Biomechanics of a Tennis Serve with Increased Ball Velocity

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Purpose: The tennis serve is widely considered the most important shot in tennis, and a faster serve is highly sought after. This paper proposes an adjustment to the conventional tennis serve, showing experimentally and analytically that stepping forward with the lead foot and continuing the forward motion of the body before ball contact increases the momentum of the player and swinging arm, thereby allowing the ball to be hit at higher speeds. With this new proposed serve motion, tennis players will be able to hit their serves faster. **Method**: Mathematical analysis confirms that the expected improvement to the speed of the tennis serve is approximately twice the speed of the forward step. Complementary experimentation was conducted with multiple tennis players of different genders, ages, and skill levels. Prior to the experiment, the players, under appropriate guidance, learned and practiced the new service motion for three weeks. Each player, over multiple trials, had their conventional and new serves measured for racket speed and ball speed. These trials were then compared and analyzed. **Results**: In the testing sample, the players showed an average ball speed increase of 11.36%. A confidence test was done on the experimental data, and a p-value of 0.0007 proved that the new serve produces faster serves. **Conclusions and Applications in Sport**: The developed biomechanics can be utilized by any player game to significantly increase racket and ball velocity and improve their skillset. Since a faster serve is desired by all tennis players, this new service motion will soon be taught to players and implemented into modern tennis. The sport will eventually change as more and more players learn this service motion and it will result in faster serves and more interesting matches.

Keywords: Serve; Speed; Foot Movement; Sports; Momentum; Racket Speed

Introduction

Tennis is a huge sport, with over 18 million players in 2018 in the U.S. alone (Gough, 2019). Millions of people enjoy watching and playing the sport around the world. At the 2019 Wimbledon, over half a million people attended, approximately 10 million people viewed the televised broadcast, and many more watched online. Hundreds of millions of dollars are spent on the sport by players of all skill levels, making the tennis industry one of the biggest sports industries in the world.

Many consider the serve to be the most important stroke in tennis. The ability to win service games is important at all levels of the game. In professional tennis, the serve is the most dominant shot of the game and is responsible for the outcomes of most games. Most players' serves require many advanced upper body rotations and movements, making it one of the most complex and widely practiced shots in the game (Ellenbecker & Renstrom, 2018). Because of its importance and complexity, it is also a very likely shot to cause injury to the players (Donoghue et al., 2008). A key study in (Abrams et al., 2011), shows that the tennis serve can be divided into 3 phases: preparation, acceleration, and follow through. The preparation and acceleration phases have the greatest effect on the speed of the ball. Lower body movements happen in these two phases, adding force in the vertical direction with minimal addition in the horizontal plane. In the standard serve taught today, the lower-body is mostly still during the preparation phase, and is predominantly used to generate force in the vertical direction during the acceleration stage.

In an ideal tennis serve, the player starts with their shoulders squared almost perpendicular to the baseline. Depending on being left-handed or right-handed, their feet are pointed towards the right or left net posts respectively, which are at a 45° angle from the baseline. They then toss the ball a few feet above their head and then swing in a circular motion, hitting the ball down and over the net, towards the other side of the court. The player starts in a stance with both feet on the ground just behind the baseline. The two most common stances in tennis are the static stance with both feet planted (Figure 1) and the rear-leg-forward stance (Elliot & Wood, 1983). In (Myers, 2016), the motion of the back leg prior to loading in a leg-up versus leg-back position was studied, showing a 4mph improvement in serve speed when the rear foot was moved towards the front foot during the ball toss. The goal of that study was to quantify the benefit of bringing the back foot forward in contrast to the conventional static stance with both feet planted that is taught around the world. Although this rear foot movement has been utilized by some players to slightly increase their serve speeds as part of coordinated lower body rotation (Bahamonde, 2000; Elliot et al., 2003; Felisig et al., 2003; Gordon & Dapena, 2006), the concept of using the front leg to directly add power to a service stroke has not been exploited in modern tennis. Almost all professional players keep the front foot in a fixed position before they explode in the vertical direction to hit the ball.

