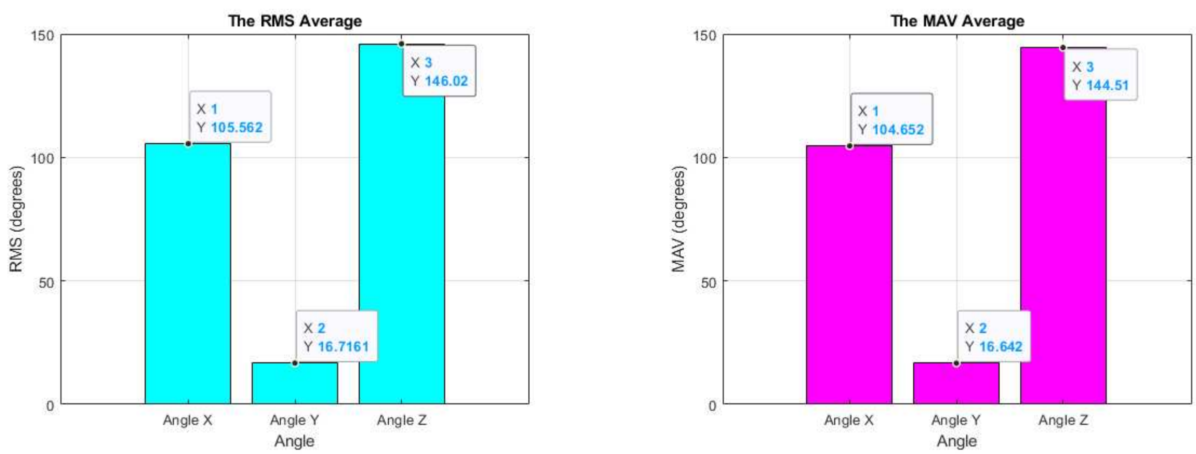

Figure 7. The angle at the forearm near the elbow for a short forehand serve

After calculating the RMS and MAV values, the next step is to find the centroid value of the RMS value of each corner point. centroid is the center point of an object or area in multidimensional space (Windarto, 2017). The results of the centroid calculation can be seen in Figure 8.

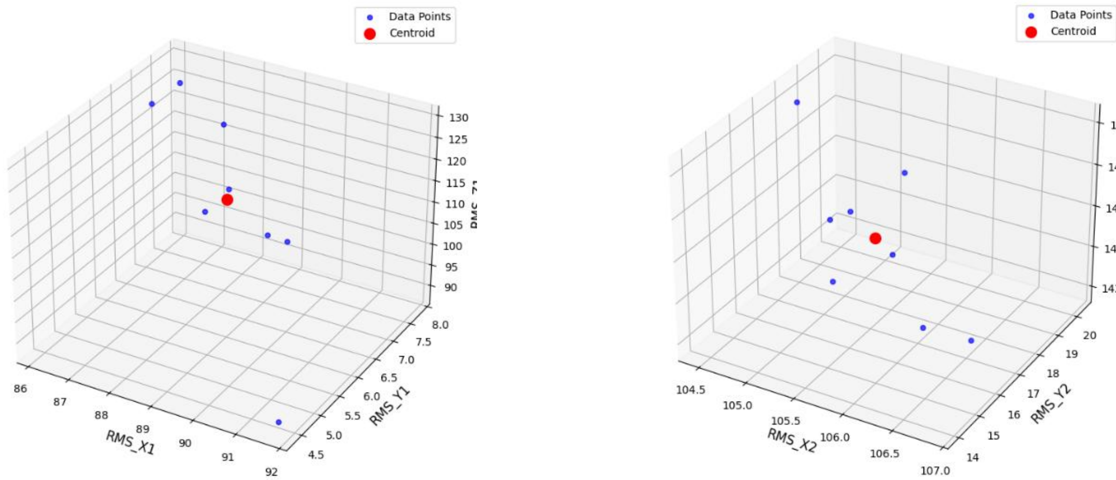

Figure 8. Centroid value of 2 corner points in short forehand serve

Based on the results of the calculation of the centroid value in Figure 8, it is found that the centroid point for the sensor on the dorsum of the hand is equal to 88,9447 for angle X, 6,0748 for angle Y, 117,2558 for angle Z. The centroid point for the sensor on the forearm elbow is equal to 105,6141 for angle X, 16,7264 for angle Y, 146,076 for angle Z. Based on the calculation results of the angular centroid in the short forehand serve motion, there is a difference in angular distribution between the IMU sensors placed on the dorsum of the hand and the forearm below the elbow. This indicates that the elbow forearm experiences greater angluar changes than the dorsum of the hand during the execution of the short forehand serve. This difference in angular distribution indicates that the main movement in the short forehand serve is controlled more by the rotation and movement of the forearm than the wrist. However, the wrist still has a contribution in adjusting the direction and accuracty of the shot, as seen from the difference in angles in the Z angle.

