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ORIGINAL SCIENTIFIC ARTICLE

BIOMECHANICAL MOTION OF THE TENNIS FOREHAND STROKE: ANALYZING THE IMPACT ON THE BALL SPEED USING BIOFOR ANALYSIS SOFTWARE

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Authors' Contribution: A – Study design; B – Data collection; C – Statistical analysis; D – Manuscript Preparation; E – Funds Collection

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Abstract

Background. The inefficiency of the forehand stroke technique often stems from suboptimal execution of an athlete's biomechanical movements. For a forehand stroke to be effective, each biomechanical component – the ankles, knees, hips, shoulders, and elbows – must function in an optimal manner. Disconnection of any of these elements can lead to ineffective technique. High speed, influenced by the racket speed at the point of impact, is a key indicator of a perfect forehand stroke. However, the challenge lies in the fact that an athlete's movement and ball impact cannot be accurately observed with the naked eye, necessitating specialized tools for analysis.

Study purpose. The study aims to develop software that assists in predicting ball speed outcomes based on an athlete's biomechanical movement during a forehand stroke execution.

Materials and methods. The research method employed R&D. Data collection techniques consisted of video recordings of athletes' forehand strokes, which were later analyzed using software that examines movement angles of 10 national athletes.

Results. The results indicated the average angles of elbows = 106.23, shoulders = 153.62, hips = 165.33, knees = 167.63, ankles = 164.54; and ball speed = 199.41 cm/s.

Conclusions. The conclusion drawn is that to execute an effective forehand stroke with good ball speed, a moment of inertia must occur at the point of impact. The athletes should bend their elbow slightly, thereby reducing rotational resistance and increasing the speed of the racket head. The ankles, hips, and shoulders must move in synchronization within a continuous coordination chain, thereby allowing the athlete to fully leverage kinetic chain. The flexion movement of the elbow during the forward swing step is more effective than the extension movement where the elbow is slightly bent, resulting in a perfect shot.

Keywords: biomechanics, software, forehand, tennis.

Introduction

Tennis encompasses a variety of techniques such as the forehand, backhand, volley, smash, and service. Among these, the forehand stroke remains the most prevalently used by tennis players (İbrahim et al., 2013; Keaney & Reid, 2018). Advanced players utilize the forehand stroke technique approximately 85% of the time in every match (Martin-Lorente et al., 2017). This technique is the most natural, simplest to learn, and most frequently deployed in tennis (Brown & Soulier, 2013).

In competitive tennis, it is widely acknowledged that points are often secured or conceded based on a powerful and consistent forehand groundstroke (Kwon et al., 2017). An analysis of point acquisition among elite tennis players highlighted that more points were won with the forehand than the backhand (Genevois et al., 2015); in competitive settings, forehand strokes are employed 25% more frequently than backhand strokes (Nangia et al., 2021).

The forehand stroke can be broken down into three stages: preparation, acceleration, and follow-through. The preparation stage encompasses the backswing movement up to the forward swing. The acceleration stage starts from the forward swing until impact. The follow-through stage is marked by the racket's impact and subsequent follow-through (Rigozzi et al., 2023). In this study, the impact phase, where the ball and racket collide to generate ball speed, is used as a variable for product research.

One frequent issue observed on the court is an ineffective forehand stroke technique, which limits the power of the forehand stroke. This is often attributed to coaches' limited understanding of biomechanics. Without the ability to accurately analyze techniques, athletes struggle to enhance their performance, risking potential injuries that could hinder their achievements. Unresolved incorrect movements become ingrained through repetitive training, complicating technical progression and potentially leading to musculoskeletal joint damage (Gao et al., 2019).

Work biomechanics focuses on mechanical processes such as force, speed, acceleration, momentum, and pressure within the human body, in relation to the physical activities performed by athletes (Sari et al., 2017). The biomechanical foundation for executing a forehand stroke is vital for optimal performance and injury prevention (Elliott et al., 2018). The primary aim of applying work biomechanics is to enhance human movement performance and mitigate the risk of injury to the human musculoskeletal system (Iridiastadi et al., 2014).