In this paper we show by mathematical analysis and preliminary experimental data on a sample of players that the preparation phase can be improved with a front foot movement that propels the server's centre-of-mass forward and therefore adds momentum to the server and the serving arm. This is a radical change to the service biomechanics that transforms the entire service dynamic. Adding speed from the entire body to the racket before hitting the ball increases force on the racket, therefore increasing the speed of the ball. When the acceleration phase begins, the server transfers the extra momentum to their racket, hitting the ball with more power. This motion is similar to that of a baseball pitcher or cricket bowler, whose dynamic forward motion in the preparation phase is key to maximizing forward projectile velocity.

Most players try to gain power by generating maximum force on the ball with their racket starting in a static position. This paper exploits techniques used in other sports such as baseball to perfect the kinetic chain and achieve greater power and spin, creating a more fluid and explosive motion. The central thesis of this paper is that stepping forward with lead foot and continuing the forward motion of the body before swinging the racket will increase acceleration and force on the racket, allowing the ball to be hit harder.

Materials and Methods

Improved Service Motion

In order to get maximum speed on the ball while maintaining a comfortable arm swing, lower body movements must be used to gain forward momentum. The added front foot step adds forward motion and speed to the torso and swinging arm. After tossing the ball, the player does this step while loading the arms, knees, and hips for explosion into the swing. Finally, after the server fully steps forward, the server jumps into the court and swings. The jump into the court using the knee flexion from the front leg brings the player into the court after contacting the ball.

The forward motion into the court just before contact point increases the speed of the ball. Because of the arm's forward motion when the player is moving forward, the racket hits the ball with increased momentum, and the ball after contact will move faster compared to if the ball was hit when the server's body and torso is not moving. This improvement is shown in Appendix A to be 2x of the speed of the front foot movement.

Instead of a traditional motion, in which the server plants both feet on the ground and uses mainly upper-body muscles to impart force on the ball and lower-body muscles to launch upward, this serve utilizes the lower-body muscles to directly create faster forward motion through an improved kinetic chain [adapted from (Kovacs & Ellenbecker, 2011)]:

(1) Step forward with the opposing leg to the edge of the court
(2) Extend hip, bend trunk, knees, and back, and extend non-dominant hand upward and forward to place ball into striking position
(3) Launch upward and forward while rotating shoulder
(4) Snap elbow upward and forward while extending arm
(5) Pronate wrist at contact for maximum power transfer to ball

The serve is pictorially shown in Figure 2 with step 1 shown in subfigures a-e, step 2 in subfigures f-g, step 3 in subfigures h-i, and step 4 in subfigures j-m. Subfigures n-q show the follow-through footwork and arm movements and subfigures r-t show an optional defensive step back and leg stiffening behind the service line in preparation for an aggressive return of serve (Mecheri et al., 2019).

Players can easily add this adjustment to their stroke. This serve shares elements with the traditional serve, particularly the hand and wrist movements. The primary changes a player will make to their serve are the toss location and arm movement. The new motion allows the server to hit the ball in a comfortable way while getting the maximum speed on the ball from the step.

Having a short and fast step with the front foot just before hitting the ball pushes the server forward. This increases the velocity of a player, and therefore increases the velocity of their racket. The extra force gained by the increased velocity of the racket can be combined with swinging the arm to make a faster serve. Since a short step before serving won't change the kinetic chain of a traditional serve, the server can have a full and comfortable swing, allowing the server to gain maximum power and speed. This step is similar in principle to the more exaggerated step used in the baseball pitching motion, as shown in (Fortenbaugh et al., 2009).

The arm movements in this serve are similar to those of other serves. However, adding a step before starting the swing delays the cocking phase of the serve, since the player does not have any knee flexion until right before the explosion off the ground that occurs just before contact. So, the player must have a quick cocking phase after taking the step forward. Because of the step, the player does not have enough time to lower the trunk with knee flexion and explode upwards into their swing. Therefore, torso angle with respect to the ground is slightly greater than it is in a traditional serve. However, after the step, the player can move forward, leading with their front knee and rotating their torso and trunk while keeping front knee flexion at a comfortable angle. This is delayed until just before the player starts the swing.

