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Biomechanical Kinetic Chain Analysis of Service Motion for Speed Ball Prediction Through SBM-03 App Development

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Abstract

Background. The kinetic chain of the serve stroke is a coordinated activation of body segments (legs, torso, shoulders, arms, and hands) that begins with the ground reaction force against the legs on the ground and ends with racket acceleration through the ball. The objective of this study is to place the end segment, hand, and racket in an optimal position at an optimal speed to "make the ball travel" as best as possible. The efficient use of the kinetic chain segment creates a much greater racket velocity than its parts. On the contrary, a broken kinetic chain makes the ball speed less optimal and can even lead to injury. However, the reality is that the kinetic chain movement and ball speed rate cannot be seen simply using the observation method. Thus, a specific technology is needed to diagnose it.

Objectives. This study aimed to develop a digitalized system of software to help measure the ball speed rate based on the kinetic chain of the serve stroke.

Materials and methods. The research method employed in this study was research and development (R&D). The data were collected by recording videos of 10 professional athletes' serve strokes. These videos were then analyzed using software to check their movement angles.

Results. The findings showed that the average angles were as follows: elbow = 120.490, shoulder = 166.010, hip = 165.330, knee = 165.880, ankle = 173.790, and ball speed = 24.33 m/s.

Conclusions. Some conclusions were drawn from this study. First, the more significant portion of the kinetic energy of force produced in a serve was developed on the legs and body torso. Every segment generated force and acted as a stabilizer structure for the next segment's activity. Fifty-one percent of kinetic energy and 54 up to 60 percent of the total force were produced this way. Second, the kinetic chain was oriented towards changing the linear or straight-line momentum into an angular or rotational momentum around the stable pillar leg. Third, each segment had tilting or stabilization and acceleration phases. Fourth, a big and fast movement was needed in the joints, especially the shoulders. Finally, the broken segment or kinetic chain reduced the ultimate force or energy available to travel the ball and put enormous pressure on the surrounding segments. A decrease in kinetic energy by 10 percent from the hip or body to the shoulder while doing the serve required an increase in the shoulder's rotation by 14 percent or an increase in the shoulder's mass by 22 percent to create the same kinetic energy on the hands and racket. There were some reasons for the broken kinetic chain, but the most general ones included muscle weakness, inflexibility, joint injury, and poor stroke mechanics.

Keywords: kinetic chain, technology, serve, tennis.

Introduction

In tennis, every game begins with a serve (Fett et al., 2020). An effective, hard and accurate serve is what all athletes dream of. The main keys to a successful serve are speed, rotation and placement (Martin, 2018). The serve speed is one of a determining factor of tennis performance (Colomar et al., 2022; Fett et al., 2020). An athlete's ability to get the first serve ball speed is an important element of a successful game (Maquirriain et al., 2016) and a major advantage for a player (Martínez-Gallego et al., 2020). A good first serve makes the opponent feel pressured and less optimal to return it, allowing a server to have greater chance for points than their opponents. A good first serve enables the player to get rally points in a short time with a percentage of points won by 72-81% (Hizan et al., 2011). In addition, a successful first serve has developed into a powerful tool for gaining immediate points or taking instant initiative in a rally (Keller et al., 2021). Based on the research data in the field, male tennis players have 65% (Australia Open and France Open) and 70% (Wimbledon) change of winning if the first serve can be maintained during the match (Meffert et al., 2018).

A kinetic chain begins from the legs, develops to the hip, body torso, upper arms, lower arms, and eventually to the hands and the racket (Fu et al., 2018; Terré et al., 2024). The right kinetic chain (movement execution, technical skills, kinetic chain coordination) is needed by professional players (Fett et al., 2021). In a kinetic chain, the hip is the connector between the legs and the body, and abdominis is the connector between pelvic girdle and shoulder girdle. The pelvis and body torso are a vital connector in a set of actions while doing the serve.

Interestingly, from the biomechanic perspective, a serve is characterized by a bottle-opening movement, after the ball is thrown, the serving arm moves behind the body and the vertebral column is laterally bent and hyperextended with the lower body fully loaded. The racket and arm acceleration when serving before the impact point is accompanied by counter-rotational acceleration of the lumbar spine, from hyperextension to flexion from right rotation to left rotation (Kovacs & Ellenbecker, 2011). When starting the service, the front foot is placed to the right net post and the back foot is parallel to the baseline. The front heel and the back toes are aligned to create stability (Fett et al., 2021).