The biomechanical movement of the forehand stroke technique is crucial in executing a dynamic stroke with speed, necessitating consistent and strong muscle contraction training. Functional tennis should incorporate dynamic strength training, rather than static training. This involves controlling, stabilizing, and slowing the body using eccentric contractions, while concentric contractions generate rapid body movements. For instance, to recover the forehand stroke movement after a series of movements, eccentric contraction occurs in the thigh muscles when the foot lands and will recover again when preparing for a forehand stroke. To execute a perfect forehand stroke with effective and efficient biomechanical movement, concentric contraction is performed in front of the shoulder when swinging as swiftly as possible.

Analyzing biomechanical movement is not feasible through observation alone; it necessitates the utilization of technology. Past research (Evita & Subagio, 2020) conducted an analysis of biomechanical movement using Kinovea software, assessing arm and leg angles during the initial, preparation, backswing, forward swing, and follow-through phases. In another study (Sari et al., 2017), a body movement measurement instrument was developed using a sensor medium named ESMOCA, which measures angles and calculates biomechanics. This study employed two models for biomechanical measurements: the hand-elbow model and the lower back model. The hand-elbow model focused on measurements of the palm, forearm, and upper arm, while the lower back model focused on measurements of the upper and lower back. Research by (Bakhtiar et al., 2020) developed a system that could estimate the impact force on the forehand stroke by embedding signals into the racket.

In this context, the researcher developed a software tool called "Biofor Analysis Software". This tool functions by recording the athlete's forehand stroke movement on video, which is then imported into the software. The software automatically analyzes and detects the athlete's movement upon ball-racket impact. At the moment of impact, the software reads the body segment angle of biomechanical movement, including the ankle, knees, hips, shoulders, elbow, and ball speed. Thus, by understanding the angle of movement at the time of ball impact, it becomes possible to predict the resulting ball speed.

In research (Evita & Subagio, 2020), the biomechanical movement analysis using Kinovea required users to manually analyze the athlete's movement angle. The analyzed movement angles were limited to the leg and hand angles, and there was no measurement for the resulting ball speed. In contrast, the research conducted by the current researcher includes a comprehensive analysis of body segments such as the ankles, knees, hips, shoulders, elbows, and also measures the ball speed.

The research (Sari et al., 2017) utilized a sensor medium named ESMOCA, attaching sensors to both the leg and arm angles. However, attaching sensors to the legs and body can restrict the athlete's movement, and the sensors can easily detach and are expensive. In contrast, the current research measures the body segment angles of the ankles, knees, hips, shoulders, and elbows without using sensor media, making the process simpler, more practical, and cost-effective.

Research (Bakhtiar et al., 2020) used a single variable of impact force to determine ball speed by attaching a signal to the racket, which is less straightforward and requires additional hardware, and it does not cover the aspect of biomechanics that the current research aims to develop. The current research is more practical and straightforward as it does not require hardware, can directly detect ball speed through ball collision (impact), and can detect biomechanical movement through body segments such as the ankles, knees, hips, shoulders, and elbows. The study aims to develop software that assists in predicting ball speed outcomes based on an athlete's biomechanical movement during a forehand strike impact.

Materials and methods

Study participants

The research methodology adopted in this study is Research & Development, incorporating both qualitative and quantitative data. The study's population comprises 10 athletes from Pre-PON Jateng, consisting of five male and five female athletes, and 10 Unnes tennis UKM athletes, again with an equal gender distribution. The sample is saturated with all the population members serving as sample members, and the criteria for selection are male athletes, resulting in a total sample of 10 athletes.

Study organization

The research design is experimental and data collection techniques include questionnaires for experts to assess the validity of the instrument. The sample was tested three times. The test instrument uses a ball launcher and a video camcorder/android phone. The product developed in this study is the Biofor Motion Analysis Software application, designed to predict forehand stroke speed based on the angle of biomechanical movement at the point of ball impact.

The product observes the biomechanical movement from the ankles, knees, hips, shoulders, and elbows at the moment of ball impact. The system can automatically calculate the angle. The system operates by collecting image data of the tennis player using an Internet of Things (IoT) Modbus sensor image acquisition circuit (Peng & Tang, 2022). The product will detect the player's movement angle using the principle of human pose detection, which has 32 detection points on the human body, and detect ball speed. The results of detecting the player's movement angle and ball speed are stored in Excel as the final result of this product.