A step with the front foot 10-20 inches from the starting position of the lead foot is ideal for players who want maximum speed on the ball. A big gap between the two feet after taking the step allows greater potential for body acceleration since it forces the player to transfer their weight onto the lead foot before loading. This requires the player to stand back 10-20 inches from the baseline to prevent foot faulting. Since the player needs to have both their feet behind the baseline when they launch upwards and forwards to hit the ball, 10-20 inches back is ideal to make sure that the player is close to the line when they jump, but not past it. For an accurate toss that provides maximum speed on the ball, the player should toss the ball around 2 feet in front of their starting position. When the ball is contacted, the player is already in the court due to the forward movement of the front foot. Ball toss position should be changed, but the ball contact position should be the same as it is in a conventional serve relative to the server's body position. This should eliminate the potential discomfort of hitting the ball too far or close to their body.

This service motion can work for any player, regardless of their height, power, or racket type. The step speed and swing of a player will determine how fast the ball will move. Although arm mechanics can influence the speed of the ball and results will vary from player to player, lower body movements can be added to any serve to make sure the entire body is working towards hitting the ball into the court with increased speed. The correct timing and location of the toss has to be learned and care must be taken to ensure that the serve is practiced under the supervision of a coach.

In addition to the speed of the serve, it is important to consider the service percentage and the accuracy of the serve placement when considering total serve performance (Brody, 2012). The service percentage is related to the angle of the tennis racket at contact relative to the range acceptable angles for the given racket face for the specific serve. This range critically depends on the height of the contact point above ground (favouring taller players with higher elevations above ground), the height of the net (which is fixed), and the distance to the net. As we show in Appendix 2, by moving forward and producing a contact point above ground inside the service line, the acceptable angles of the tennis racket are improved relative to a fixed position without forward motion, pointing to an expected improvement in service percentage can also be obtained. The service placement accuracy will depend on the accuracy of the ball toss which the player will adjust for the added forward momentum. This was not specifically studied in this paper. However, there is evidence that the placement accuracy and consistency of the serve can be improved through motor imagery training with improved focus on ball trajectory (Guillot et al., 2013). Such training techniques have proved beneficial in sports where lateral movement and vertical jumps are incorporated into precision throwing and striking skills such as basketball and volleyball. It remains to be seen if the same will be true of the new tennis service motion.

Experimental Study

Players of various skill levels and ages were asked to serve with and without the forward foot step. Proper consent was given by the player before they could participate in the experiment. Risks as well as ethical principles regarding how the experiment would be conducted, which conferred to the USPTA code of ethics, were understood by the player before they could agree to participate. All test subjects had learned a traditional serve first, and were taught the new concept of adding the front foot step and the correct toss prior to the experiment.

All five players had their original and new serves measured on both ad and deuce courts under a coach's supervision. All data was taken with the same pair of sensors. The QLIPP sensor reported the ball speed derived from the speed of the ball at point of contact (labeled racket speed in Figure 4). The ball speed was also measured on the opposite side of the court, approximately 3 feet past the net (labeled ball speed in Figure 4), using a SpeedTracX doppler velocity measurement tool. Each subject's fastest 6 serves out of the first 20 serves in a data set were used for the final calculations. No other variables like spin, consistency, or angle were measured. Only serves that landed within the service box boundaries were counted toward their data set.

To begin with, we tested the original serves of 5 players of varying age and experience. Player 1 was a 15-year-old male, with a UTR score of 9. Players 2 was a 19-year-old male, with a UTR of 7. Player 3 was a 55-year-old male, with a UTR of 5. Player 4 was a 12-year-old female, with a UTR of 2. And player 5 was a 15-year-old male, with a UTR of 8. The differences in UTR scores (Universal tennis rating), age, and gender show that all the players in the sample were very different, and this allows us to generalize our conclusions to all tennis players. From various coaches, these players all had learned the traditional serve prior to the experiment. Players warmed and then were asked to serve. For each player, a new can of 3 Penn tennis balls were used. Each player served continuously with appropriate breaks, until they had 6 serves that went in from the deuce side of the court. The player then moved to the ad side of the court and served until they had 6 serves that went in. Again, the first 6 serves that were in, counted towards that player's data.

After the old serve was tested, we then moved on to the second phase of the experiment: the new serve. This serve was taught to the players in 4 phases: the toss, the step, and finally, the swing.