Considering the problems above, it is important to conduct research analyzing the kinetic chain (Liang et al., 2023) in producing a serve stroke that has high speed and accuracy. Nevertheless, a service is the most difficult technique to master compared to other techniques as it needs a complex combination and coordination of joints and leg movements required to transfer force from the bottom to the racket head known as the kinetic chain (Kovacs & Ellenbecker, 2011). Hence, a precise and in-depth investigation on kinetic chain is needed to generate an optimal stroke. It will surely be not an easy task if a coach analyzes this kinetic chain and predict the resulting ball speed when they only rely on observation without involving any science and technology in it.

Most studies on kinetic chain start from the lower limbs up and the body torso joint movements (Wagner et al., 2014), racket and ball kinematics (Whiteside et al., 2013), gender, age, performance, and injury-related kinematics (Campbell, 2013), the effects of flat or slice serves (Carboch et al., 2018), and body and ball kinematics in deuce and Ad situations (Fett et al., 2021). However, to the best of researchers' knowledge, no studies have been conducted on the predicted correlation between the kinetic chain of service stroke and the produced ball speed rate. The analysis was done through the kinetic chain at the time of ball impact (Eaton et al., 2013). In each phase (Wang et al., 2021), the kinetic chain angle of the athlete's biomechanical movements during service will be read, including: elbow, shoulder, hip, knee and ankle (Fleisig et al., 2003; Parunchaya et al., 2025). The analysis was carried out using a readily accessible and operatable Android-based application to make it easier for coaches to analyze the athletes' movement problems. This application system works by reading one athlete's movement into several detailed series of movements taken from live video recordings or replays, then connected to an Android mobile phone or computer that has the application installed. The application was also designed to automatically read the ball speed as the athlete did the serve (Zhao et al., 2019).

Materials and Methods

Participants of Study

Research and Development (R&D) was used for the current research with quantitative data. The research population consisted of 5 male 12th-grade student national athletes of Central Java and 5 male athletes from Tennis Club at UNNES. As every individual in the population participated in the research, the sample reached saturation, with the only criterion being male athletes, resulting in a total of 10 athletes as the sample.

Organization of Study

For this research with experimental design, the data were collected by distributing questionnaire to experts to allow them to determine whether the instrument was valid or not. The test was done in three repetitions. A ball launcher and a camcorder were used in the test. In addition, the camcorder was integrated to an Android mobile phone to record the video. The product developed in this research was SBM-03 application. Its design allowed the researcher to predict the speed of forehand stroke as shown by the angle of biomechanic movement when the ball impact occurred.

This product observed the biomechanic movement of some body parts involved in the movement such as hips, ankles, shoulders, knees, and elbows at the moment of ball contact. Additionally, the system was capable of automatically computing the angle. Furthermore, it collected data from pictures of tennis players employing an image acquisition circuit of Modbus IoT (Internet of Things) sensor. The product utilized the principle known as human pose detection to measure the player's movement angle, using 32 points on the body, while tracking the speed of the ball. Once the numbers regarding angles of movement and ball speed were obtained, they were then saved in Excel as the deliverables.

The procedures for developing the research involved: 1) analyzing the product, 2) developing the software and

Table 1. Main Components of Software

Software Name	Icon	Function
Python 3	Python 3 Essential Training	A programming language used as communication to make it possible to track objects. In this case the objects were human beings and a tennis ball.
VS Code	Visual Studio	To edit the programming language.
Irun		To link the webcam to the computer via a Wi-Fi connection.

Table 2. Main Components of Hardware

Hardware Name	Figure	Function
Webcam		Used to record videos real-time at the predetermined corner of the court.
Tripod		Serving to support the webcam in recording the video.
Surveyor's tape		To determine the angle from which the video was taken and the dimensions of the court.

product prototypes, 3) having the product assessed by experts, 4) testing the product, and 5) revising the product.

The research started with an analysis of the components to be used. The product's output would be data on ball speed and poses of the players while the game was ongoing. The data needed were spatial ones in RGB format the frame of which contained the players and the ball. Below is the list of main components used.

The movement angle of players was detected based on the so-called human pose detection principle, that had 32 points on the body and the speed of the ball was also tracked. The deliverables of this athlete movement and ball speed detection were saved in Excel. The flowchart of how this system worked is as follows:

Statistical Analysis

Since descriptive, inferential analysis with Two-Way ANOVA classification was employed in this study, the following formula was used.