Based on the tendency of the euler angle pattern in the forehand, the forearm and elbow are indeed more active in a controlled linear movement, which suits the needs of a short stroke (Rusydi et al., 2016). The dominance of the forearm in short forehand serve is in line with the role of the forearm in forehand stroke to generate power. However, the short forehand serve is more controlled and does not engage the shoulders as mush as overhead stroke. This result can enrich the understanding of forearm control in hitting techniques that require high accuracy.

3.3 Results of Angle Analysis on Long Forehand Serve Movements

Raw data generated by the IMU sensor will go through a filtering process first. The filtering feature used is a 4^{th} order butterworth filter with a cut-off frequency of 10 Hz to remove noise and get a smoother signal. After the filtering process, the feature extraction process is carried out by calculating the RMS and MAV values of the filtered signal. The results of the angle data processing process can be seen in Figure 9 for the IMU sensor on the dorsum of the hand and Figure 10 for the IMU sensor on the forearm near the elbow.

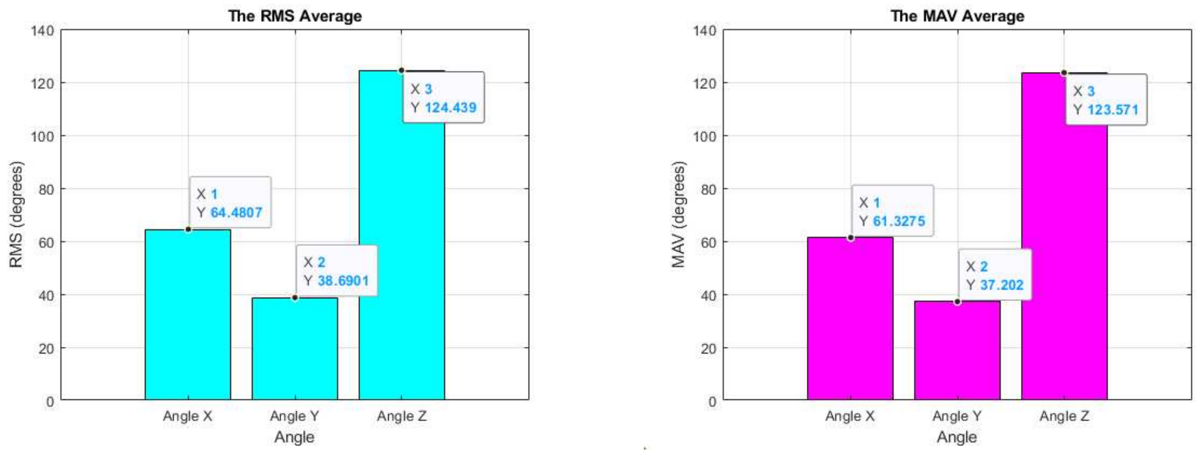

Figure 9. The angle at the dorsum of the hand for a long forehand serve

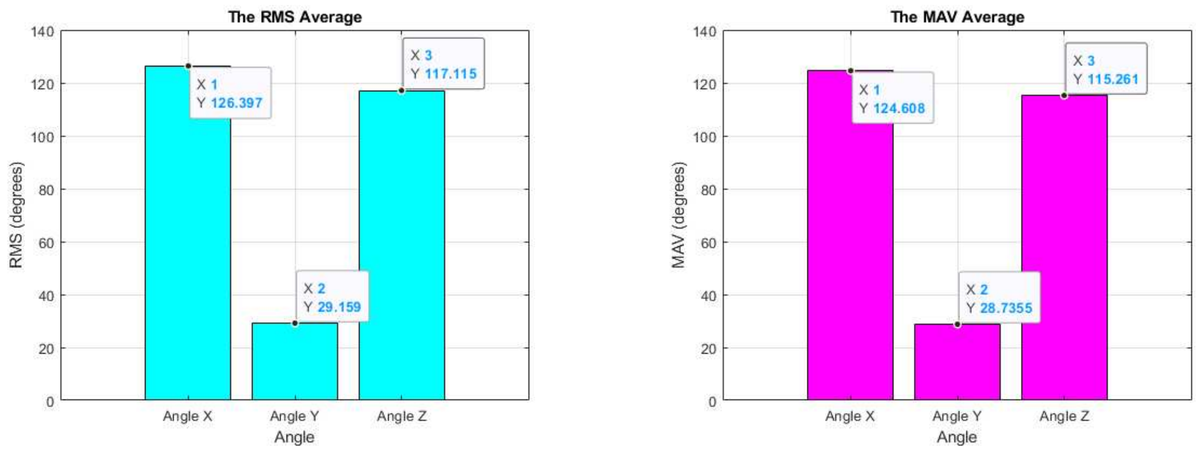

Figure 10. The angle at the forearm near the elbow for a long forehand serve

