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Kinematic Analysis of Basketball Free Throw Trajectory

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Abstract

Free throw shooting is a fundamental skill in basketball that requires a combination of technique, consistency, mental focus, and the ability to perform under pressure. The purpose of this study was to analyze the kinematic parameters of the ball trajectory during a successful free throw. The study involved 20 players from the Kosovo Basketball League during the 2020 season. Ten kinematic variables were selected for analysis. Three Canon cameras (Canon Inc., Tokyo, Japan), recording at 60 frames per second, were used to capture the free throw motion. The recorded videos were analyzed using the Ariel Performance Analysis System (APAS) to extract kinematic data. Significant correlations were found between kinematic variables in the ball trajectory during a successful free throw between: Initial distance between the ball and the center of gravity and height of release (r=0.68), Final distance between the ball and the center of gravity and height of release (r=0.61), Height of release and vertical displacement of the ball's trajectory (r=-0.72), Release angle and entry angle of the ball (r=0.65). The results of this research enrich the scientific knowledge of the kinematic analysis of the ball trajectory in basketball free throws, contributing to the development of more accurate methodologies for evaluating and improving performance in the sport of basketball. These findings contribute to a deeper understanding of the kinematic principles underlying successful free throw shooting and provide valuable information for coaches and athletes seeking to enhance performance.

Keywords: *basketball, kinematic, ball trajectory, free throw shoot, Pearson's correlation*

Introduction

Basketball is considered one of the most popular sports worldwide. This beautiful game is played by more than 450 million people worldwide (Kachanathu, Dhamija, & Malhotra, 2013). Previous research has shown that free throw performance is one of the key factors in determining whether a team wins or loses at some of the highest levels of basketball competition (Sampaio & Janeira, 2003). The biomechanical parameters of the player determine the accuracy of free throws in basketball during the performance (Fontanella, 2006). When discussing the kinematic parameters of the shot, authors Miller and Bartlett (1993) believe that an optimal combination of kinematic parameters is important for a successful shot in the game of basketball. Ibana and Saenzy (2003) showed that the factors determining a successful shot include arm action, foot movement, body position, height, and distance of the shot. Malone (1999) stated that for a successful shot in basketball, the force used by the flexion of the arms must be consistent with the angle of release of the ball. One of the kinematic parameters of the shot is the trajectory of the ball in the sport of basketball (Satti, 2004). The analysis of the trajectory of the ball in basketball has been an interesting topic, but also important for many researchers around the world (Brancazio, 1981; Satern, 1988; Southard & Miracle, 1993). At the moment when the player is released from the ball, the elements that he performs are: the height of the ball release, the trajectory of the ball movement, the horizontal and vertical displacement, the angle of the ball release, the speed of the ball and the angle of entry of the ball. The path followed by a projectile is called its trajectory (Changjan & Mueanply, 2015). The study of ball

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trajectory in basketball has been a topic of great interest to researchers worldwide (Brancazio, 1981; Satern, 1988; Southard & Miracle, 1993). Once the ball leaves the player's hand, becomes a projectile subject to the laws of gravity, air resistance, and spin. According to Perse et. al. (2009), the ball trajectory in basketball provides valuable information for developing effective training tactics and strategies.

The research on the ball trajectory by the authors (Miller & Bartlett, 1996) has identified several key components of a successful free throw: angle of entry, velocity, and height of release. The angle of entry for the ball is determined by three ball factors: vertical displacement, horizontal displacement, and velocity (Okazaki et al., 2015). According to Perse et al. (2009), analysis of the ball trajectory in basketball provides valuable information for the development of effective training tactics and strategies. The values of kinematic indicators are a reference point for the level of technique realization. The evaluation of the main kinematic indicators in quality basketball players provides accurate information for the level of technique and the possibilities for improving technique. The aim of this study is to analyze the kinematic variables of the ball trajectory that influence the success of a free throw in basketball.