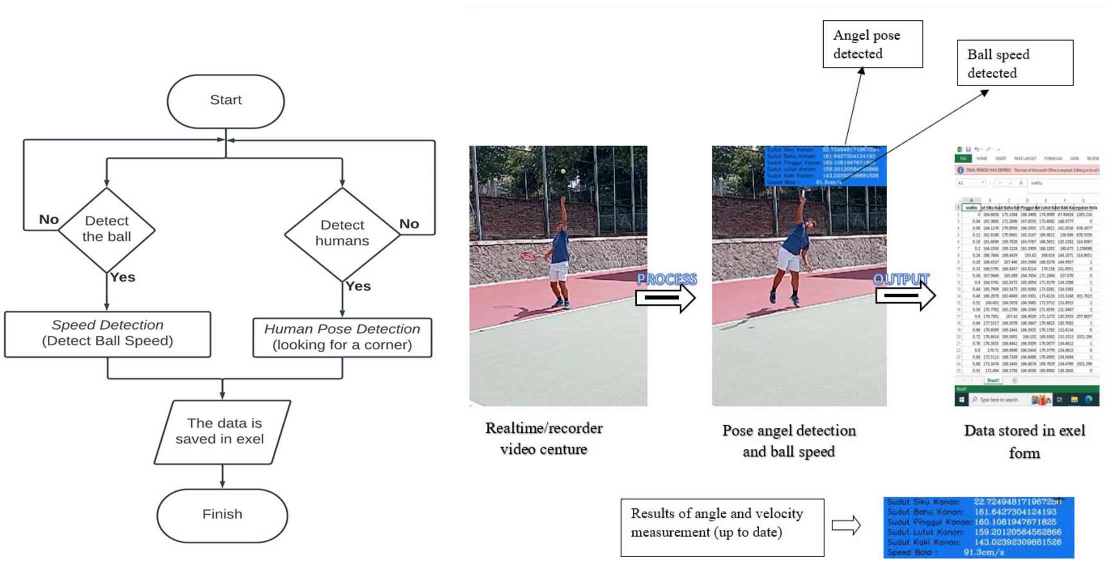

Fig. 1. Workflow of System

Table 3. Average ball impact of athletes' first serve

No	Player's	EIbows	Shoulders	Hips	Knees	Ankle	Ball Speed, m/s
1	A	108.53	163.83	172.07	179.98	169.32	26.8
2	B	33.85	151.38	161.34	176.89	166.19	24.8
3	C	95.19	157.27	165.08	175.69	174.48	24.67
4	D	155.08	170.1	165.64	179.64	178.56	24.54
5	E	176.29	174.09	162.73	162.6	174.3	24.22
6	F	159.55	164.71	162.48	174.7	177.8	24
7	G	152.58	168.01	166.09	168.42	164.75	23.75
8	H	62.84	178.84	177.6	168.8	168.85	23.54
9	I	111.16	173.82	164.93	176.64	169.3	23.52
10	J	149.84	158.08	160.81	174.61	173.78	23.47
Avarage		120.491	166.013	165.877	173.797	171.733	24.331
SD		44.076269	8.193724489	4.950935366	5.237692335	4.486457511	0.946503566

$$F = \frac{RKa}{RKd} > Fk-1;\ n-k \text{ or } Sig.\ (P\_value)$$

Where:

$$JKa = nS\,X^2 - \frac{\sum X^2}{k}$$

$JKd = JKsmk$
$JKT = Jka + JKd$
$df\ JKa = k\text{-}1$
$df\ JKd = N\text{-}k$

To make sure that the results were accurate, this research used SPSS version 25. Figure 1 shows the sample tested in the trial. Furthermore, it presents how the system product functions.

Results

This study on serve stroke was conducted at tennis courts of GOR Jati Diri, Semarang Municipality, on 16 October 2024. In the first serve stroke trial with 10 athletes in 10 repetitions respectively, and after being calculated on average, the following results were obtained:

Table 3 shows that when the ball made contact, the angles, on average, were 171.730 for ankles, 173.790 for knees, 165.880 for hips, 166.010 for shoulders, and 120.490 for elbows with the ball speed being 24.33 m/s at 0.95 ball speed standard deviation. From these findings, it could be said that the software could measure the angles of kinetic chain and the speed of the ball in an accurate manner. Upon analyzing as many as 206 frames, every stroke was computed by the system. All that the researchers needed to do was deciding on the point to make the ball impact optimal and analyzing every movement as per the movement mechanics.