The toss was first taught to the players since this was the base of the serve. In order to learn how to step forward, the toss must be in the correct place to hit the ball. The players learned this first so once they learned the foot movement, the ball would be in the correct place to strike. Instruction for the front foot step followed. A small step was first introduced to the players and as the player became more comfortable with stepping and tossing, the step was able to become larger, until the desired distance of around 10-20 inches. The players were told to step towards the baseline and launch upwards just before swinging the racket. The contact position would come in the air, after the step. The final phase of instruction was the swing. Players needed to develop a slightly different swing to accommodate for the change in position and motion the new serve required. This was done by swinging soon after tossing the ball and launching upwards. Players first practiced this new motion starting in a static position, with both feet on the ground. The players then jumped then immediately hit the ball. Players did this training along with other swing techniques until they could accurately swing and make precise contact with the

After these aspects of the serve were mastered, the player spent a few days practicing the complete serve. Once the player felt comfortable with the serve and decided that they were ready to test, the second part of the experiment began. We then repeated the experimental process used for the original serve.

Results

The graphs below (figure 3) show box and whisker plots of each player's serves into the ad and deuce courts. Each set of data includes the player's mean, interquartile values, and range for both the traditional serve and the new serve with the front foot step. The middle line in each plot is the mean of the data set, with 2 lines above and below showing the interquartile values of that plot. The top and bottom lines of each plot show the minimum and maximum values of the 6 data points collected.

Discussion

As shown in Figure 3, the average increase of ball speed, in miles per hour, measured at the net with the foot step was 12.08 (16.0%) for player one, 8.67 (11.2%) for player five, 5.42 (9.2%) for player three, 5.92 (8.4%) for player two, 5.75 (12.0%) for player four. The average increase in racket speed, in miles per hour, measured at contact was 13.17 (14.5%) for player one, 5.83 (6.4%) for player five, 3.5 (4.8%) for player three, 3.92 (4.4%) for player two, and 10.92 (20.2) for player four.

For all players, serves without the foot movement produced lower averages, minimums, and maximums of the ball speed measured at the net. This experiment demonstrated improvements to the serve of all players regardless of player level, age, or gender. Both ad and deuce sides produced positive results when averaged across players, which shows that the serve works equally on both sides of the court.

The serves on the ad and deuce side of the court do not have noticeable differences in ball and racket speeds that is consistent between the servers. This is because the biomechanics of the service motion do not favour the service of one side over the other (Elliot, 2006). By stepping forward instead of stepping sideways or rotating the torso, the biomechanics of the upper body are preserved and the ad and deuce side serves can be performed with similar results.

To validate our results, we conducted a two-sample t-test for m1-m2. Our null hypothesis was that there was no difference in the mean of the speeds between the 2 types of serves, and our alternate hypothesis was that the serve with the foot step had a higher mean speed than the static serve. Because our experiment consisted of 5 very different players, we could generalize our conclusions to the population. Our experiment was conducted with independence between players, and since the sample sizes with and without the front-foot step were both greater than 30, the central limit theorem provides that our distribution could be treated as approximately normal. After the procedure, we ended with a test statistic of 3.25 and a p-value of 0.0007. Since our p-value is less than the a-value of 0.01, we may reject the null hypothesis. Hence, we have convincing experimental and analytical evidence that the serve with the front-foot step can produce faster serves than the traditional serve without the forward step.

This preliminary experiment showed that the added front foot step immediately allowed the servers to achieve a ball speed improvement at both contact positions. This improvement consisted of a 6.8 mph average increase in ball speed measured at the net, and an 8.1 mph increase in ball speed measured at contact. This is also consistent with the mathematical analysis below, which predicts a ball speed improvement at contact of twice the forward step speed. The maximum increase in ball speed at contact was 17 mph, and the maximum increase in ball speed at net was 11.5 mph. These improvements were achieved by Player 1, who had the most explosive forward step.

Due to the strings absorbing some force as they hit the ball (Bower & Cross, 2005), and the ball traveling approximately 40 feet before its speed is measured, the recorded ball speed is slightly less the corresponding racket speed. This can be observed in figure 3, since the racket speed for a given serve was, on average, 19.76% greater than the ball speed for that serve.

Mathematical Model

The following section presents a simplified analysis of the new serve, quantifying the benefit of adding an explosive first step to the serve. This step increases forward momentum at collision time, thereby increasing the speed of the ball immediately after the tennis racket.