After calculating the RMS and MAV values, the next step is to find the centroid value of the RMS value of each corner point. centroid is the center point of an object or area in multidimensional space (Windarto, 2017). The results of the centroid calculation can be seen in Figure 11.

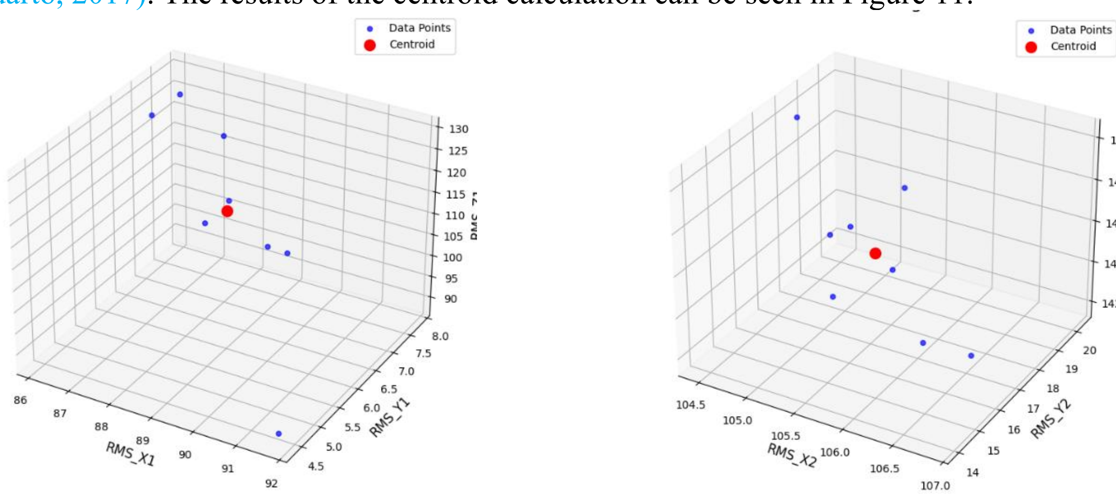

Figure 11. Centroid value of 2 corner points in long forehand serve

Based on the results of the calculation of the centroid value in Figure 11, it is found that the centroid point for the sensor on the dorsum of the hand is equal to 64,4807 for angle X, 38,6901 for angle Y, 124,4388 for angle Z. The centroid point for the sensor on the forearm elbow is equal to 126,3973 for angle X, 29,1590 for angle Y, 117,1149 for angle Z. Based on the results of the calculation of the angular centroid in the long forehand serve movement, it shows that the forearm elbow experiences greater movement than the dorsum of the hand in the X angle rotation direction. Meanwhile, the angular differences in the Y angle and Z angle are relatively smaller. This difference in angular distribution indicates that in the long forehand serve, the main movement is dominated by the rotation of the forearm to produce stronger hitting power. The wrist still plays a role in adjusting the direction and precision of the shot, as seen from the angle values on the Z angle, which are higher on the dorsum of the hand than the forearm at the elbow. The difference in angle in the Y angle also indicates the contribution of wrist flexibility in assisting stroke control during serve execution.