The stages of the research development procedure include: 1) product analysis, 2) initial software instrument and product development, 3) expert judgment, 4) product trials, and 5) product revision.

The implementation of the research began with the component analysis stage. This tool product will produce output in the form of ball speed data and the pose of players during the game. The required input data are spatial data in RGB format where the player and ball are present. The main components used are listed below.

Software	**Python 3** A programming language used to detect objects in the form of humans and tennis balls.
	Visual Studio Code An application for editing programming languages.
	Iriun A tool to connect the webcam to the PC using a wifi network.
Hardware 	**Webcam** Used to record in real time at a predetermined court angle.
	**Tripod** A supporting tool for the webcam during video shooting.
	**Meter** A tool to measure the angle of video shooting or the size of the field.

The product will detect the player's movement angle using the principle of human pose detection, which has 32 detection points on the human body, and detect ball speed. The results of detecting the player's movement angle and ball speed are stored in Excel as the final result of this product. The flow diagram of how the system works:

Statistical analysis

This study uses descriptive and inferential analysis with Two-Way ANOVA classification using the formula:

$F = (RKa/RKd) > F_{k-1;\, n-k}$ or Sig. (P_value)

Where:

$JKa = nS\, X^2 - (\Sigma x^2/k)$

$JKd = JKsmk$

$JKT = Jka + JKd$

$df\ JKa = k-1$

$df\ JKd = N-k$

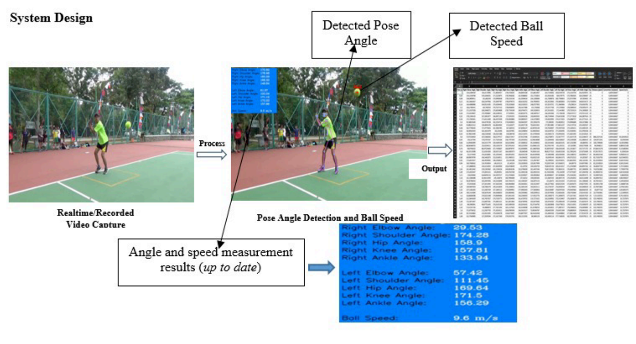

Fig. 1. Workflow System

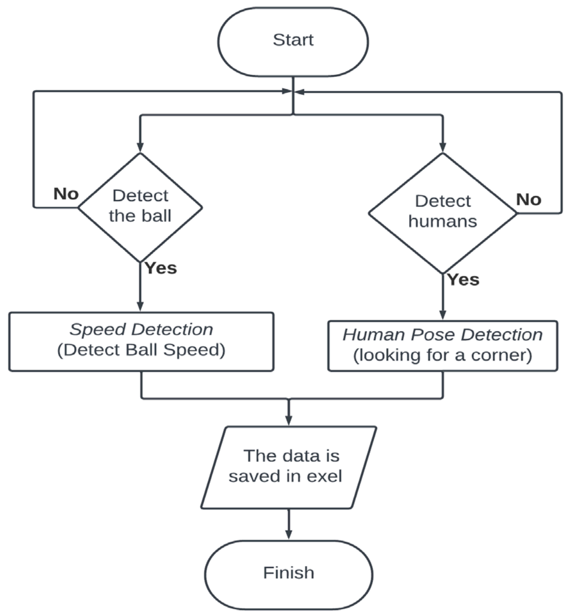

Fig. 2. How Product System Works

To ensure accuracy, the SPSS version 25 program is used. The sample used in the research trial is illustrated in Figure 1, which presents the system product work.

Results

The research on forehand stroke technique using a ball launcher was conducted at the Dr. Sajoto tennis court, FIK, Unnes from 14 July to 14 October 2023. The results of the biomechanical movement test of the forehand stroke are as follows.

From Table 1, at the moment of ball impact, the average angles were – ankles: 164.54, knees: 167.63, hips: 165.33, shoulders: 153.62, elbows: 106.23, and ball speed: 199.41 with a standard deviation of 42.41. The data show that the software can accurately read the angles of biomechanical movement and ball speed. Each stroke is analyzed by the system up to 206 frames. The researcher only needs to determine the optimal point position when the ball impact occurs and then analyze each movement based on the appropriate movement mechanics.

