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CASUISTIC PAPER

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Upper limb analysis measured by inertial measurement unit tool: a case report

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ABSTRACT

Introduction. This article reports differences in accurate and inaccurate forehand and backhand strokes in tennis. The tests were carried out on a professional tennis player. The duration of a stroke, the heights of the individual segments of the right upper limb and differences in the heights of the segments at the beginning and at the end of every phase of stroke were examined.

Aim. The major aim of the work was to expose upper limb disparity in stokes. **Description of the case report.** The research tool was inertial motion sensors (IMS) based on an accelerometer, a gyroscope and a magnetometer. A professional tennis player was examined using the individual case method and kinematic analysis.

Results. The analysis concerned the average time to perform forehand and backhand strokes during all phases of the stroke, i.e. preparation, acceleration and follow-through phases. The average heights of the individual upper limb segments during a stroke were also taken into account. The results of the study are meant to show how the movement of the upper limb affects the accuracy and velocity of a stroke.

Conclusion. The movements of individual segments in some accurate strokes were similar to those in inaccurate strokes.

Keywords. biomechanics, IMU, tennis, timing, upper limb

Introduction

It is generally accepted that sport results are affected by variables such as motor preparation, psychological preparation, physical development of the body, biomechanical conditions, tactics and also nutrition, genetics, general health, well-being and socio-cultural factors.[1] The main issue explored in this article is biomechanics in tennis, and, more specifically, the kinematic analysis of forehands and backhands.

Biomechanics is applied in many scientific fields, such as physiotherapy, physical education and sports. Biomechanical research can be successfully applied in various sports disciplines. To learn more about movement and its structure, kinematic studies are conducted. They help athletes achieve the best results at the highest level. Many modern methods have been recently used in tennis, such as optoelectronics and systems for three-dimensional kinematic motion analysis.[2] An instructor or

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trainer gets natural feedback during training from the sensory system. Recently, feedback has been provided by technical equipment and sports equipment.[3]

Optical motion capture systems are today's trend in the assessment of human movement. These systems are expensive but they provide reliable analysis and reduce the accumulation of laboratory data. Devices such as inertial measurement units (IMU), or IMS, have been invented as an alternative research tool for studying motion kinematics. The advantage of these innovative devices is mobility, which allows testing outside the laboratory. IMUs available on the market have various applications. Their main purpose is to identify motion disorders.[4]

The first step in the analysis of motion in sport when using the feedback system is to obtain a signal. The motion capture system (MCS) technique is important in obtaining feedback in research. Most of these systems are based on different optical systems and inertial sensors. Athletes' movements are captured by measuring various physical quantities, such as acceleration, velocity, position, angular velocity, rotation, angle, force, power and energy. Optical MCSs generally show the spatial position of markers. Inertial sensors based on the MCS show acceleration through an accelerometer, angular velocity through a gyroscope and orientation in space through a magnetometer. Markers are most commonly placed on the athlete's body and should not block or absorb his movements.[2] The quantity of forces through the elbow during tennis stroke can make enormous elongation and valgus overload in players. Tennis has been represented as a power game cause of the explosive physical action of the players and very high ball rapidity.[5]

A tennis game consists of many shots and movements that are performed to accurately hit the ball into the court. Forehands and backhands are the most frequent strokes used by tennis players during a game.[6]

In professional tennis, in addition to serves, forehands and backhands are responsible for the largest number of points gained. In the 2007 US Open, forehands performed by Roger Federer and Novak Djoković, two of the best tennis players in history, accounted for 29.2% and 31.2%, respectively, of all strokes made. For comparison, their backhands accounted for 33.4% and 34.2%, respectively, of all shots performed.[7]

The aim of the study is to find and describe the correct motion patterns based on the basics of biomechanics of solid bodies and, more specifically, biomechanics in tennis. The study focuses primarily on the impact of variables, such as the duration of a stroke and the heights of individual upper limb segments, during a stroke on its accuracy and the velocity of the ball. The study primarily involved forehands and backhands, which largely determine success in scoring points and the game itself. Forehands and backhands consist of many phases and in-depth analysis of every phase allows for broader understanding than if strokes were explored as a whole.

