Physics of Punting a Football

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A digital video camcorder was used to film the kicking leg and initial ball trajectory when punting a football. The film was analyzed frame by frame and velocities for the knee, shin, ankle, toe and two tips of the football were calculated as well as the launch angle of each punt. Upper and lower leg velocities agreed with published results for similar types of kicks. Using initial velocities and launch angles in projectile motion equations, the estimated distances and hang times, neglecting air viscous forces, were calculated and compared to the actual results. Each punt's actual distance was 24-33% less than estimated, but the hang time for two of three punts was consistent with estimates.

INTRODUCTION

Sports provide an environment of controlled movements, and thus allow practical studies of classical Newtonian physics. The human leg is utilized in several types of specific kicking actions: martial arts, placekicking a ball from the ground, and dropkicking a ball in mid-air. This report will focus on the leg and ball velocities for punting an American football (dropkick in mid-air).

When air viscous forces are neglected a projectile's range is symmetric about 45˚. Under actual conditions, however, a punt's range may be maximized at angles less than 45˚. This is of concern to a punter whose objective is two-fold: maximize hang time to allow time for his teammates to run down field and maximize distance to help his team's field position. The maximization of both goals is what Brancazio[1] refers to as the "kicker's dilemma."

In a kicking motion, the leg acts like a whip. The hip muscles accelerate the upper leg through the back swing while the knee is bent. Once the foot has cleared the ground, the upper leg muscles extend the lower leg at the knee to strike the ball with the foot at maximum velocity. The foot meets the ball for a punt after the ball is dropped from the hands. The height at which it impacts the foot is the *impact height*. A well-kicked punt will leave the foot with a rotation about its long axis, providing a stable spiral throughout the punt's flight.

Initial velocities and launch angles of three punts were calculated from video analysis and used to estimate distances and hang times based on simple projectile motion equations. The estimated values were then compared to the actual results. Differences can be attributed to air resistances and lifts resulting from the ball's orientation during its flight path. The impact heights and foot angles of three other punts were compared to their launch angles. Velocities of the knee, shin, ankle, and toe on the kicking leg were also determined.

THEORY

Equations for hang time and horizontal distance can be derived from the projectile equations of motion

$$y(t) = v_{oy}t - \frac{1}{2}a_y t^2 \qquad (1)$$

$$x = v_{ox}t \qquad (2)$$

where y and x are the height and horizontal displacements of the football respectively, v_{oy} and v_{ox} are its vertical and horizontal velocities, a_y is its vertical acceleration, and t is its time in flight.

An expression for hang time, T, results from solving equation 1 for t when y=0 and $a=9.8 m/s^2$,

$$T = \frac{v_o \sin(\theta_o)}{4.9} \qquad (3)$$

where θ_o is the initial launch angle. Equation 3 shows that hang time depends on the ball's initial velocity and launch angle.

Equation 2 can be solved for horizontal range, R, which is dependent on initial velocity and launch angle:

$$R = \frac{{v_o}^2 \sin(2\theta_o)}{9.8} \qquad (4)$$

Equations 3 and 4 allow quick calculation of expected hang time and horizontal range from the values measured from video analysis – initial velocity and launch angle. These equations are based on fundamental physical principles that neglect air resistance. Air resistance, or drag, is a viscous force in a direction opposing the velocity of the projectile. Air drag, W, is given by the relation[2]

$$W = \frac{1}{2}\rho C_D A v^2 \qquad (5)$$

where ρ is the air density, C_D is the drag coefficient, A is the cross-sectional area of the projectile normal to the trajectory, and v is the speed of the projectile relative to the air. Air drag varies widely for a football in flight because a ball's orientation with respect to its forward motion can change rapidly and often. A football is an ellipsoid, so the most favorable orientation is point first with a spiraling motion about its long axis. This behavior limits the cross sectional area perpendicular to motion and thus air resistance.

The only factors affecting a punt after contact with the foot include launch angle, launch speed, air density, wind, spin, shape, and surface.[2] Launch speed and angle were measured using video analysis, and the factors which were not measured contribute to air drag.