Table 1. Average ball impact of athletes' forehand stroke

No.	Player's	Result					
		Elbows	Shoulders	Hips	Knees	Legs	Ball Speed
1	A-1-1	59.02	149.88	163.78	147.89	140.73	266.4
	A-1-2	67.19	175.56	160.01	169.47	152.44	176.8
	A-1-3	71.34	165.23	162.34	152.84	154.96	258.8
2	A-2-1	85.99	137.61	160.32	177.87	177.63	268.4
	A-2-2	98.35	156.29	166.5	169.55	159.25	157.7
	A-2-3	133.08	135.6	167.26	168.17	157.65	133.7
3	A-3-1	96.47	126.33	172.19	159.95	156.76	155.4
	A-3-2	82.62	133.79	172.17	173.38	171.89	291.3
	A-3-3	77.59	123.77	176.67	160.9	159.11	182.8
4	A-4-1	176.49	173.55	165.75	177.52	172.45	129.7
	A-4-2	177.56	173.9	159.0	177.57	172.42	127.7
	A-4-3	149.84	158.08	160.81	174.61	173.78	239.2
5	A-5-1	156.44	160.95	161.48	165.97	159.18	92.6
	A-5-2	88.25	178.73	165.72	178.12	175.76	147.3
	A-5-3	126.47	122.04	165.62	162.85	151.77	91.8
6	A-6-1	146.67	141.13	163.82	169.29	168.79	112.6
	A-6-2	121.10	154.2	162.88	172.68	162.80	134.4
	A-6-3	129.53	149.33	161.14	175.95	164.78	131.1
7	A-7-1	75	142.49	163.53	175.18	174.18	120.9
	A-7-2	73.62	156.27	175.52	166.17	159.96	162.6
	A-7-3	88.75	133.17	168.25	166.69	179.98	117.1
8	A-8-1	58.68	148.71	170.41	156.71	163.23	262
	A-8-2	69.95	117.91	175.5	165.37	158.98	169.8
	A-8-3	107.21	132.44	169.09	170.03	161.17	140.9
9	A-9-1	152.58	168.01	166.09	168.42	164.75	345.9
	A-9-2	170.44	179.87	156.73	177.89	178.62	165.6
	A-9-3	159.55	164.71	162.48	174.7	177.8	394.2
10	A-10-1	70.25	159.65	159.25	154.24	157.86	359.8
	A-10-2	55.26	172.9	163.9	178.44	162.63	361.2
	A-10-3	61.43	163.95	163.64	155.57	162.58	246.2
	Average	106.23	153.62	165.33	167.63	164.54	199.41
	SD	42.41					

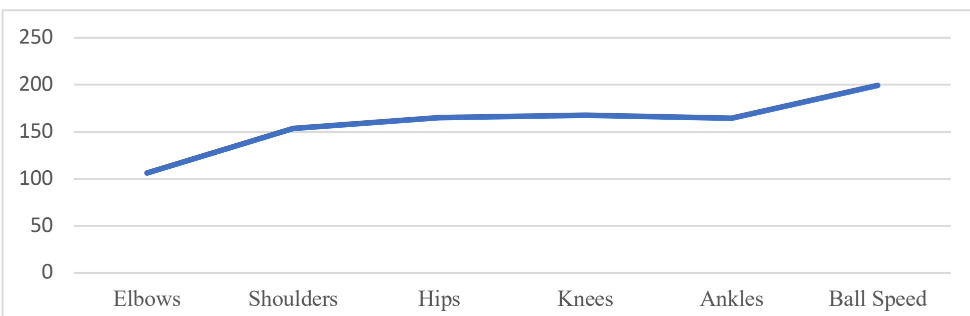

Fig. 3. Average Biomechanics of Forehand Stroke Impact

Discussion

A well-executed racket strike is when the racket head trails the handle, allowing the player to utilize the ball's momentum for added power upon impact. The ball's effect on the racket at the point of impact assists the player in generating additional power and control. The racket plays a crucial role upon impact. The racket experiences an impact force from the ball, causing vibrations and generating a unique frequency. Sunku Kwon (Kwon et al., 2017) suggested that the angle of the racket head (open/closed) affects ball speed. Tom Allen (Allen et al., 2011) argued that alterations