Description of the case report

The study involved a professional tennis player. As a junior, he was very successful at both national and international tournaments. He reached doubles and singles semi-finals and finals at inter-university level. He was a multiple winner of the Polish Junior Championships and participated in International Tennis Federation (ITF) tournaments. The subject took part in the study voluntarily and was informed in detail about the purpose of the tests. The tests took place during one training session.

In this study, the individual case method was used, which was helpful in evaluating the results obtained by the tennis player. The individual case method helped analyse the tennis player being examined. "Axis Neuron" software was the research tool. The device consists of a system of modules and are based on IMU. The apparatus consists of triaxial gyroscopes, triaxial accelerometers and triaxial magnetometers. Accurate and real motion with minimal delay was obtained based on the dynamics of the human body and algorithms.

Analysis of the forehand. Place: Gym with lines marking out the tennis court. Equipment: MCS, IMU, tennis racket, radar. The conduct of the test: Initially, the device was calibrated to produce reliable results. The subject took the basic tennis position around 1 m from the baseline on the right hand corner of the tennis court. The tennis player performed a forehand stroke on the spot, after dropping the tennis ball perpendicular to the ground. The ball dropped by gravitational force from a height of 2 m to the forehand side of the subject. The tennis player had to strike the ball after it bounced off the ground into a designated area on the other side of the net, which was positioned diagonally near the baseline at the corner. This area was a square of 4 m^2. After the stroke, the subject returned to the starting position. The tennis player was asked to perform a total of 36 forehand strokes with the entire system being recalibrated after each series of six strokes. Evaluation: The accuracy of the forehand stroke and the velocity of the ball were evaluated. All registration data and export data were sent directly to the recording equipment via motion sensors.

Analysis of the backhand. Place: Gym with lines marking out the tennis court. Equipment: MCS, IMU, tennis racket, radar. The conduct of the test: Similar to the forehand strokes, the device was calibrated to produce reliable results. The subject took the basic tennis position around 1 m from the baseline of the court on the left hand corner of the tennis court. The tennis player performed a backhand stroke on the spot, after dropping the tennis ball perpendicular to the ground. The ball dropped by gravitational force from a height of 2 m to the backhand side of the subject. The tennis player had to strike the ball after it bounced off the ground into a designated area on the other side of the net, which was positioned diagonally near the baseline at the corner. This area was a square of 4 m^2. After the stroke, the subject returned to the starting position. The tennis player was asked to perform a total of 36 backhand strokes with the entire system being recalibrated after each series of six strokes. Evaluation: The accuracy of the backhand stroke and the velocity of the ball were evaluated. All registration data and export data were sent directly to the recording equipment via motion sensors.

Fig. 1. Photos presenting tennis player in (IMU) "outfit"
Source: Own elaboration

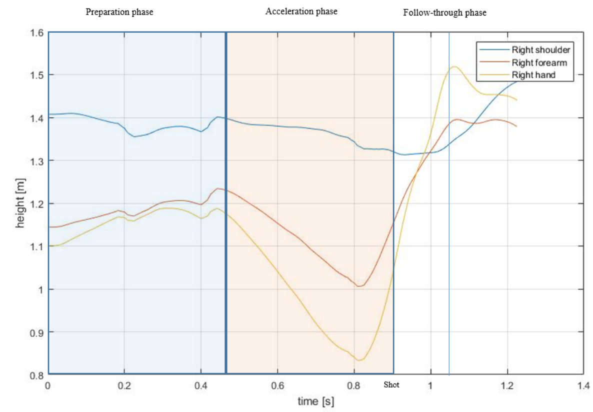

Fig. 2. Accurate forehand stroke

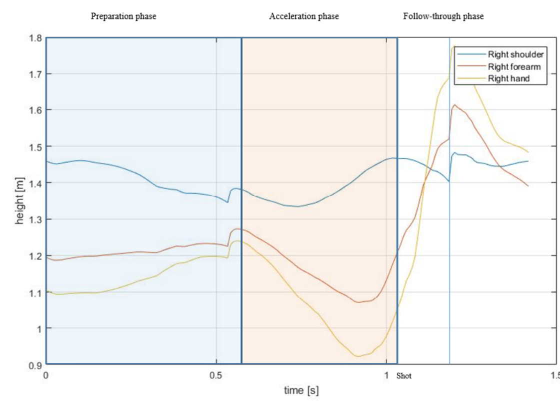

Fig. 3. Inaccurate forehand stroke

Results

The analysis concerned the average time to perform forehand and backhand strokes during all phases of the stroke, i.e. preparation, acceleration and follow-through phases. The average heights of the individual upper limb segments during a stroke were also taken into account. The results of the study are meant to show how the movement of the upper limb affects the accuracy and velocity of a stroke. They also demonstrate when the strings of the tennis racket hit the ball. Differences in the height of every limb segment examined correspond to the initial phase and the final phase of each stroke section described, e.g. the beginning and the end of the follow-through phase. The analysis involved three accurate forehand and three accurate backhand strokes, as well as three inaccurate forehand and three inaccurate backhand strokes.