This finding suggests that this movement is a combination of power and control, which demands synergistic coordination between the forearm and wrist. Although Rusydi et al. (2015) and Rusydi et al. (2016) did not specifically address the long forehand, the movement patterns in smashes they studied can serve as a point of comparison, where the complex euler gradient distribution also signifies the need for multi-segmental coordination. Therefore, this study broadens the context by showing that not only smashes, but also long forehands involve similar dynamics.

4. Conclusions

This study analyzed the angle distribution of three types of badminton serves (backhand, short forehand, and long forehand) using IMU sensors on the back of the hand and forearm. Results showed different angle distribution patterns for each type of serve, with the forearm being more dominant on the forehand serve and the wrist being more active on the backhand serve. These findings indicate the importance of coordination training between the forearm and wrist according to the type of stroke. The use of IMU sensors provides quantitative objective data, extends the study of sports biomechanics through RMS centroid-based angle analysis, and offers a new approach compared to the previous euler method. Practically, these results can be used to design more specific and efficient service technique training programs, and open up opportunities for the development of wearable sensor-based motion classification systems. Theoretically, this study extends the study of sports biomechanics by providing quantitative data based on the centroid RMS of local angles on various types of serves. Limitations of this study include a small sample size and limited sensor coverage, so further studies are recommended involving more participants as well as thorough upper and lower body movement analysis.

5. Acknowledgment

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6. References

Aksan, H. (2012). *Mahir Bulutangkis* (1st ed.). Penerbit Nuansa Cendekia.

Aschenbrenner, P., Krawczyński, B., Krawczyński, M., Grzywacz, T., & Erdmann, W. (2023). Description of Telemark Skiing Technique Using Full Body Inertial Measurement Unit. *Sensors*, *23*, 1–9. https://doi.org/10.3390/s23073448

Association, W. M. (2013). *Ethical Principles For Medical Research Involving Human Subjects*.

Bastiaansen, B. J. C., Wilmes, E., Brink, M. S., de Ruiter, C. J., Savelsbergh, G. J. P., Steijlen, A., Jansen, K. M. B., van der Helm, F. C. T., Goedhart, E. A., van der Laan, D., Vegter, R. J. K., & Lemmink, K. A. P. M. (2020). An inertial measurement unit based method to estimate hip and knee joint kinematics in team sport athletes on the field. *Journal of Visualized Experiments*, *159*, 1–8. https://doi.org/10.3791/60857

Brice, S. M., Phillips, E. J., Millett, E. L., Hunter, A., & Philippa, B. (2019). Comparing inertial measurement units and marker-based biomechanical models during dynamic rotation of the torso. *European Journal of Sport Science*, 767–775. https://doi.org/10.1080/17461391.2019.1666167

Espitia-Mora, L. A., Vélez-Guerrero, M. A., & Callejas-Cuervo, M. (2024). Development of a Low-Cost Markerless Optical Motion Capture System for Gait Analysis and Anthropometric Parameter Quantification. *Sensors*, *24*. https://doi.org/10.3390/s24113371

Guignard, B., Ayad, O., Baillet, H., Mell, F., Simbaña Escobar, D., Boulanger, J., & Seifert, L. (2021). Validity, reliability and accuracy of inertial measurement units (IMUs) to measure angles: application in swimming. *Sports Biomechanics*, 1–34. https://doi.org/10.1080/14763141.2021.1945136

Hardwis, S., & Williyanto, S. (2023). Pengembangan Instrumen Tes Keterampilan Backhand Servis untuk Atlet Bulu Tangkis Usia Dini. *Journal of Sport Coaching and Physical Education*, *8*(1), 16–27.

Jacob, A., Nurshazwani, W., Zakaria, W., & Razali, M. (2016, September). Implementation of IMU Sensor for Elbow Movement Measurement of Badminton Players. *2016 2nd IEEE International Symposium on Robotics and Manufacturing Automation (ROMA)*.