Table 2. Biomechanical Movement at the Moment of Impact

Body Part	Description
Shoulder	**Body work:** the head has to keep in line with the shoulders to keep balanced. The shoulders guide the arm movement. **Biomechanical consequences:** Head and shoulders co-operate to keep balance throughout the impact. **Practical points:** Teach your players to "watch" the ball at impact and to keep the chin up and forward.
Trunk and upper body	**Body work:** Correct use of all body parts,. Grip: the further the grip is towards "western" the sharper the arc of the racket path at contact point. Grip tension: is required to counteract any "off-centre" impact which create torque, good timing. **Biomechanical consequences:** By correct use of the body's co-ordination chain, racket head speed is generated, as angular momentum is transferred through the heavy parts of the body (which are the moving slowly) (eg. Torso) to the light parts (wrist) (which therefore have to move very fast), to keep the formula of weight x speed balanced. The western grips create topspin through applying torque on the ball. The torque is a product of the ball's momentum at impact and how far off the centre of the racket the impact occurred. By controlling the co-ordination chain and its constituent units, and interpreting tha ball's flight path. **Practical points:** Remember that extreme grips have disadvanteges associated with shot variety and shot improvisation. Ball hit from the "sweet-spot" require very little tension. Grip tension during the take-back and swing is counter-productive. Helping the player to hit with rhythm or flow is essential when searching for racket head speed. Help the player to hit the ball well rather than just trying to hit hard.
Hips	**Body work:** They keep in line with the shoulders. Biomechanical consequences: Hips, trunk and shoulders are the basic elements to maintain the balance throughout the impact. **Practical points:** Teach your players that during impact (0.004 secs) balance is extremely important.

to the racket head influence the racket's operating system. A closed racket head angle results in a higher ball speed compared to an open racket head angle (Ikenaga et al., 2020), and the speed of the racket head influences ball speed upon forehand stroke impact (Elliott et al., 2018).

At the moment of racket and ball impact, the shoulders swing forcefully to generate explosive power. According to (Reid et al., 2013) and (Genevois et al., 2015), in terms of kinematics, skilled players apply more body rotation during the execution of the forehand stroke, resulting in a higher shoulder speed.

The results from the study (Iino, 2018) demonstrate that the rotational speed of the hips on the player's side is positively related to the horizontal racket speed at the moment of impact.

The movement of the back foot following impact influences the ball speed (Shimokawa et al., 2022). The more forward the back foot moves after impact, the greater the power generated. In biomechanics, this is referred to as linear momentum, which involves moving body weight forward towards the stroke.

The legs, hips, and trunk should move in a synchronized chain of coordination, enabling athletes to fully harness the kinetic chain (Roetert et al., 2009).

The flexion movement of the elbow during the forward swing phase is more effective than the extension movement of the elbow (Widiyatmoko et al., 2021). Keeping the elbow slightly bent leads to a perfect shot and minimizes the risk of injuries.

Cyril Genevois (Genevois et al., 2020) stated that the internal rotation of the humerus and pronation of the lower arm contribute to an ideal shot. This action should occur naturally without forcing the wrist into extension; it should happen as a result of stroke mechanics and good power preparation. Most professional players achieve a degree of delay before making contact with the ball. With a semi-western grip at impact, certain outcomes are produced (Bahamonde, 2001), including:

- Due to the semi-western grip, the wrist is pulled back at impact.
- The head remains entirely still, and the eyes focus on the stroke.
- Typically, an open-stance foot positioning is observed at the time of impact. Research has shown that top players (both men and women) use an open-stance on the forehand 90% of the time.
- Knee extension, along with right hip rotation, ensures the load is transferred along the racket head's path from the swing before and after collision.
- The racket head may be slightly below the wrist at impact, which can be acceptable.
- If the racket head is significantly below the wrist, then the grip will weaken and control will decrease.