The body parts acted as a system of chain links where energy (or force) was produced by one of the chain links (or body parts), transferred in sequence to the next chain link. Its application in the serve was as follows:

Discussion

This research aimed at analyzing the kinetic chain of serve stroke using a digitalization technology. The main problem was how to measure the angle of joint kinetic chain and racket speed to produce an optimal ball speed. In general, the angles of joint kinetic chain and racket speed could be measured well by the product.

In a serve, there were a number of similarities that were prerequisites for the stroke to be executed most efficiently and effectively. The first one was stable foundation. The legs should be parallel, open, and positioned sideways to allow the knees to do some flexion and develop the lower and upper body rotational momentum. Greater knee flexion during preparation contributes to racquet speed (Hornestam et al., 2021).The second one was simultaneous movement of both arms. The throwing arm followed the line of rotation of the body when the hitting arm was in the cocked position (racket face closed). This closed racket position was best achieved with a proper (continental) serve grip. As both of their arms working together in such a way, the player would be better able to achieve the desired trunk and shoulder rotation. The third one was the hitting phase. This phase began when the hitting hips, body and shoulder rotated. This was followed by the deceleration of the right hip (blocker), which allowed the transfer of energy to the shoulder and arm. The shoulder internal rotation (front elbow) affected the racket's fall continuity and the elbow's forward acceleration. The fourth one was extension movement. The racket started to rise quickly on the edge. This allowed for optimal shoulder internal rotation and forearm pronation. The fifth one was contact. At this point, the full extension of the hitting side was shown. The forearm pronation and the wrist outward rotation continued until impact. When contact occurred, the vertical racket speed was positively related to the hip rotation (Vacek et al., 2023). The ball speed was also affected by whether the head angle was opened or closed (Vaverka et al., 2018). To optimize the high racket head speed, flexibility of hands and upper arms as well as trunk and shoulder internal rotations were needed (Delgado-Garcia et al., 2019). Some studies reported that when the contact occurred, the elbow was not fully extended (Fett et al., 2021) since it would reduce the pathological risk such as loose body formation. Just like the elbow, when the serve contacted, the configuration of the shoulder joint could cause pain and pathology (Gillet et al., 2017). The sixth similarity was deceleration. After a powerful ball-hitting motion and a long follow-through, the player regained their balance.

To produce kinetic chain force efficiently for a serve, four common points in the kinetic chain sequence were needed. First, the leg/hip segment needed some degree of knee flexion when cocking. Knee extension from flexion then provided upward linear momentum, transferring the