Kuo, C., Liang, Z., Fan, Y., Blouin, J. S., & Pai, D. K. (2019). Creating impactful characters: Correcting human impact accelerations using high rate imus in dynamic activities. *ACM Transactions on Graphics*, *38*(4), 47:1-47:12. https://doi.org/10.1145/3306346.3322978

Lee, Y. S., Ho, C. S., Shih, Y., Chang, S. Y., Róbert, F. J., & Shiang, T. Y. (2015). Assessment of walking, running, and jumping movement features by using the inertial measurement unit. *Gait and Posture*, *41*, 877–881. https://doi.org/10.1016/j.gaitpost.2015.03.007

Li, J., Zhu, K., Li, D., Kang, P., & Shull, P. B. (2024). 3D Knee and Hip Angle Estimation with Reduced Wearable IMUs via Transfer Learning during Yoga, Golf, Swimming, Badminton, and Dance. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *32*, 325–338. https://doi.org/10.1109/TNSRE.2024.3349639

Liu, M., Xin, P., Tang, Y., Shan, Y., Zhu, Z., Guo, Z., Zhou, L., Zhang, L., Liu, H., Huang, Y., & Li, B. (2025). Application of Inertial Measurement Units and Machine Learning for Fatigue Assessment in Badminton Athletes. *Research Square*, 1–12. https://doi.org/10.21203/rs.3.rs-6204201/v1

Pedro, B., Cabral, S., & Veloso, A. P. (2021). Concurrent validity of an inertial measurement system in tennis forehand drive. *Journal of Biomechanics*, *121*, 1. https://doi.org/10.1016/j.jbiomech.2021.110410

Phinyomark, A., Phukpattaranont, P., & Limsakul, C. (2012). Feature reduction and selection for EMG signal classification. *Expert Systems with Applications*, *39*(8), 7420–7431. https://doi.org/10.1016/j.eswa.2012.01.102

Purnama, S. K. (2010). *Kepelatihan Bulu Tangkis Modern* (1st ed.). Yuma Pustaka.

Rechy-Ramirez, E. J., & Hu, H. (2015). Bio-signal based control in assistive robots: a survey. *Digital Communications and Networks*, *1*, 85–101. https://doi.org/10.1016/j.dcan.2015.02.004

Reuter, A. S., & Schindler, M. (2023). Motion Capture Systems and Their Use in Educational Research: Insights from a Systematic Literature Review. *Education Sciences*, *13*, 1. https://doi.org/10.3390/educsci13020167

Rusydi, M. I., Huda, S., Rusydi, F., Sucipto, M. H., & Sasaki, M. (2016). Pattern recognition of overhead forehand and backhand in badminton based on the sign of local Euler angle. *Indonesian Journal of Electrical Engineering and Computer Science*, *2*(3), 625–635. https://doi.org/10.11591/ijeecs.v2.i3.pp625-635

Rusydi, M. I., Sasaki, M., Sucipto, M. H., Zaini, & Windasari, N. (2015). Local Euler angle pattern recognition for smash and backhand in badminton based on arm position. *6th International Conference on Applied Human Factors and Ergonomics*, *00*, 1–6. www.sciencedirect.com

Shiang, T. Y., Hsieh, T. Y., Lee, Y. S., Wu, C. C., Yu, M. C., Mei, C. H., & Tai, I. H. (2016). Determine the Foot Strike Pattern Using Inertial Sensors. *Journal of Sensors*, *2016*, 1–6. https://doi.org/10.1155/2016/4759626

Tomita, Y., Iizuka, T., Irisawa, K., & Imura, S. (2021). Detection of movement events of long-track speed skating using wearable inertial sensors. *Sensors*, *21*, 1–9. https://doi.org/10.3390/s21113649

Van Herbruggen, B., Fontaine, J., Simoen, J., De Mey, L., Peralta, D., Shahid, A., & De Poorter, E. (2024). Strategy analysis of badminton players using deep learning from IMU and UWB wearables. *Internet of Things (Netherlands)*, *27*, 1–13. https://doi.org/10.1016/j.iot.2024.101260

Wang, J., Liu, W., & Moffit, J. (2009). Steps for arm and trunk actions of overhead forehand stroke used in badminton games across skill levels. *Perceptual and Motor Skills*, *109*, 177–186. https://doi.org/10.2466/PMS.109.1.177-186

Wardijono, B. A. (2013). Studi tentang Penangkap Gerakan (Motion Capture) Manusia. *Jurnal Ilmiah Komputasi*, *12*(1), 1–6.

Windarto, A. P. (2017). Penerapan Data Mining Pada Ekspor Buah-Buahan Menurut Negara Tujuan Menggunakan K-Means Clustering. *Techno.COM*, *16*(4), 348–357. https://www.bps.go.id.