EXPERIMENT

A Canon ZR10 Digital Video Camcorder captured the kicking leg and initial velocity of the football for each punt at a frame rate of 30 Hz and shutter speed of 1/8000. Four pieces of white athletic tape were placed on the kicking leg: one on the knee, shin, ankle and toe. The tape served as reference points from frame to frame in the video analysis.

The distance of each punt was measured with a 60 m measuring tape from the plant foot to the estimated catch point. The hang time was measured with a handheld stopwatch from the impact with the foot to the catch by a returner.

Each punt was imported into iMovie and then to Video Point 2.1 for analysis. The four taped locations on the leg as well as the two tips of the football were tracked through each frame of each punt. The scale was determined by a meter stick placed on the ground approximately 20 cm closer to the camera than the plane of the kicking leg. Each punt was scaled to within 0.06% of every other punt. The average scale was 672.3 pixels/meter.

The data tables of times and positions created in Video Point were exported into Microsoft Excel. Excel was used to calculate velocities of each marked point on the kicking leg and the two tips of the football.

The velocities calculated from the videos are average velocities from two position measurements over a time period of 0.033 seconds. The calculated velocity is associated with the latter of the two positions and should not be confused with an instantaneous velocity. Equation 11 was utilized to find the velocity recorded at a frame, n.

$$v_n = \frac{\sqrt{(x_n - x_{n-1})^2 + (y_n - y_{n-1})^2}}{t_n - t_{n-1}} \qquad (11)$$

The launch angle was calculated from the left tip of each punt (and the right tip of the punts in which it was captured on film) in two consecutive frames after impact. Equation 12 was used to find the launch angle from position measurements.

$$\theta_o = \tan^{-1}\left(\frac{y_n - y_{n-1}}{x_n - x_{n-1}}\right) \qquad (12)$$

RESULTS

Of the 13 total punts filmed, three punts' videos contained two frames of initial trajectory. These were used to determine initial velocities and launch angles. Using equations 3 and 4, distance and hang time were estimated for each of the three punts (numbered 5, 8, and 11).

Figure 1 shows the velocities of the various points on the kicking leg and two tips of the football from punt 8. The lines connecting velocities of a given part of the leg or football simply serve as guides from frame to frame. The lines compose a very rough estimate of the actual velocities at any time, and they are limited in their accuracy by the frame rate of the camcorder.

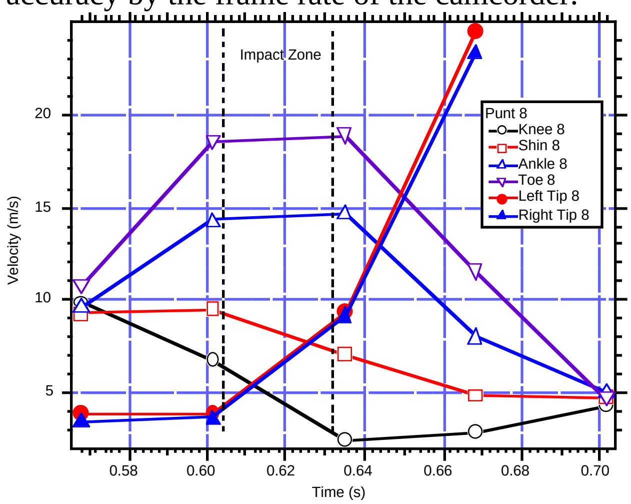

FIG. 1. This is a velocity vs. time plot for 4 points on the kicking leg and two tips of the football in punt 8.

In a characteristic kick, the parts of the leg move at similar velocities in the back swing. As the leg approaches impact, the knee slows down, the shin's velocity remains nearly constant, and the ankle and toe accelerate to reach the ball at their maximum velocities sometime within the impact zone. In Figure 1, it appears that the toe's maximum velocity is about 19.5 m/s, but it was most likely greater than that at some point in the impact zone. It is seen initially that the ball drops to meet the foot at about 4 m/s. Its next position is captured after impact when its trajectory has been drastically altered, so the ball velocity determined just after the impact zone is not realistic. The final velocity measurement for the ball seen in figure 1 is based on two positions in flight and thus is the initial velocity.