The first stroke analysed (Figure 2) was the forehand, which was considered an accurate stroke. The velocity of the ball during this test was 105 km/h. The time of this stroke from the preparation phase to the follow-through phase was 1.05 s. The preparation phase, i.e. abduction of the racket hand, lasted 0.43 s. The duration of the acceleration phase was approximately 0.48 seconds. The strings of the racket hit the ball at the end of the acceleration phase, at 0.9 s of the stroke. The follow-through phase lasted 0.15 s. The heights of the hand in the preparation phase oscillated from 1.1 m to 1.18 m. The heights of the forearm in the preparation phase were close to the heights of the hand and ranged from 1.15 m to 1.2 m. In the preparation phase, the shoulder was at around 1.4 m without a noticeable change in height and dropped slightly at the end of the phase. Significant height amplitude was observed during the acceleration phase in each segment of the upper limb examined, with the exception of the shoulder. The level at which the shoulder was located did not change significantly, decreasing from approximately 1.4 m to 1.3 m. The height of the forearm decreased from 1.22 m to 1.05 m and rose to around 1.15 m at the moment when the ball touched the strings of the racket. In the follow-through phase, the height of the shoulder increased to about 1.3 m and 1.4 m, while the highest amplitude was recorded in the heights of the forearm and the hand: the height of the forearm increased to 1.4 m and the height of the hand rose to 1.52 m. It was observed that the time of the entire second forehand stroke was 0.98 s, i.e. 0.7 s shorter than that of the first one. It was also discovered that the preparation and acceleration phases in the second forehand were significantly shorter, in contrast to the follow-through phase, which lasted longer. The moment of impact occurred earlier, i.e. at 0.79 s of the entire stroke. Differences in heights in the preparation phase were not clear, but the difference in the heights of the hand in the acceleration phase amounted to 0.09 m. In the follow-through phase, a noticeable difference was noted in the heights of the shoulder amounting to 0.09 m. Attention should also be paid to the fact that the hand moved higher than in the first stroke. At the lowest point, it dropped to 0.94 m, while in the first stoke it reached 0.84 m. In the third forehand stroke, the difference in the heights of the hand between the beginning and the end of the preparation phase was significantly greater amounting to 0.22 m. Interestingly, the forearm was higher than the hand in the preparation phase. The next three forehands tested were considered as missed. The differences observed range from a few to several centimetres and from hundredths to tenths of a second. The velocities of missed balls hit by the tennis player were on average comparable to those of accurate strokes. The duration of a missed stroke was on average

Table 1. Data of accurate forehand stroke

	F_1	F_2	F_3	$\bar{X}$
Accuracy	in	in	in	**100%**
Ball speed (km/h)	105	115	121	**113.67**
Stroke duration (s)	1.05	0.98	1.00	**1.01**
Length of preparation phase (s)	0.43	0.39	0.35	**0.39**
Length of acceleration phase (s)	0.48	0.40	0.52	**0.47**
Length of follow-through phase (s)	0.15	0.19	0.13	**0.16**
Moment of impact (s)	0.90	0.79	0.87	**0.85**
Height disparity of hand in preparation phase (m)*	0.08	0.06	0.22	**0.12**
Height disparity of forearm in preparation phase (m)*	0.08	0.07	0.10	**0.08**
Height disparity of shoulder in preparation phase (m)*	0.01	0.02	0.06	**0.03**
Height disparity of hand in acceleration phase (m)*	0.23	0.14	0.12	**0.16**
Height disparity of forearm in acceleration phase (m)*	0.08	0.07	0.08	**0.08**
Height disparity of shoulder in acceleration phase (m)*	0.09	0.09	0.11	**0.10**
Height disparity of hand in follow-through phase (m)*	0.52	0.54	0.56	**0.54**
Height disparity of forearm in follow-through phase (m)*	0.27	0.27	0.25	**0.26**
Height disparity of shoulder in follow-through phase (m)*	0.03	0.12	0.07	**0.07**

* Difference in the heights of the segment between the beginning and the end of the phase. The result is given in absolute value.