Materials and methods

Participants

This study involved twenty professional male players (n=20) from the top two basketball clubs in the Kosovo Basketball League during the 2020 season. All participants took part voluntarily and with the written permission of their clubs. The participants' anthropometric characteristics and experience were as follows: average weight of 84.90±7.86 kg, average height of 192.10±6.62 cm, and an average of 13±3 years of basketball experience, with ages ranging from 18 to 25 years.

Procedure

The free throw was executed from the regulation free-throw line at a distance of 4.57 meters. Prior to testing, participants completed a 15-minute warm-up followed by 10 trial shots. Each participant then performed a single shot during the actual test, which was used for further analysis. In total, 20 shots were analyzed in this study.

The ball release phase was defined as the moment the ball leaves the shooter's hands, including its subsequent trajectory and entry into the hoop. This phase was analyzed to evaluate key kinematic parameters that influence shot accuracy.

Analyzed Variables

For the purposes of this study, ten kinematic variables (n=10) were analyzed and are presented in Table 1: initial distance between the ball and the center of gravity, final distance between the ball and the center of gravity, height of the ball's release, horizontal displacement of the ball's trajectory, vertical displacement of the ball's trajectory, angle of the ball's release, angle of the ball's entrance, ball movement speed, ball movement time, and total time. Figure 1 illustrates the basketball shot and the trajectory of the ball as it moves toward the hoop.

Table 1. Description of parameters used in analysis

Abbreviation	Variable
IDCG (cm)	Initial distance between the ball and the center of gravity
FDCG (cm)	Final distance between the ball and the center of gravity
HBR (°)	Height of the ball's release
HDT (°)	Horizontal displacement of the ball's trajectory
VDT (°)	Vertical displacement of the ball's trajectory
ABR (°)	Angle of the ball's release
ABE (m/s)	Angle of the ball's entrance
BMS (m/s)	Ball movement speed
BMT (sec)	Ball movement time
TT (sec)	Total time

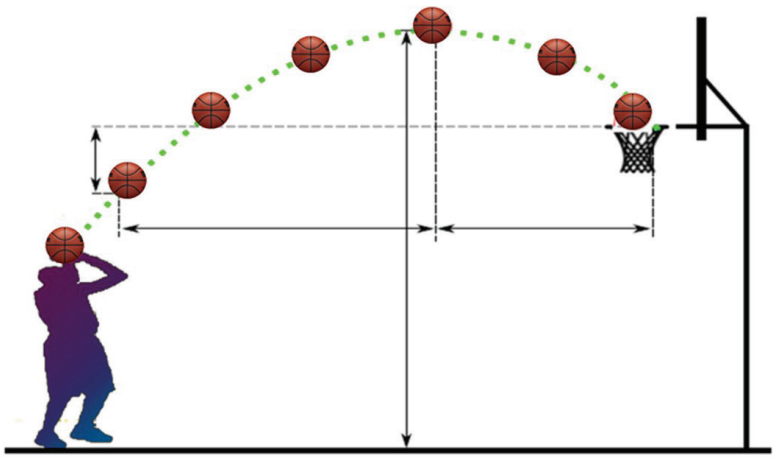

FIGURE 1. The moment the ball is released from the hands, its trajectory during flight, and the point at which it enters the basket are all crucial elements of a successful shot.

Data collection and processing methods

Ariel Performance Analysis System (APAS) is a video-based 3D motion analysis system from the producer Ariel Dynamics Inc., Trabuco Canyon, CA 92679 USA, that accurately quantifies and provides objective data, which professionals can use to assess and enhance treatment. The successful applications of the APAS system include evaluating human (athlete) movement performance, assessing movements during the rehabilitation process, equipment evaluation, product testing, and development, and identifying potential or actual risks associated with products (equipment) and related activities.

This system accurately quantifies and provides objective data that can be used to evaluate and improve treatment, enhance athletic performance, assess rehabilitation progress, and test and develop products. It also aids in determining potential or actual risks associated with equipment. For this study, the basketball shooting techniques were filmed using three Canon digital cameras (Canon Inc., Tokyo, Japan) positioned approximately 120 degrees apart. The cameras were placed at a distance of about seven meters from the performance area.