The ball's initial velocity of the left tip in punt 8 was found to be 24.5 ± 0.6 m/s at a launch angle of 49.4 ± 1.5˚. The punt yielded a reduced distance of 76% from the estimated distance but a hang time comparable to its estimate. Punt 8 was the only punt out of the three used for distance and hang time estimates in which initial velocity and launch angle were able to be calculated for both tips of the ball. The average initial velocity from left and right tips was 23.9 m with an uncertainty of 0.6 m. The average angle was 50.9˚ with an uncertainty of 1.5˚. These uncertainties were the only reference for distance and hang time precision for punts 5, 8, and 11, so the uncertainty of each punt's distance and hang time was propagated using these uncertainties for velocity and angle. The results from punts 5, 8, and 11 are listed in Table 1 and shown graphically in Figure 2.

	Estimated Distance	Estimated Hang-Time	Actual Distance (±1.5 m)	Actual Hang-Time (±0.10 s)	Comments
Punt 5	70.8 ± 3.1 m	3.92 ± 0.13 s	48.1 m	3.88 s	Good Punt
Punt 8	57.2 ± 2.9 m	3.79 ± 0.12 s	46.1 m	3.94 s	Spiral Turned Over
Punt 11	56.3 ± 2.8 m	3.70 ± 0.12 s	38.0 m	4.03 s	Almost vertical spiral, Impact towards toe

Table 1: Estimated and actual distances and hang-times of three punts with initial trajectory frames. These punts were chosen because their video contained two frames of initial punt trajectory, allowing calculation of initial velocities and launch angles. (Note on comments: "spiral turned over" is the best type of punt – orients ball nose first throughout punt)

In Figure 2, Equations 3 and 4 were used to produce theoretical curves at given velocities and varying angles. The estimated values from Table 1 are given as the hollow symbols, and the actual values are seen as solid symbols.

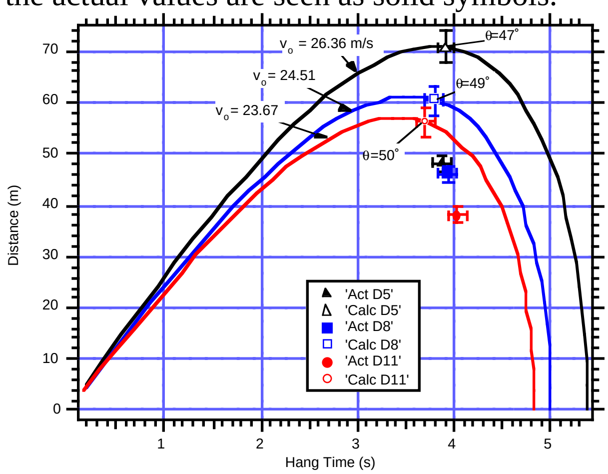

FIG 2: Distance vs Hang Time theoretical curves for initial velocities of each of the three punts. Equations 4 and 9 were used to form the curves. The launch angles of each punt are labeled at the theoretically predicted results for each punt located by the hollow symbols. The corresponding solid symbols indicate actual results.

The actual distance in all three cases is less than the predicted distances based on the initial velocities and launch angles. The decrease in distances ranged from 24-33% of the estimates. The decreases may be attributed to air drag, and are comparable to percentage decreases cited in Hay[3] of 20-50%. Brancazio[4] found air resistance reduced the distance of punts by 18% for "nose-first", well-spiraling punts. The range of reduced distances found in this study suggests moderately well spiraled punts - consistent with qualitative observations.

For punts 5 and 8, the actual hang time was within one standard deviation to predictions by motion equation 3. Punt 11 had an 11% longer hang time than predicted by equation 3. The longer hang time may be attributable to air viscous lift factors acting perpendicular to the direction of motion.

CONCLUSION

Initial velocity and launch angle determine the horizontal range and hang time of a punt, with a significant dependence on air resistance resulting from various spins on the ball. Air resistance reduced distances of punts by 24-33% and had a nearly negligible effect on hang times estimated from simple equations for projectile motion. The equations of motion provide a reasonable approximation for hang times, but need to include air drag factors to accurately model distances.

ACKNOWLEDGMENTS

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References:

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[4] Brancazio, P.J. *Sport Science: Physical Laws and Optimal Performance*, pp. 345-346.