Table 2. Data of inaccurate forehand stroke

	F_4	F_5	F_6	$\bar{X}$
Accuracy	out	out	out	**100%**
Ball speed (km/h)	117	113	120	**116.67**
Stroke duration (s)	0.94	1.05	1.20	**1.06**
Length of preparation phase (s)	0.39	0.50	0.60	**0.50**
Length of acceleration phase (s)	0.43	0.32	0.42	**0.39**
Length of follow-through phase (s)	0.13	0.23	0.18	**0.18**
Moment of impact (s)	0.81	0.82	1.02	**0.88**
Height disparity of hand in preparation phase (m)*	0.21	0.26	0.13	**0.20**
Height disparity of forearm in preparation phase (m)*	0.10	0.19	0.06	**0.12**
Height disparity of shoulder in preparation phase (m)*	0.09	0.01	0.08	**0.06**
Height disparity of hand in acceleration phase (m)*	0.17	0.26	0.21	**0.21**
Height disparity of forearm in acceleration phase (m)*	0.02	0.06	0.07	**0.05**
Height disparity of shoulder in acceleration phase (m)*	0.03	0.08	0.07	**0.06**
Height disparity of hand in follow-through phase (m)*	0.42	0.75	0.78	**0.65**
Height disparity of forearm in follow-through phase (m)*	0.20	0.42	0.41	**0.34**
Height disparity of shoulder in follow-through phase (m)*	0.00	0.04	0.02	**0.02**

* Difference in the heights of the segment between the beginning and the end of the phase. The result is given in absolute value.

0.05 s longer than that of an inaccurate stroke. In the third stroke, the value was 1.2 s while the duration of accurate strokes was at a constant level of around 1 s. The swing in inaccurate strokes was also longer, unlike the acceleration phase. The duration of the stroke in the follow-through phase was on the same level. The estimated moment of impact was similar in accurate and missed strokes. Differences in the heights of the upper limb segments in the preparation phase in inaccurate stokes did not significantly differ from those in accurate strokes. The differences in the heights of the hand, the forearm and the shoulder between the beginning and the end of the acceleration phase were 0.05 m, 0.03 m and 0.04 m respectively. While greater differences in the heights of the hand and the forearm were observed in missed strokes, the differences in the heights of the shoulder in inaccurate strokes were small. In some missed strokes, in addition to differences in the time taken performing a stroke, attention should be paid to differences in the values of individual strokes at impact, differences in the heights of individual segments in the preparation phase, and the heights of the shoulder, the hand and the forearm in the acceleration phase.

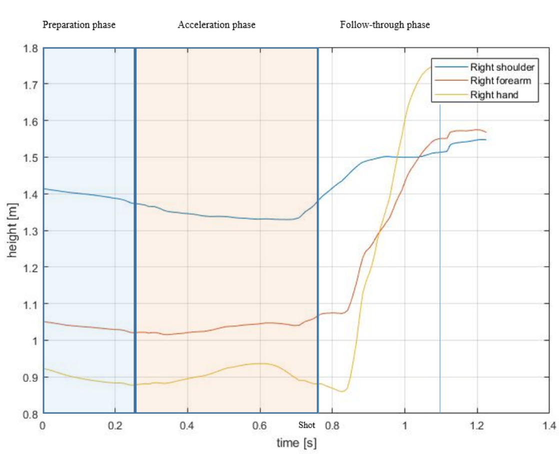

Fig. 4. Accurate backhand strok

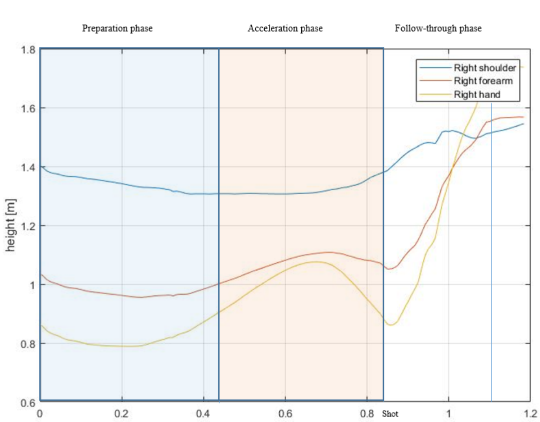

Fig. 5. Inaccurate backhand stroke

Backhands were also divided into three accurate and three inaccurate strokes. The method and technique of the tests used to obtain the results diagnosing backhand strokes was analogous to those used in the forehand stroke test. It is worth mentioning that the tennis player preferred two-handed backhands.