After fixing the cameras, a 200x200x200 cm calibration frame was recorded and subsequently removed. The camera arrangement was designed to ensure that all reference points (markers that were attached to the body) of the athletes' bodies were within the camera's field of view and visible. The filming of the basketball shooting techniques was then conducted, capturing images at a rate of 60 Hz, ensuring optimal reproduction (Tang & Shung, 2005).

Statistical Processing Methods

The collected data were processed using IBM SPSS Statistics 20 software, and statistical parameters were determined using the following methods: Arithmetic Mean, Standard Deviation, Minimum Value, Maximum Value, Skewness, and Kurtosis. The significance of the mutual influence between the variables was verified using Pearson's Correlation Method. Correlation Method, which measures the strength and direction of the linear relationship between two variables. If the calculated correlation coefficient (r) and associated p-value (a measure of statistical significance) indicate a non-zero correlation, it suggests that a linear relationship exists between the variables. In accordance with Cohen's (1988) guidelines, the strength of the correlation was interpreted as follows: values of r between 0.10 and 0.29 indicate a weak relationship, values from 0.30 to 0.49 reflect a moderate relationship, while values of r equal to or greater than 0.50 signify a strong correlation. Statistical significance was set at $p<0.05$.

Results

Table 2 shows the descriptive statistics for 10 kinematic variables related to the ball trajectory during successful free throws in basketball. The values for the arithmetic mean (Mean), standard deviation (Std. Deviation), minimum (Minimum), and maximum (Maximum) fall within the expected ranges.

The average initial distance between the ball and the center of gravity (IDCG) was 65.95 cm with a standard deviation (SD) of 9.99 cm, ranging from 51.00 to 98.00 cm. The final distance between the ball and the center of gravity (FDCG) had a mean value of 129.05 cm (SD=12.15), with a minimum of 113.00 cm and a maximum of 155.00 cm.

The height of the ball's release (HBR) averaged 248.05° (SD=15.08), while horizontal displacement of the ball trajectory (HDT) was on average 415.85° (SD=24.83). Vertical displacement (VDT) had a mean of 149.25° with a standard deviation of 19.55.

The average release angle (ABR) was 32.65° (SD=5.60). The ball entry speed (ABE) averaged 36.35 m/s (SD=6.43), and the ball movement speed (BMS) was 8.90 m/s with a standard deviation of 1.51. Regarding time variables, ball movement time (BMT) averaged 1.11 seconds (SD=0.17), and total shot time (TT) was 1.48 seconds (SD=0.20). Overall, the results indicate consistent and expected variability in the kinematic parameters of successful free throws, reflecting stable and repeatable movement patterns across participants.

The majority of kinematic parameters demonstrated skewness and kurtosis values within the normal distribution range, indicating the stability and reliability of the obtained results.

Table 2. The results of the basic statistical parameters for the analysis of 10 kinematic variables related to the ball trajectory during a basketball free throw are presented.

Kinematic variables	Mean	SD	Minimum	Maximum	Skewness	Kurtosis
IDCG (cm)	65.95	9.99	51.00	98.00	1.58	4.81
FDCG (cm)	129.05	12.15	113.00	155.00	0.49	-0.54
HBR (°)	248.05	15.08	221.00	279.00	-0.03	-0.11
HDT (°)	415.85	24.83	367.00	468.00	0.39	0.32
VDT (°)	149.25	19.55	112.00	188.00	0.13	-0.41
ABR (°)	32.65	5.60	20.00	44.00	-0.27	0.46
ABE (m/s)	36.35	6.43	25.00	55.00	0.98	2.81
BMS (m/s)	8.90	1.51	6.48	13.83	1.67	5.36
BMT (sec)	1.11	0.17	0.91	1.55	1.64	2.01
TT (sec)	1.48	0.20	1.02	1.85	-0.86	1.52

Legend: IDCG – Initial distance between the ball and the center of gravity; FDCG – Final distance between the ball and the center of gravity; HBR – Height of the ball's release; HDT – Horizontal displacement of the ball's trajectory; VDT – Vertical displacement of the ball's trajectory; ABR – Angle of the ball's release; ABE – Angle of the ball's entrance; BMS – Ball movement speed; BMT – Ball movement time; TT – Total time.