The advantage of the product developed in this research is its ease and practicality of use for measuring biomechanical movement and ball speed, and its cost-effectiveness. However, the product also has a limitation: the forehand speed in the program is still measured in pixels/second in the 2D space of the video image, and not in actual measurements. Therefore, it needs to be adjusted to the dimensions of the field size and the athlete's forehand speed reference.

There were several challenges encountered during data collection, including the need for a sterile field free from surrounding objects such as scattered leaves, rolling balls during the athlete test, and clothing that must not be similar in color to the ball. Despite these challenges, the strength of this research is that the data collection process is straightforward because it only relies on a video camcorder or Android phone.

Conclusions

The analysis of the biomechanical motion of a forehand stroke, specifically in relation to ball speed, can be evaluated through the observed impact of the ball and the corresponding angles of the ankles, knees, hips, shoulders, and elbows. The findings of this study confirm that the developed product can precisely detect the angular movements of athletes and the corresponding ball speed. It is thus inferred that this tool is apt for athletes and trainers to scrutinize and appraise forehand stroke techniques, resulting in the optimization and enhancement of biomechanical movements. It is advisable for coaches to utilize this tool to augment the forehand technique and amplify the power of their athletes' forehand strokes. In the event of movement discrepancies, the software is proficient in identifying the precise location of these errors, thus enabling coaches to implement corrective strategies in subsequent training sessions.

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Conflict of interest

All author have declared no conflict of interest.

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БІОМЕХАНІЧНИЙ РУХ ТЕНІСНОГО УДАРУ ВІДКРИТОЮ РАКЕТКОЮ: АНАЛІЗ ВПЛИВУ НА ШВИДКІСТЬ М'ЯЧА ЗА ДОПОМОГОЮ ПРОГРАМНОГО ЗАБЕЗПЕЧЕННЯ BIOFOR ANALYSIS

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Авторський вклад: A – дизайн дослідження; B – збір даних; C – статаналіз; D – підготовка рукопису; E – збір коштів

Реферат. Стаття: 7 с., 2 табл., 3 рис., 24 джерела.

Історія питання. Неефективність техніки удару відкритою ракеткою часто пов'язана з неоптимальним виконанням біомеханічних рухів спортсменом. Для того, щоб удар відкритою ракеткою був ефективним, кожен біомеханічний компонент – щиколотки, коліна, стегна, плечі та лікті – повинен функціонувати оптимальним чином. Відключення будь-якого із цих елементів може призвести до неефективності техніки. Висока швидкість, яка залежить від швидкості ракетки в точці удару, є ключовим показником ідеального удару відкритою ракеткою. Проте проблема полягає в тому, що рух спортсмена та удар по м'ячу неможливо точно спостерігати неозброєним оком, тому для аналізу потрібні спеціальні інструменти.

Мета дослідження. Метою дослідження є розробка програмного забезпечення, яке допомагає прогнозувати результати швидкості м'яча залежно від біомеханічного руху спортсмена під час виконання удару відкритою ракеткою.

Матеріали та методи. Метод дослідження передбачав застосування НДДКР. Методи збору даних включали відеозаписи ударів спортсменів відкритою ракеткою, які пізніше аналізували за допомогою програмного забезпечення, яке аналізує кути рухів 10 національних спортсменів.

Результати. Результати показали середні кути ліктів = 106,23, плечей = 153,62, стегон = 165,33, колін = 167,63, щиколоток = 164,54; і швидкість м'яча = 199,41 см/с.

Висновки. Зроблений висновок полягає в тому, що для виконання ефективного удару відкритою ракеткою з гарною швидкістю м'яча в точці удару має виникнути момент інерції. Спортсменам слід трохи згинати лікоть, тим самим зменшуючи опір обертанню та збільшуючи швидкість голови ракетки. Щиколотки, стегна та плечі повинні рухатися синхронно в межах безперервного координаційного ланцюга, тим самим дозволяючи спортсмену повністю й максимально ефективно використовувати кінетичний ланцюг. Рух згинання ліктя під час виконання маху вперед є ефективнішим, ніж рух розгинання, коли лікоть трохи зігнутий, що дає в результаті ідеальний удар.

Ключові слова: біомеханіка, програмне забезпечення, удар відкритою ракеткою, теніс.

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