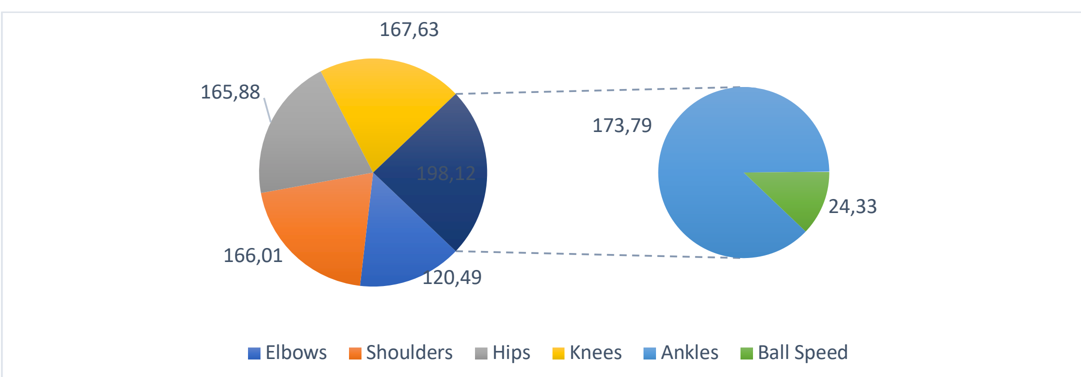

Fig. 2. Mean Kinetic Chain of First Serve Impact

Table 4. Working System of Serve Kinetic Chain

Body Part	Description
Leg drive	Increases velocity of hip
Trunk and shoulders rotation	Increases shoulders velocity
Upper arm	Increases elbow velocity
Elevation	Aligns the racket for impact and Increases wrist velocity
Forearm extension and pronation	Increases racket speed
Hand flexion	The second part of the link in the chain is the use of the hips.
Hip rotation	The Advanced player will transfer the power generated by the knees to the trunk through the hips. Hip rotation occurs after the knees bend, and then straighten. Such an action upwards drivers the shoulder up and out which forces the racket further down the back of the server. This phenomenon is called displacement and requires excellent co-ordination.
Trunk rotation	Once the force has been transferred from the ground, through the legs to the hips, and the hips achieve maximum rotation speed, then trunk is rotated. Most good servers have considerable trunk rotation. Note that as the trunk rotates the left arm is tucked in front of and across the body. This arm action acts to decelerate the trunk rotation thus allowing the arm to accelerate out towards the target.
Rotation of the arm about the shoulder (power loop)	Following the trunk rotation, the next link in the system is the rotation of the arm about the shoulders. When the arm is at the bottom of the backswing behind the back, it is externally rotated at the shoulder. On the upward or forward swing, the upper arm internally rotates at a very high speed.
Elbow Extention – Forearm pronation	The next part of the link involves the elbow in two ways: The elbow extends from position when the racket is behind the back (in the power loop), and Pronation (turning outward) of the forearm and hand around the elbow occurs The speed of these two actions is very high and care should be taken to avoid injury.
Wrist flexion	In the backswing (behind the back) and early forward swing the wrist is hyperextended (the hand bends back at the wrist). As the racket head accelerates towards the impact points, the hand flexes at the wrist until, at impact, it is relatively straight compared to the forearm, and then racket head continues at high speed so that the wrist flexes. The wrist action from a hyperextended positition, through to a straight (at impact) and then flexed position (after impact), is the final stage in the chain of links which produces a powerful serve.
Follow through and landing foot	The completion of the weight transfer forward moves the body into the court. The face of the racket does an outward rotation that reduces the strain of the shoulder joint. The racket moves across the body and decelerates. The body starts to recover its balance for the next shot.

ground reaction forces to the body (Fett et al., 2021). The leg in the back provided most of the upward and forward thrust, while the front leg provided a stable pole to allow for rotational momentum. This created a "pushing" motion from the ground to the racket. Second, the body and scapula had to rotate and retract, to allow for a shoulder/arm position when cocking. This served to store a full tank of energy. A stable body position allowed a quick acceleration to the ball. Third, the shoulder needed to rotate externally and abducted horizontally to reach the cock, and rotated internally while accelerating. The shoulder internal rotation from the cocked position to acceleration was the single most important biomechanical variable in the kinetic chain of a serve, had the highest speed, occurred the closest to the ball impact, and allowed maximum acceleration through the ball (Moreno-Pérez et al., 2019).

The flexibility and internal rotation of the upper shoulder during the rotation phase played an important role in racket (Antrenmanların, 2020; Martin et al., 2014; Söğüt, 2017). The acceleration phase began with maximum lateral rotation of the shoulder at the end of the cocking phase (Zappala et al., 2017). Finally, the forearm pronated to accelerate the racket through the hitting zone. This movement was combined with internal rotation of the shoulder (Whiteside et al., 2013).

The capacity to increase the absolute ball speed started with lower body mechanics and followed by that of the upper body (Butler et al., 2020; Gallo-Salazar et al., 2017). It is important for angle and shoulder to be tilted and accompanied by knee flexion (Antúnez et al., 2012). The knee extension during trunk/scapular rotation acceleration reached the "full tank of energy" while tilting external shoulder rotation (backward) and internal rotation (forward). (Zhang & Chen, 2024)suggested that internal rotation of the humerus and pronation of the forearm contributed to the effectiveness of tennis strokes. The same applied to the forearm pronation (outward rotation of the wrist) (Palmer et al., 2018).

The advantages of this research product included its ease and practicality for use as well as its effectiveness to measure the kinetic chain and the resulting ball speed. Nevertheless, this product still had its limitations, such the different correlation between measurement angle of kinetic chain and the resulting ball speed among players. It was possible that this was a result of some factors, including heights, weights, arm length and angel position when the video was taken.

The previous studies showed that arm length and height affected the serve speed (Ma et al., 2024). The correlation of first serve between anthropometry and speed: height, upper arm length, arm circumference and Body Mass Index BMI (Moreno-Pérez et al., 2019). A significant correlation occurred between serve speed and BMI, and this was associated with the potential increased muscle mass on power (Vaverka and Cernosek, 2013).