Table 3 presents the Pearson correlation coefficients for the kinematic indicators of the ball trajectory during a basketball free throw. Variables that showed strong statistically significant correlations at the p=0.01 level included: Initial distance between the ball and the center of gravity (IDCG) and the height of the ball's release (HBR), with a correlation coeffi-

cient of 0.68; Final distance between the ball and the center of gravity (FDCG) and the height of the ball's release (HBR), with a correlation coefficient of 0.61; Height of the ball's release (HBR) and vertical displacement of the ball's trajectory (VDT), with a correlation coefficient of -0.72; and angle of the ball's entrance (ABE) and angle of the ball's release (ABR), with a correlation coefficient of 0.65. Statistically significant correlations at the p=0.05 level were found between: Initial distance between the ball and the center of gravity (IDCG) and horizontal displacement of the ball's trajectory (HDT), with a correlation coefficient of 0.48; and horizontal displacement of the ball's trajectory (HDT) and total time (TT), with a correlation coefficient of 0.44.

Figure 2 illustrates the trajectory of vertical displacement, showing the changes in the height of the body's center of gravity from the ground during a subject's free throw.

Table 3. Presents the results of the Pearson coefficient correlation of the kinematic indicators for the ball trajectory for the free throw in basketball.

Kinematic variables	IDCG (cm)	FDCG (cm)	HBR (°)	HDT (°)	VDT (°)	ABR (°)	ABE (m/s)	BMS (m/s)	BMT (sec)
FDCG (cm)	0.30								
HBR (°)	0.68**	0.61**							
HDT (°)	0.48*	0.09	0.18						
VDT (°)	-0.24	-0.31	-0.72**	0.01					
ABR (°)	0.08	0.27	0.16	-0.08	-0.32				
ABE (m/s)	0.18	0.13	0.25	-0.05	-0.28	0.65**			
BMS (m/s)	0.26	0.27	0.18	0.30	0.04	0.21	0.08		
BMT (sec)	-0.19	0.16	-0.09	-0.30	0.10	0.35	0.40	0.09	
TT (sec)	0.09	-0.25	-0.35	0.44*	0.59**	-0.27	-0.35	-0.17	-0.34

Legend: IDCG – Initial distance between the ball and the center of gravity; FDCG – Final distance between the ball and the center of gravity; HBR – Height of the ball's release; HDT – Horizontal displacement of the ball's trajectory; VDT – Vertical displacement of the ball's trajectory; ABR – Angle of the ball's release; ABE – Angle of the ball's entrance; BMS – Ball movement speed; BMT – Ball movement time; TT – Total time.

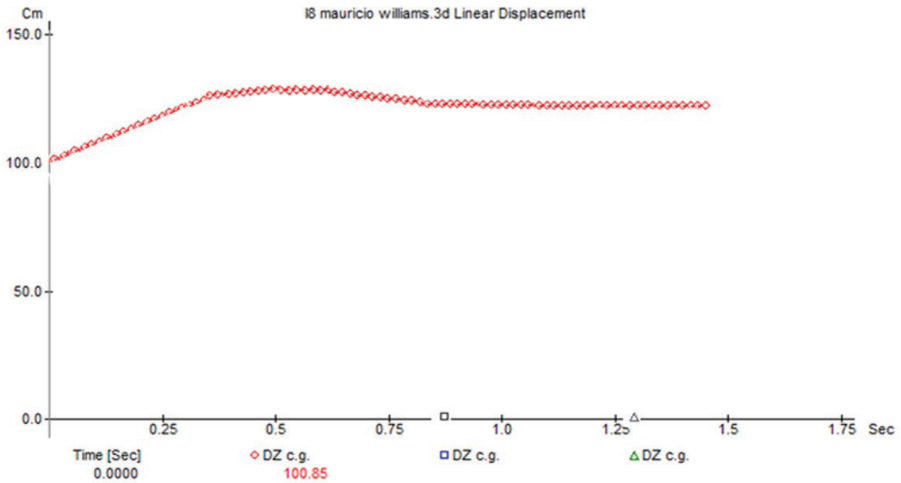

FIGURE 2. The curve of the change in the height of the center of gravity of the body from the ground, (displacement in the vertical axis - z), during the free throw of a subject.