For this simplified model, we assume that the momentum of the swing is the mass of the player's arm multiplied by the velocity of the swing, the ball is practically still when it contacts the racquet, and that the collision is elastic. To calculate the swing's momentum, we can assume that the momentum of the swing can be modelled as the velocity of the swing multiplied by an effective mass of the player's arm. We will label the effective mass of the player's arm m_p, the mass of the ball m_b, the initial speed of the swing v_i, the final speed of the swing v_f, and the final speed of ball w. In an elastic collision, no kinetic energy is lost to the surroundings, so the final kinetic energy of the system must equal the initial kinetic energy of the system. Then, $\frac{1}{2}m_b w^2 + \frac{1}{2}m_p {v_f}^2 = \frac{1}{2}m_p {v_i}^2$. Also, since momentum is conserved in any collision, $m_b w + m_p v_f = m_p v_i$. Here, we can utilize the conservation of momentum with speeds, scalar quantities, because all the corresponding velocities are in the same direction. Solving this system, we find that $w = \frac{2v_i m_p}{m_b + m_p}$. Since the mass of the ball is very small compared to the effective mass of the player's arm, $m_b + m_p \approx m_p$, and then $w \approx 2v_i$.

A step creates a boost in the initial speed of the player that translates into an increased initial speed of the player's arm. According to the equation, the resulting increase in the speed of the ball is about double the boost in initial speed taken in the direction of the ball's initial velocity using vector components (Figure 4). Because the height of the contact point is much smaller than the distance the ball travels to reach the other side of the court, the component of interest will be approximately equal in magnitude to the initial velocity boost. This can be significant. An improvement of 1.47feet/s is equivalent to 1mph. Hence, a step forward motion of 6 ft/s can result in over 8mph improvement in ball velocity. The greater the speed of this first step, the greater the benefit to the server.

Accuracy was not analyzed but was reported by players to be reasonable, since the players did not have to change other components of the serve except their front foot movement and ball contact position. In addition to increasing ball speed, the serve also creates a greater allowable racquet head range, leading to more consistency. Appendix A describes the analysis of allowable angles that shows the allowable racquet-face angle range is greater for the serve with the step, making it a more consistent serve. This was not verified experimentally, but will be the subject of future work.

Conclusions

This paper presents an adjustment to the conventional tennis serve, showing through experimental measurements and mathematical analysis that stepping forward with lead foot and continuing the forward motion of the body before swinging the racket increases its acceleration and allows the ball to be hit harder. In a traditional serve, the server keeps both feet planted and uses leg force to gain momentum solely in the vertical plane. In the new serve, an explosive step with the lead foot utilizes the legs to increase momentum in the forward plane, parallel to the direction of the ball. A mathematical analysis shows that this adjustment provides ball speed improvements of approximately twice the speed of the forward step. The benefit is also confirmed with experimental data showing an 8% average improvement in ball speed with the improved service motion for tennis players of varying ages and abilities.

Prior to this study, power from the legs was not used to gain forward motion, parallel to the direction the ball was hit. Because of this, players could not hit their serve with maximum speed. With a front foot step before the serve, the maximum potential speed can be reached by any type of player. Relative to a traditional tennis serve, a toss further into the court is required in order to maximize power from kinetic chain movements. This adjustment will allow the front foot movement to be implemented into all service styles.

This simple but effective concept of using a step to gain momentum on the swinging arm, can be applied to all levels of tennis. A fast serve is desired by every player, and can be achieved by utilizing a loading step between the loading and contact phase of the swing. This movement is simple, and can be introduced to beginners or advanced players. Although almost all players, at junior and professional levels, use the traditional serve, with more players experiencing faster serves with this new concept, the entire sport could be improved, making the game go faster, due to players adapting to this quick type of serve. This new kind of game will attract more viewers, allowing tennis to grow as a sport and an industry.

An additional consequence of the serve motion is that the forward momentum can be translated to a quicker first step to a serve-and-volley point. Although the serve-and-volley tactic has been marginalized at the highest levels of modern tennis, owing to the improvement in racket and string technology that affords the returner greater angles and control of the ball, the ability to reach the net quickly is still a potentially important benefit of the new service motion, especially in doubles play.

