# Foot Velocity and Coefficient of Restitution in a Soccer Ball

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**Abstract**

The coefficient of restitution (COR) of a soccer ball was measured by using a high speed camera to record an instep kick at a range of speeds typical of normal play. It was found that the COR decreased linearly as foot impact velocity increased, indicating increased energy loss with increased foot impact velocity.

***Keywords:*** soccer, coefficient of restitution, instep kick

## I. INTRODUCTION

In the sport of soccer, controlling ball speed is very important because of different speeds needed in different situations. When making a short pass, a slow ball may be needed, whereas when shooting at goal, a faster ball is desired. How fast the ball travels, depending on foot speed, is an important aspect of play and will be studied here. One way this relationship can be modeled is measuring the coefficient of restitution (COR). COR is defined as the ratio of the final relative velocity to the initial relative velocity between two objects when they collide, and can be modeled by the equation below[1]:

$$C_R = \frac{v_{bf} - v_{af}}{v_{ai} - v_{bi}} \quad , \qquad (1)$$

where $C_R$ represents the coefficient of restitution, $v_{bf}$ and $v_{bi}$ are the final and initial velocities of object *b* (ball), respectively, and $v_{af}$ and $v_{ai}$ are the final and initial velocities of object *a* (foot), respectively. In this case, a stationary ball will be kicked, so $v_{bi}$ is 0.

There have been a number of studies on the factors affecting the velocity of a soccer ball when kicked. One study by John De Witt and Richard Hinrichs[2] measured the pelvis, thigh and lower leg as three separate components, and found that the speed of these components has a high correlation with the resultant ball velocity. Another study by Yo Chen and Jia-Hao Chang[3] studied the relationship between the velocity of a ball and the range of motion of the arm swinging during the kick. They found that kicking with an arm swinging causes a higher ball velocity. A study by the National University of Malaysia[4] investigated how a different number of runup steps affect the ball velocity. They found that taking a three step runup will produce higher velocity and distance in the ball than a one or two step runup. A study by a group of universities in Japan[5] found the effect of impact point on resultant velocity, and concluded that there are many other factors that also affect the ball velocity. There was also a paper published by Thomas Andersen et al[6], which studied the COR during a toe kick and an instep kick. They used a size 5 ball and pumped it to a gauge pressure of 0.9 bar. The relationship they found between COR and initial foot velocity can be seen in Figure 1.

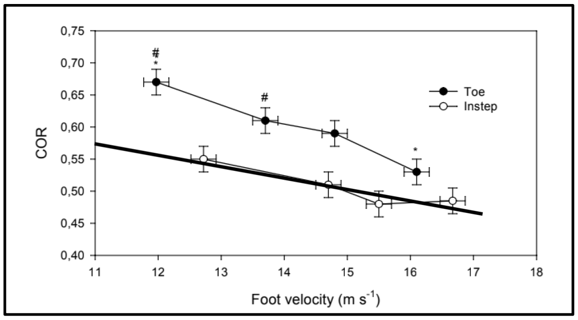


**Figure 1.** COR for Kicks in Andersen[6]

The relationship for the instep kick in Andersen's paper can be modeled by equation 2,

$$C_R = 0.73 - 0.014\, v_{ai}\ . \tag{2}$$

When the foot impacts the ball, some of the foot's kinetic energy is converted to internal energy, therefore when the ball continues travelling, it will result in a lower kinetic energy than the foot had. A higher impact velocity will cause a greater ball deformation, a greater proportion of energy lost and therefore a lower COR.

In Andersen's paper, only four velocities were used for each kicking style. In this paper, the relationship between foot impact velocity and COR will be investigated for a different kicker over a lower and larger velocity range.

## II. METHODS

A leather Adidas Tango Size 5 ball with diameter 0.216 ± 0.004 m was inflated to 0.95 ± 0.02 bar and placed approximately 1 meter away from a camera on a stand. The camera filmed at 240 fps with a resolution of 1080p. The ball was kicked with the laces, a typical instep soccer kick. For each of the thirty trials, Logger Pro was used to determine the velocity of the foot before and after impacting the ball as well as of the ball after being

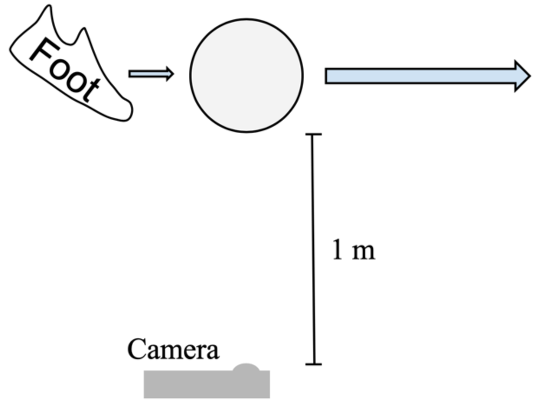


**Figure 2.** Experimental Setup (bird's eye view)

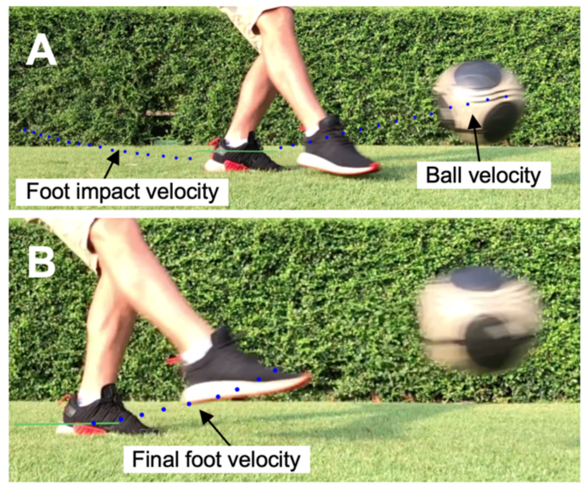


**Figure 3.** Analysis of Motion. Images A and B show how each velocity was measured.

impacted, as shown in Figure 3. These values were then used to calculate the COR. The temperature at the time of the experiment was constant at 36 ± 1 º C.