The velocity of the ball after the first backhand stroke was 96 km/h. The stroke was performed in 1.10 seconds. The duration of the backhand was similar to that of the forehand. The moment of impact was estimated at 0.78 s of the entire stroke. The acceleration phase was the longest phase of the stroke. In the first backhand analysed, attention should be paid to the height of the racket trajectory and, consequently, the upper limb elevation because the in-depth analysis of the first stoke did not show particularly large changes in height between the preparation phase and the acceleration phase. It can therefore be said that the swing and acceleration of the tennis racket were horizontal. The heights of the forearm and the hand only changed significantly in the follow-through phase. The average velocities of the balls after the strokes were 101 km/h in the second case and 109 km/h in the third case. With each attempt, the player increased the accuracy of strokes. The average velocity of all 36 backhand balls was more than 104 km/h, and the average speed of 36 forehand balls was more than 114 km/h. As in the case of the first stroke, in the second accurate stroke, the racket moved practically horizontally. In this attempt, the moment of impact was delayed and the swing lasted longer. Only the height of the shoulder changed significantly. The difference in height measured from the beginning to the end of the phase was 28 cm larger than at the first attempt. Differences in the heights of the shoulder, the forearm and the hand did not change much when considering the initial and the final phases of the third stroke. It was observed that the racket moved along a larger parabola than in the two previous strokes, which apparently did not affect the accuracy of the stroke. There was a noticeable change in the height of the hand in the follow-through phase of the third stroke and there were large differences in the heights of the shoulder in all accurate backhands.

The first backhanded tested was characterised by a similar racket trajectory to the first two accurate backhand strokes. The trajectories of the second and third inaccurate backhands were similar to that of the last accurate backhand stroke. In the second missed backhand, the hand moved higher than the forearm in the acceleration phase. A similar situation occurred with the third forehand. Missed backhands were characterised by a slightly higher velocity of the ball after the stroke, amounting, on average, to more than 2 km/h than in the case of accurate strokes. The average duration of the stroke was practically identical; however, the difference in duration between certain strokes was

0.14 s, i.e. around 11% of the longest stroke. The average difference in the duration of the preparation phase between accurate and inaccurate strokes was 0.06 s. The longest swing in all forehands tested was found to be inaccurate. The difference in the mean lengths of the acceleration phase is not large and amounts to 0.01 s. In all the strokes tested, there are differences in the parabolas of the upper limb motion in the acceleration phase. In the fourth backhand, the preparation and acceleration phases were longer than the follow-through phase. The moment of impact in missed strokes occurred on average 0.05 s later than in accurate strokes. In the fourth backhand, attention should be paid to the result of the follow-through phase and the moment of impact. The longer swing and acceleration phases and the shorter follow-through phase and delayed stroke may correlate with each other. This can be explained as "making up for" bad timing with a shorter follow-through phase.

Discussion

The research on forehand and backhand biomechanics focuses primarily on the areas of medicine and rehabilitation. The areas of research are diverse and refer to many factors making up a tennis game. For example,

Table 3. Data of accurate backhand stroke

	B_1	B_2	B_3	$\bar{X}$
Accuracy	in	in	in	**100%**
Ball speed (km/h)	96	101	109	**102.00**
Stroke duration (s)	1.10	1.24	1.12	**1.15**
Length of preparation phase (s)	0.23	0.40	0.38	**0.34**
Length of acceleration phase (s)	0.53	0.51	0.39	**0.48**
Length of follow-through phase (s)	0.32	0.33	0.35	**0.33**
Moment of impact (s)	0.78	0.91	0.77	**0.82**
Height disparity of hand in preparation phase (m)*	0.05	0.02	0.13	**0.07**
Height disparity of forearm in preparation phase (m)*	0.04	0.03	0.01	**0.03**
Height disparity of shoulder in preparation phase (m)*	0.04	0.05	0.14	**0.08**
Height disparity of hand in acceleration phase (m)*	0.07	0.19	0	**0.09**
Height disparity of forearm in acceleration phase (m)*	0.02	0.06	0.02	**0.03**
Height disparity of shoulder in acceleration phase (m)*	0.11	0.02	0.03	**0.05**
Height disparity of hand in follow-through phase (m)*	0.85	0.72	0.59	**0.72**
Height disparity of forearm in follow-through phase (m)*	0.47	0.44	0.45	**0.45**
Height disparity of shoulder in follow-through phase (m)*	0.02	0.34	0.19	**0.18**