A key question is the impact to serve consistency. The new ball-toss dynamic will potentially change the consistency of the toss, and consequently the serve, and could therefore affect the value of the serve and likelihood it will be used. The complexity of the ball-toss is increased, given that the server must step forward prior to contact. However, it turns out that by propelling the server's centre-of-mass into the court, the range of acceptable angles available to the server in order to successfully hit the serve into the correct service box is increased, hence enabling an improvement in consistency when properly executed. This is shown in Appendix A for a simplified flat serve and does not include the effect of ball spin. For our limited sample of players, all were able to make the adjustment to the new toss after some practice, and none noted a significant reduction in consistency. Nevertheless, this remains as an open question for further quantitative investigation. Another question is the impact on the joint and muscle health of the server, which is beyond the scope of this investigation, but should be studied further.

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Appendix A: Analysis of Serve Consistency

This section will show that the forward step increases the range of acceptable racket face angles for a serve that falls within the service box. We define the allowable angle range θ for a serve as shown in Figure 5. We will only consider the allowable angle range for a fixed serve speed in this model.

When the player does not take a step forward while serving, the initial velocities are approximately perpendicular to the racquet face, because the arm's motion is the only source of momentum, and we can approximate the moving arm as a rigid rotating body. Therefore, the allowable range in the angle of the racquet face equals θ. When the player does take a step forward while serving, the initial velocities are not perpendicular to the racquet face. Instead, the velocity of the ball consists of the vector sum of a horizontal boost velocity from the step and the perpendicular velocity directly from the racquet face. This concept is shown in Figure 6.

Now we will consider these components for both the limiting trajectories from Figure 7 at the same time, and consider the angle between corresponding components. The blue component, the final velocity, is in the same direction as the racquet face would need to be without the boost from the step. We will show that the angle between the green components is greater than the angle between the blue components, proving that the allowable racquet-face angle range is greater for the serve with the step, making it a potentially more consistent serve.

Using Euclidean geometry, we label the five points of interest A through E, and we hope to show that the measure of angle CAE is greater than the measure of angle BAD. It is clear from the Pythagorean Theorem that the length of segment AB is greater than the length of segment AC, and the length of segment AD is greater than the length of segment AE. Since the length of the velocity boost vector is fixed, the length of segment BC equals the length of segment DE, so the length of BD equals the length of CE. Using the Law of Sines, $\sin\angle(\mathrm{BAD}) = (\frac{\overline{BD}}{\overline{AB}})(\sin\angle(\mathrm{BDA})$, and $\sin\angle(\mathrm{CAE}) = (\frac{\overline{CE}}{\overline{AC}})(\sin\angle(\mathrm{CEA})$. Since it is clear that $\sin\angle(\mathrm{BDA}) < (\sin\angle(\mathrm{CEA})$ and $\overline{AB} > \overline{AC}$, $\sin\angle(\mathrm{BAD}) < (\sin\angle(\mathrm{CAE})$. Since angles BAD and CAE are both acute, this implies that angle CAE is larger than angle BAD. Therefore, the allowable racket face range increases with the step, so consistency improves.

Figure 1. Roger Federer's traditional serve with both feet planted before ball contact (Maira, 2019)

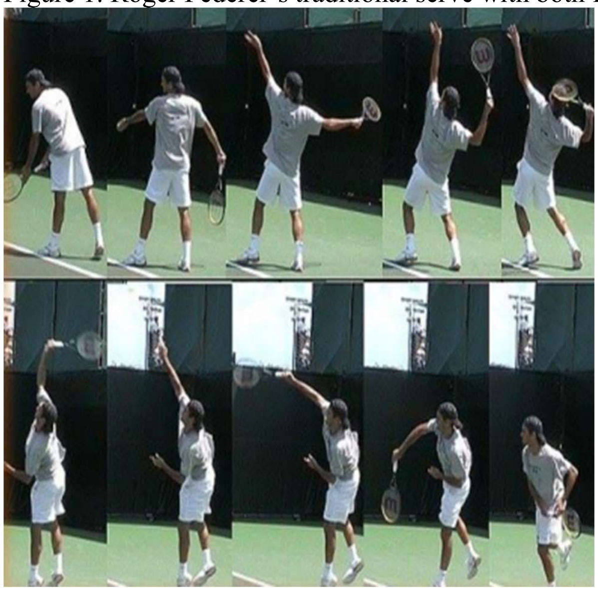

Figure 2a-2t. Server demonstrating the new serve technique with front foot step. Photographs taken at 30 frames per second.