Each of the blue dots on Figure 3 represent a point where the foot and ball were at in that specific time frame. Figure 4, below, was plotted using the points from Figure 3 of the final ball velocity.

The points on Figure 3 were graphed in Figure 4. This process was repeated to measure the velocity of the foot before and after impact for each trial.

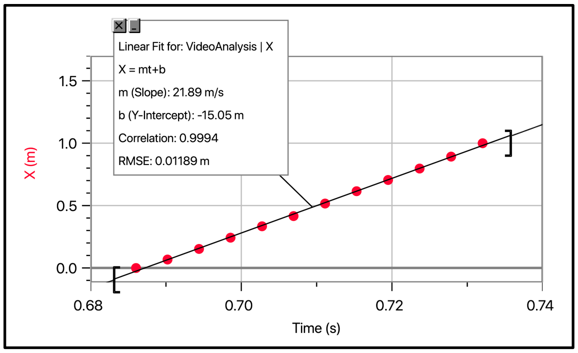


**Figure 4.** Position-Time graph to calculate the speed of the ball after impact

A limitation with the methods of this investigation was the variability of the kicks. Because the kicking method was a natural kick, it is expected that the kick would vary slightly in where on the foot was hit, where on the ball was hit, or if the ball left the foot with a spin.

## III. RESULTS & DISCUSSION

Calculating COR from initial and final foot and ball velocities, the relationship between initial foot velocity and COR was graphed as shown in Figure 5. This relationship seems best modeled by a linear equation. As the foot impact velocity increases, the resultant COR decreases linearly.

Figure 5 can be modeled by the equation,

$$C_R = 0.87 - 0.023\, v_{ai} \,. \qquad (3)$$

There is a negative linear relationship between initial foot velocity and COR, as expected, modeled by Equation 3. The harder a ball is kicked, the more energy is lost when the foot impacts the ball.

The relationship in Figure 5, from this investigation, is quite similar to Andersen's findings shown in Figure 2. Figure 6 shows both

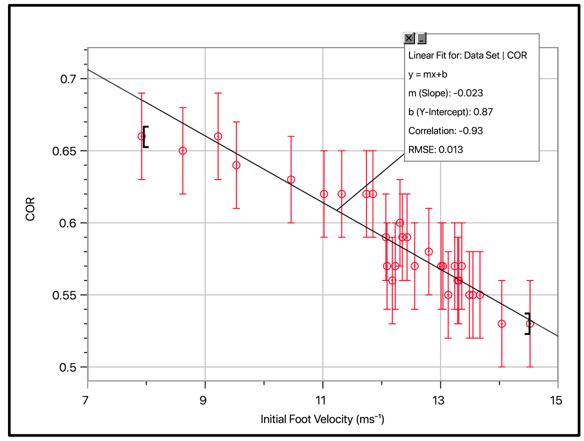


**Figure 5.** Initial Foot Velocity vs COR

sets of data on one graph, with the red points representing this investigation, and the blue points showing Andersen's data. For the majority of low foot velocities, it appears that this investigation resulted in higher CORs. One reason for this could be that the ball pressure was higher in this investigation, therefore the deformation of the ball was smaller.

However, as can be seen, the best fit lines from both investigations are fairly close to each other. This investigation confirmed Andersen's results, increasing confidence levels in the finding, and also extended the range of speeds for which the relationship is shown to hold.

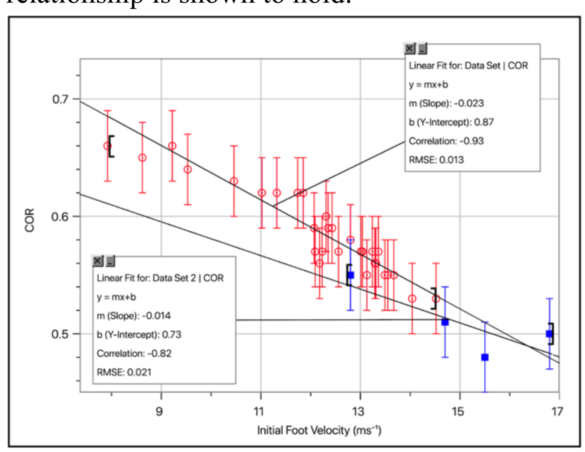


**Figure 6.** Initial Foot Velocity vs COR, comparison with Anderson[6].

One area of further research within soccer could be investigating this relationship with a different size soccer ball. This would test whether the volume or surface area of a ball affects its COR. The effect of ball pressure on COR should also be studied for pressures within the FIFA regulation range.

## IV. CONCLUSION

A negative linear relationship was found between the initial foot velocity and the resultant COR of a soccer ball for velocities between 8 $ms^{-1}$ and 14.5 $ms^{-1}$. This suggests that the greater the foot velocity, the greater the energy loss.

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