* Difference in the heights of the segment between the beginning and the end of the phase. The result is given in absolute value.

Table 4. Data of inaccurate backhand stroke

	B_4	B_5	B_6	$\bar{X}$
Accuracy	out	out	out	**100%**
Ball speed (km/h)	94	110	109	**104.33**
Stroke duration (s)	1.18	1.14	1.11	**1.14**
Length of preparation phase (s)	0.44	0.34	0.43	**0.40**
Length of acceleration phase (s)	0.56	0.45	0.39	**0.47**
Length of follow-through phase (s)	0.18	0.35	0.29	**0.27**
Moment of impact (s)	1.00	0.79	0.82	**0.87**
Height disparity of hand in preparation phase (m)*	0.10	0.06	0.07	**0.08**
Height disparity of forearm in preparation phase (m)*	0.06	0.04	0	**0.03**
Height disparity of shoulder in preparation phase (m)*	0.05	0.09	0.10	**0.08**
Height disparity of hand in acceleration phase (m)*	0.15	0.20	0.10	**0.15**
Height disparity of forearm in acceleration phase (m)*	0.17	0.13	0.08	**0.13**
Height disparity of shoulder in acceleration phase (m)*	0.09	0.03	0.02	**0.05**
Height disparity of hand in follow-through phase (m)*	0.72	0.53	0.79	**0.68**
Height disparity of forearm in follow-through phase (m)*	0.31	0.31	0.46	**0.36**
Height disparity of shoulder in follow-through phase (m)*	0.07	0.06	0.12	**0.08**

* Difference in the heights of the segment between the beginning and the end of the phase. The result is given in absolute value.

the study of reactions to the change of friction during a game played on a clay surface has shown that the free surface has a significant impact on reducing the risk of injury by increasing the moment of sliding.[8] The issues of diagnosis, management and treatment of injuries to which tennis players are exposed were studied using the example of arm pain during its rotation.[9] Moreover, kinematic analysis of the shoulder joint was conducted as a non-invasive method of studying the kinematic chain of stroke and arm instability.[10] For example in table tennis investigations about forehand are concerned in upper limb kinematics, upper limb kinetics and lower limb kinematics analysis.[11-13] The study concerning the development of methodology to determine the relationship between the size of the grip and the kinematic share of angular velocity is an example of research that focuses on tennis equipment and its impact on the player's performance.[14] Biomechanics in tennis also involved a kinematic comparison of successful and unsuccessful tennis serves across the elite development pathway, where it has been proven that there are no clear differences in body kinematics during serves.[15]

Conclusion

Correlations determined and results obtained through the in-depth analysis lead to the conclusion that the velocity of the ball after forehand and backhand strokes does not affect the accuracy of the stroke. It can be assumed that the ball flying on average 2 km/h faster did not reach the designated place. Considering that the majority of strokes were over 100 km/h, this variable does not affect the achievement of the intended goal. It was noticed that the average duration of accurate and inaccurate strokes was similar, but with visible differences in the duration of individual phases. This can be described as the tennis player's ability to match the duration of the swing, the acceleration phase and the moment of impact to achieve a good result. Height modulation helped the subject perform correct and accurate forehand and backhand strokes. The movements of individual segments in some accurate strokes were similar to those in inaccurate strokes. After comparing accurate and inaccurate strokes, conclusions regarding the movement of the upper limb clearly show that differences in the movements of the hand, the forearm and the shoulder are dependent on the tennis player himself, taking into account the automation of his movements. Most of the analysed strokes do not differ significantly. Some details concerning height and length during the research process were optimised by the subject. If he was an amateur tennis player, the results would be completely different and would show differences in movements of the upper limb during each stroke.

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