Discussion

This research aimed to analyze the kinematic parameters of the ball trajectory during a successful free throw. In the results of the Pearson correlation coefficients, of the Kosovo elite basketball players, for the analysis of the ball trajectory, the variables that have shown high correlations with statistical significance at the level (p=0.01) are: the height of the ball release (HBR) turned out to be one of the most important variables, as it showed strong correlations with the distances between the center of gravity and the ball, both in the initial position (IDCG) and in the final position (FDCG). This shows that correct body positioning during the moment of release directly affects the height of the ball throw and consequently the accuracy of the shot. In this study, a negative correlation was found in these variables between the height of the ball release (HBR) and the trajectory of the ball movement (vertical displacement) (VDT). This result suggests that the higher the release point is, the ball reaches its greatest height along its trajectory, which helps create a more stable and more suitable arc to enter the basket.

Also, other variables that have shown a strong correlation are the ball release angle (ABR) and the ball entry angle into the basket (ABE), indicating that the release angle directly affects how the ball ends up in the basket, as a key factor for the successful shot.

Variables that have shown high correlations with statistical significance at the p=0.05 level are: the distance between the center of gravity and the ball in the initial position (DQPF) and the horizontal trajectory of the ball's movement (TLZH); as well as between the horizontal trajectory of the ball (TLZH)

and the total time (KT). These relationships show that the horizontal distance the ball travels and the time it spends in the air are closely related and affect shooting efficiency, in accordance with the laws of physics that imply that a greater distance requires more travel time.

The results of this study are consistent with previous findings by various authors, who have emphasized the importance of kinematic parameters in free throw success. Radenković et al. (2018) and Malone (1999) emphasize the role of the height of the center of mass at the moment of release as a key factor, as is also observed in this research.

Similarly, Malone et al. (2002), and Hamilton and Reinschmidt (1997) show that a higher release height allows the use of a smaller angle and lower speed, helping with the accuracy of the throws. A clear correlation was also observed with the findings of Hara et al. (2006), Yogi et al. (2006), and Okazaki & Rodacki (2012), who identify the relationship between the release angle and the entry angle, both of which are key factors in the effectiveness of a free throw. There is a direct correlation between release angle and entry angle, both of which are key factors in the effectiveness of a free throw (Hara et al., 2006; Yogi et al., 2006). Blazevich (2010) also confirms that the trajectory is influenced by the speed, angle and height of the projection.

Increasing the height of release of the ball permits the player to use a smaller release angle, thereby reducing the need for high movement velocity to execute a successful shot (Malone et al., 2002). Therefore, obtaining appropriate movement techniques of the body segments during the learning process may contribute to the development of a shooting technique that results in a successful shot.

The results of this research enrich the scientific knowledge of the kinematic analysis of the ball trajectory in free throws, contributing to the development of more accurate methodologies for evaluating and improving performance in the sport of basketball. We recommend that future research include a larger sample size and also consider analyzing unsuccessful shots.

Conclusions

This study analyzed the kinematic factors influencing trajectory of free throw success in basketball, offering valuable insights for performance enhancement. Kinematic indicator values provide a crucial benchmark for evaluating and refining shooting technique. The precise measurement of these parameters, including release height, the distance between the center of gravity and the ball (both initially and at release), and release and entry angles, offers players, coaches, and basketball experts a practical guide for improvement. The results of this research revealed significant relationships between these indicators and ball trajectory. Notably, strong correlations were found between release height and both vertical and horizontal ball displacement, underscoring the importance of release height for optimizing trajectory and maximizing shot accuracy. These findings contribute to a deeper understanding of the kinematic principles underlying successful free throw shooting and provide valuable information for coaches and athletes seeking to enhance performance.

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Conflict of interest
The authors declare that there is no conflict of interest.

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