Investigating the Range of Flight of a Kicked Football

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Abstract
In 1999 the NFL implemented a standardization of kicking balls, requiring 12 new footballs, each distinguishable by the marking of a 'K', to be used for all game time kicks. In doing so, the controversy of variably worn footballs correlating to different flight ranges became nullified. However, the standardization of the weather conditions and other variables is impossible. Potentially, temperature, pressure, placement of the football on the kicking tee, and launch angle are all variables that can alter range. A greater understanding of these slight changes can provide one team an advantage over the other. In the experiment presented here, a kicking machine was constructed of springs, steel rods, and an aluminum foot and was used for all trials. A combination of the potential energy converted into kinetic energy by the springs and the transfer of momentum from the accelerated foot and leg into the football propelled the designated ball from the tee, providing a quantifiable range. Three significant results were found evident after the trials were run: 1) surprisingly, pressures ranging from 26-5psi exhibited little variation in the range of the kicked footballs; 2) for the trials varying temperature, a 10% decrease in range was observed from the room temperature to the -17.0 °C balls; 3) the same effect was shown in the variable football wear trials. The new balls went 10% shorter than the weathered balls. An in depth analysis of the experiment and results of the kick and flight mechanics of a football are presented.

Design

The mechanics of the machine dealt with three concepts of physics: the transfer of rotational kinetic energy, potential elastic energy, and momentum into the stationary football. The leg mechanism worked as following: an aluminum rod of 1.61 meters was mounted into another rod that ran parallel to the ground. When released from a certain height, the leg swung in a circular motion around the fixed center, thus exhibiting rotational energy (i.e. $K_{rot}=1/2I_{rod}\omega^2$ where "I" is the rods moment of inertia and "ω" is its angular velocity). The leg was propelled by a combination of the earth's gravitational force and the force the two springs provided from the tension of the leg being pulled back. The springs each function according to the equation $V(x)=1/2k_sx^2$.

The spring constant, k_s, for each of our springs was experimentally measured to be approximately 14000 J/m². When the leg was pulled back to its 1 meter height of release, approximately 140 Joules energy was stored in the springs. Upon release, this energy was transferred to the leg as rotational kinetic energy, ultimately increasing the speed of the leg to its maximum value (15.8 meters/second) at the moment of impact between the foot and the ball. The foot's mass was measured to be 0.85 kg. The face of the aluminum foot made a 40° angle with the vertical and was covered with protective foam rubber. The increasing velocity of the leg and the mass of the foot carried the initial momentum that was transferred to the football. After the first series of trials, the initial resting angle of the kicking leg was increased from 10° to 23° away from the vertical.

Kicking machine viewed from front and side

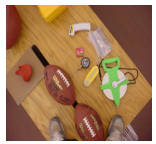
Failed Designs

Several intermediate designs were constructed, but were dropped from the final design. Initially, the machine was mounted on a smaller cart and had a kicking leg of only .66 meters. A more massive foot of 10 kg was constructed of lead in hopes of increasing the momentum transferred to the football; however, the mass was too great for the shorter leg, producing a significantly smaller leg speed and thus smaller rotational kinetic energy. The foot was replaced with aluminum. In hopes of increasing the velocity, a large amount of tension was added to the springs; however, this made the task of pulling the leg back nearly impossible. The construction of a pulley system was fastened to the cart and foot. This was dropped because it was not significantly easier to pull back, and the height of the release point was limited to the height of the second pulley. The final construction replaced the short leg with a longer leg mounted onto a larger cart as described in the previous section. A counter weight was added to the top of the leg to give the leg a further forward rest position, hoping to increase the velocity of the rotating leg at impact. This weight was subsequently removed because the kicks actually went further without it.

Procedures

Kicking

Initially, the machine was tested outside, but varying winds and temperatures altered the path of flight of the football. To remain as consistent as possible the machine was moved into DePauw University's indoor track and field facility. Before every day's trials the temperature and humidity were recorded; the machine was stabilized by placing metal rings under each of the four tires; the pressure of each football was standardized using a Tachikara Ball Pressure Gauge with a 0.05 pounds/inch² (psi) resolution; the ball's temperature was recorded using a Raytek MiniTemp infrared thermometer.