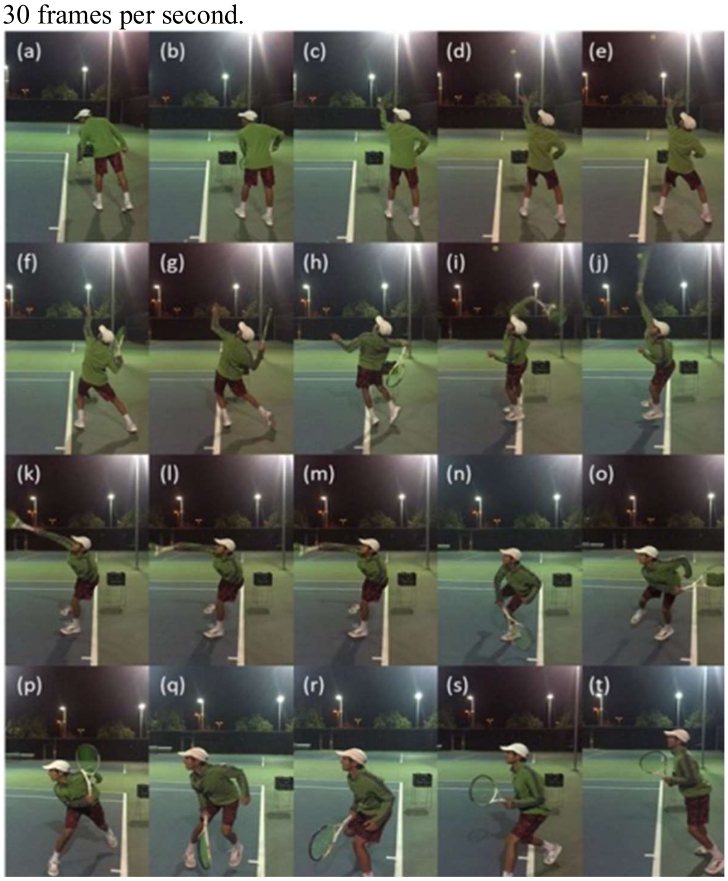

Figure 3a-3e. Box & whisker plots of mean, range, and interquartile values of ball and racket speeds, in miler per hour, measured on serves (both ad and deuce sides) with and without added front foot step for the 5 players