The challenge to deal with was to find a way to increase the accuracy degree of ball speed and the joint kinetic chain angle despite the athletes' different anatomical structure. Regardless of this challenge, this research had its own added value thanks to the ease of collecting its data, where only smartphone or Android mobile phone was sufficient to collect the data and analyze the kinetic chain and ball speed while performing the serve stroke.

Conclusions

The serve stroke technique could be assessed and measured using this tool. It is suggested for coaches and athletes to use this tool to consider the effectiveness of kinetic chain of serve stroke technique to generate an optimal ball speed. When differences in movement are spotted, this software would be able to identify what goes wrong in the movement, enabling coaches to apply a corrective strategy in the following practice session. It is recommended for future research to consider other variables such as height, weight, arm length and to use camera from multiple angles to make the product analysis more precise and accurate.

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Conflict of Interest

All authors have declared that they have no conflict of interests.

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Біомеханічний аналіз кінетичного ланцюга руху подачі щодо прогнозування швидкості польоту м'яча шляхом розроблення додатку SBM-03

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

Реферат. Стаття: 8 с., 4 табл., 2 рис., 39 джерел.

Історія питання. Кінетичний ланцюг удару під час виконання подачі представляє собою скоординовану активацію сегментів тіла (ніг, тулуба, плечей, рук і кистей), яка починається з моменту сили реакції опори, що виникає у відповідь на тиск ногою на опору і завершується прискоренням удару ракеткою по м'ячу. Мета цього дослідження полягає в позиціонуванні кінцевого сегмента, кисті руки та ракетки в оптимальному положенні з оптимальною швидкістю задля якомога ефективнішого «забезпечення польоту м'яча». Ефективне використання сегмента кінетичного ланцюга створює набагато більшу швидкість ракетки, ніж його складових. Натомість розірваний кінетичний ланцюг спричиняє менш оптимальну швидкість польоту м'яча і навіть може призвести до травмування. Однак насправді рух кінетичного ланцюга і показник швидкості польоту м'яча неможливо помітити лише за допомогою обсерваційного методу. Тому для діагностики цього процесу необхідне впровадження спеціальної технології.

Мета роботи. Метою цього дослідження було розробити цифрову систему програмного забезпечення для вимірювання показників швидкості польоту м'яча на основі кінетичного ланцюга удару під час виконання подачі.

Матеріали та методи. У представленій науковій праці застосовано методику науково-дослідних та дослідно-конструкторських робіт. Збір даних здійснювався шляхом фіксації відеозаписів ударів під час подачі 10 спортсменів-професіоналів. Згодом отримані відеозаписи були проаналізовані за допомогою програмного забезпечення для перевірки кутів їхнього руху.

Результати. Результати показали, що середні кути мали наступні параметри: лікоть = 120.490, плече = 166.010, стегно = 165.330, коліно = 165.880, надп'ятково-гомілковий суглоб = 173.790, а швидкість польоту м'яча = 24.33 м/с.

Висновки. На основі проведеного дослідження зроблено кілька висновків. По-перше, значніша частина кінетичної енергії сили, що створюється під час виконання подачі, розвивається у ногах і тулубі. Кожен сегмент генерував силу і діяв як структура-стабілізатор задля активності наступного сегмента. У такий спосіб вироблялося п'ятдесят один відсоток кінетичної енергії і від 54 до 60 відсотків загальної сили. По-друге, кінетичний ланцюг був орієнтований на зміну лінійного або прямолінійного імпульсу у кутовий або обертальний момент навколо стійкої опори. По-третє, кожен сегмент мав фази нахилу або стабілізації та прискорення. По-четверте, потрібно збільшити діапазон та швидкість рухів в суглобах, зокрема в плечах. Зрештою, розірваний сегмент або кінетичний ланцюг зменшував кінцеву силу або енергію, необхідну для руху м'яча, створюючи величезний тиск на навколишні сегменти. Зниження кінетичної енергії на 10% від стегна або тулуба до плеча під час виконання подачі вимагало збільшення обертання плеча на 14% або збільшення маси плеча на 22%, щоб створити аналогічну кінетичну енергію для кистей рук і ракетки. Серед причин розриву кінетичного ланцюга можна виділити кілька основних: м'язова слабкість, відсутність гнучкості, травми суглобів та погана механіка удару.

Ключові слова: кінетичний ланцюг, технологія, подача, теніс.

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