Equipment used in the experiment

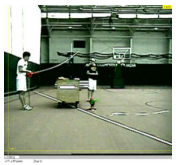
The tee's position was kept consistent for each day's trials. Finally, the leg was pulled to the height of 1 meter from the ground and then released, kicking the football. Beanbags were placed at the landing spots of each football. After a series of kicks, the ranges were measured using a 50-meter measuring tape.

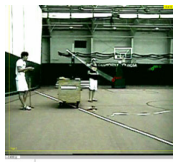
Procedures were altered testing multiple variables such as:

- The height of the leg's release point was varied between 1.0, 0.8, 0.6, 0.4 meters.
- The leg speeds and ranges were measured at each height.
- The football's air pressure varied from 26 psi to 5 psi in increments of 3 psi and the ranges were measured.
- The ranges of a football kicked on its seams, panel, and laces
- The position of the tee was altered to find and test the different launch angles and the football's respective ranges.
- By use of a freezer, the football's temperature ranged to values below –15.0°C.
- In later trials to simulate a half of a football game, the room temperature footballs were rotated between the freezer and being kicked for a period of an hour.
- Ranges of a kicked weathered, slightly worn, and brand new football was tested.

Restitution

The footballs were dropped from a height of 1.0 meter and were recorded using a video camera to measure the rebound height of the ball. Variables in pressure, temperature were tested. The coefficient of restitution is simply the ratio of rebound height to initial height.





Video Point Data – Red marker on foot and Green Marker on Football

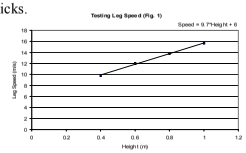
Results

Seams, Panel, Laces

A clear trend was observed: on average the balls kicked on the laces were roughly 1-3 meters shorter than the balls kicked on the panel or seams. No difference was observed between the ranges of the panel and seams kicks.

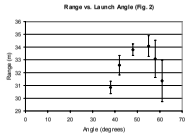
Height of Leg Release

In hopes of displaying the consistency of the machine, the leg was pulled back to different heights and the ranges and leg speeds were recorded. The results (Figure 1) clearly showed a very low error in the linear correlation between leg speeds. The ranges of the kicks displayed a similar linear correlation.



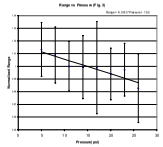
Launch Angle

The results showed that between the range of 50° and 55° the range was the greatest. The resulted correlation between points was observed to be parabolic in nature (Figure 2). Consequently, as the tee was positioned further away from the foot to increase the angle, the resulted kicks became more inconsistent.



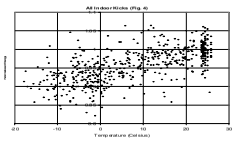
Pressure

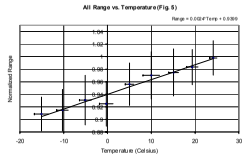
The tests of various pressures showed only a slight decrease in range (0.1% per pound/inch²) between the different pressures (Figure 3). Note that the error bars overlap suggesting that there may not be a pressure effect.



Temperature

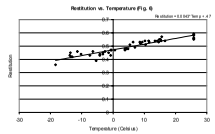
A linear correlation was observed in both graphs that were produced. (Figures 4 & 5) Because of varying results day to day (see discussion on wear below), a control ball was used to normalize every day's kicks. The normalized values showed that when a football was at the temperature of –17.0 °C, the distance traveled was approximately 10% less than the normalized range at 25 °C.





Restitution

When the pressures were varied, the coefficient of restitution was directly proportional to the pressure. (Figure 6) The higher pressure football rebounded highest and the lower pressure rebounded the lowest. This was not observed in the kicked football results (see Figure 3). However, when the temperature was varied; the results were similar to the kicked football series. The graph shows a linear relationship for the restitution versus the temperature.



Wear

Testing the wear showed that the NFL needed to standardize the kicking balls used in game play. The new footballs, compared to the old footballs, showed the same effect as a ball being chilled to a temperature of roughly –17.0 C. Furthermore, the three footballs of the varying wears, brand new, slightly worn, and weathered, showed different ranges; the greatest being the weathered and the least being the brand new. (Figure 7)