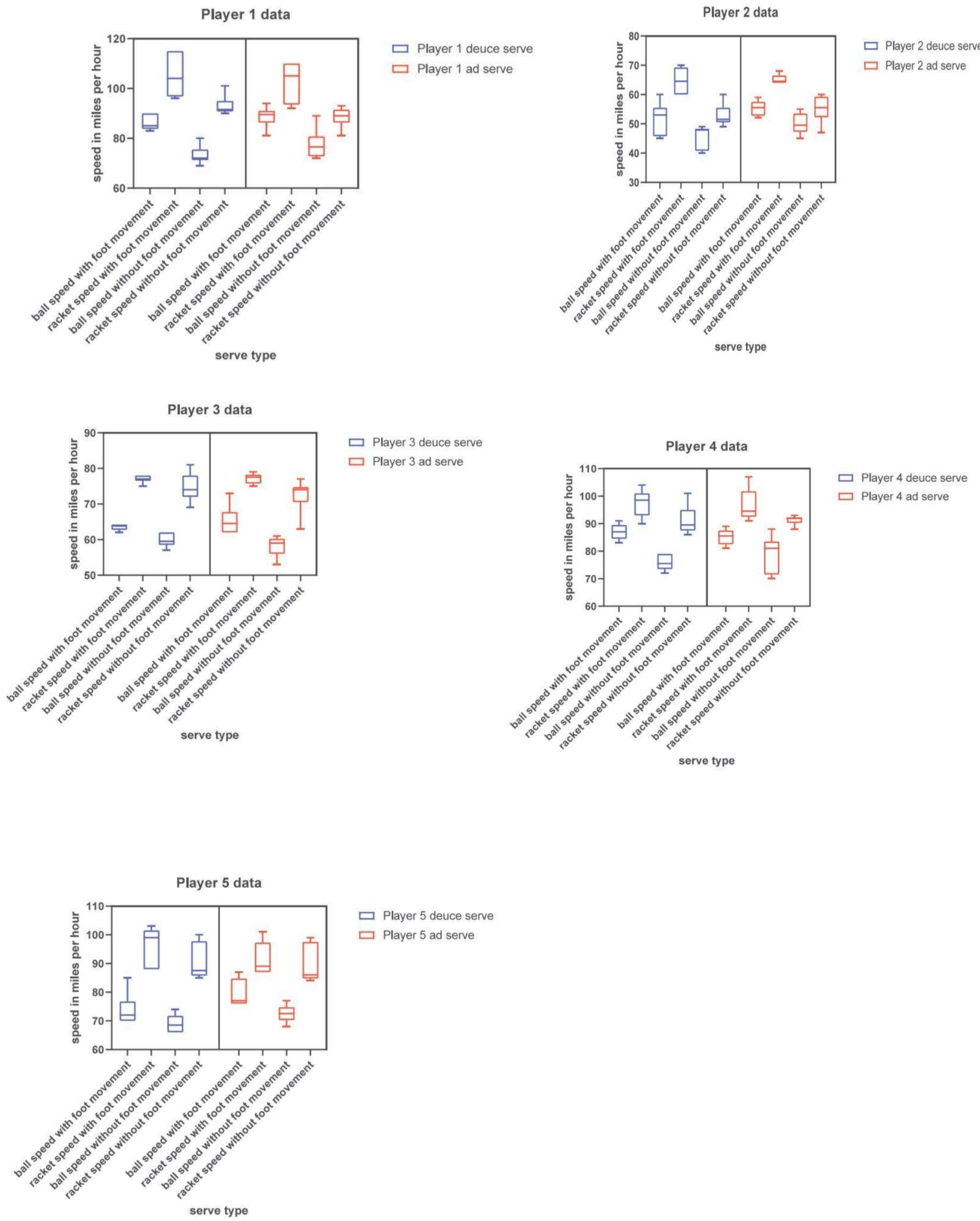

Figure 4. Breaking velocity boost from step into components.

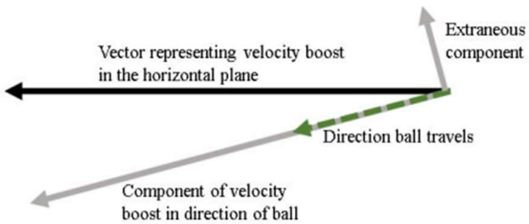

Figure 5. Given a fixed ball velocity, for the ball to land in the service box, the initial trajectory of the ball must fall within a certain angle range, as shown in this diagram.

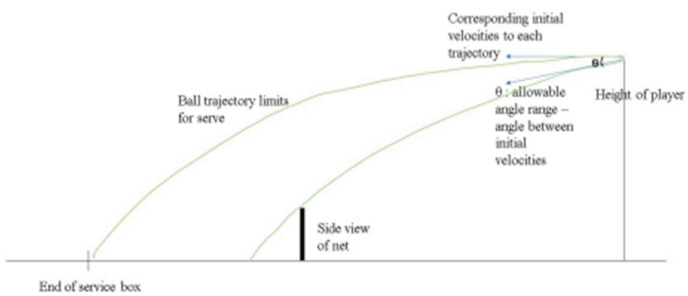

Figure 6. The green vector represents the relevant velocity component without the step, and the black vector represents the horizontal boost that the step gives. The resultant velocity is the blue vector.

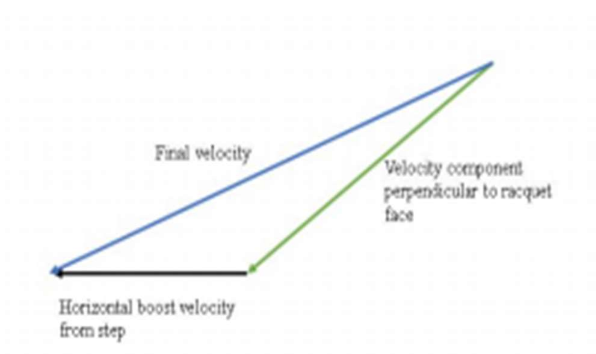

Figure 7. Similar to Figure 6 except the blue resultant velocities are at the limiting positions for which the ball lands in the service box. Subtracting the black vectors, which represent the boosts given by the step, velocities perpendicular to the racket face are obtained.