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# A study of the influence of atmospheric conditions on the range of the soccer ball goal kick

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**Abstract**
Using our ball flight simulator, we studied how the trajectory of a goal kick may be affected by atmospheric conditions such as altitude, wind and temperature. Based on our analysis we make rough approximations and recommendations for athletes and coaches. For starting velocities lying between 20 m/s and 35 m/s, the range of a goal kick started at 45° will be increased by about 0.7-2.2 m with each 1000 m increase of altitude depending on the starting velocity. At sea level each increase of the head/tail wind by 1 m/s will decrease/increase the range of such a goal kick by about 0.8-2.3 m and its trajectory will be deflected by about 0.5-1.5 m for each meter per second of a crosswind depending on the starting velocity. The increase of temperature by 5 °C at sea level is approximately equivalent to the increase of altitude by 150 m. The research also has educational purposes: knowing the strength of their kicks, the sportsmen will be able to select the best angle for a kick taking into account the wind and altitude. They will be able to better predict a trajectory of a football during a game and occupy better positions.

**Keywords:** altitude, wind, drag, projectile

## Introduction
The motion of a ball through the air is one of the most complex problems in sports science, and it is still not completely understood to this day. One of the reasons why this problem is so challenging is that, in general, there are many different forces acting on the ball, including: gravity, drag and Magnus force, which in their turn depend on the ball's mass, cross-sectional area, form and shape, as well as on the external factors such as air density and the air velocity [1-7].

Since there are many football kick simulators for modeling how the same kick behaves under different external conditions, it is often difficult to decide which one to choose. Main factors which put obstacles in the way of the use of many existing simulators are the following:

- The data published in the scientific literature often contradict each other. A good model should have enough complexity and be compatible with the reliable scientific data.
- Almost all simulators which model the effect of altitude and Magnus force are not programmed to model the effect of wind.
- We failed to find simulators modeling the wind effect for arbitrary directions of the wind and not only for head or tail winds or crosswinds.
- Many simulators have complicated interfaces and are non-intuitive.

The purpose of our research is to create a reliable computational approach for modeling a soccer ball kick trajectory taking into account the complex effect of such parameters as starting velocity, starting angle, wind speed and direction, altitude and temperature. The research also has educational purposes to make the process of modeling the motion of a soccer ball simpler and more comprehensible.

## 2. Materials and methods
### 2.1 The Method of Computer Modeling
The trajectory of a soccer ball is governed by three different forces: gravity, drag and Magnus force. The force acting on the ball could be calculated as:

$\bar{F} = \bar{F}_G + \bar{F}_D + \bar{F}_S + \bar{F}_L,$

where $\bar{F}_G$ is the downward force experienced by gravity, $\bar{F}_S$ is the sideways component of the Magnus force and $\bar{F}_L$ is the lifting component of the Magnus force [5]. Fig. 1 shows the various forces on the ball: the gravitational force $\bar{F}_G$ points down; the drag force $\bar{F}_D$ is opposite to the ball's velocity $\bar{V}$; the lift force $\bar{F}_L$ is perpendicular to the ball's velocity $\bar{V}$ and lies in the plane formed by the velocity $\bar{V}$ and the ball's weight; and the sideways force $\bar{F}_S$ (not shown) is into the page.

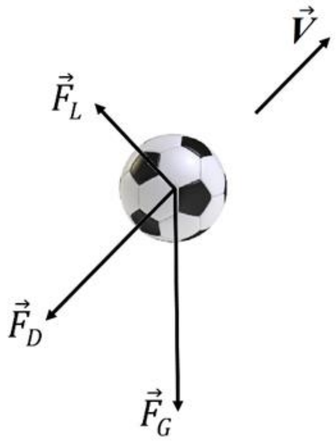


**Fig 1:** The forces acting on a soccer ball.

According to the accepted theoretical model, magnitudes of forces $F_D$, $F_S$, $F_L$ are proportional to the air density, the ball's cross-sectional area and corresponding aerodynamical coefficient, and $|\bar{F}_G|$ is proportional to the mass of the ball:

$F_D=C_D\cdot(\rho\cdot A/2.0)\cdot V^2$
$F_S=C_S\cdot(\rho\cdot A/2.0)\cdot V^2$
$F_L=C_L\cdot(\rho\cdot A/2.0)\cdot V^2$
$F_G=m\cdot g,$

where ρ is the air density, A is the cross-sectional area of the ball, m is the mass of the ball and $C_D$, $C_S$, $C_L$ are aerodynamical coefficients which depend on the air density, wind, ball's velocity V, spin, form and shape.
The typical parameter values used in our model are shown in Table 1 [5, 6]. Here we assume that the ball has no spin and $C_S = C_L = 0$.

**Table 1:** The typical parameter values.

| Parameter | Value |
|---|---|
| Ball's mass m | 0.430 kg |
| Ball's diameter D | 0.22 m |
| Ball's cross-sectional area A | 0.039 $m^2$ |
| Air density $\rho_0$ at sea level | 1.225 $kg/m^3$ |
| Temperature T | 288.15 K |
| Drag coefficient $C_D$ | 0.2 |

Air density ρ decreases with increasing altitude. An approximate relation gives about a 3% reduction in air density for every 305m increase in altitude. This relation may be described using a simple formula:

$\rho=\rho_0\cdot(100-(h\cdot 3/305))/100,$

where $\rho_0=1.225\ kg/m^3$ is air density at sea level at 15 °C.
For describing the motion of the ball in the air we use the system of differential equations (8)-(10) from Myers & Mitchell's paper [5].

$$\ddot{x} = -k_d|\bar{V}|V_x \quad (1)$$
$$\ddot{y} = -k_d|\bar{V}|V_y \quad (2)$$
$$\ddot{z} = -g - k_d|\bar{V}|V_z, \quad (3)$$

where $|\bar{V}|$ is the absolute value of the ball's velocity, $k_d=\rho AC_D/(2m)$ is the scaled drag coefficient. Axis OY is parallel to the longest sides of the field, axis OX - perpendicular. The system doesn't include wind, so we had to add the wind component. This has been done according to the method described in by Leela J. *et al.* [2]. The wind W may be represented as a superposition of two winds $W_x$ and $W_y$ - parallel to OX and parallel to OY, respectively. When a wind $\bar{W}$ is blowing, the air speed of any projectile is given by

$$\bar{V}^* = \bar{V} - \bar{W} \quad (4)$$

The drag and lift effects will depend on $\bar{V}^*$, and only on $\bar{V}$ in the absence of wind. Therefore, with the addition of wind, the basic equations (1)-(3) become

$$\ddot{x} = -k_d|\bar{V}^*|V_x^* \quad (5)$$
$$\ddot{y} = -k_d|\bar{V}^*|V_y^* \quad (6)$$
$$\ddot{z} = -g - k_d|\bar{V}^*|V_z^*. \quad (7)$$

## 3. Results & Discussion

First of all, we calculated how the range of a kick launched at α depends on the starting angle α and the starting velocity of the kick $V_0$. The results of calculations are shown in Fig. 2.

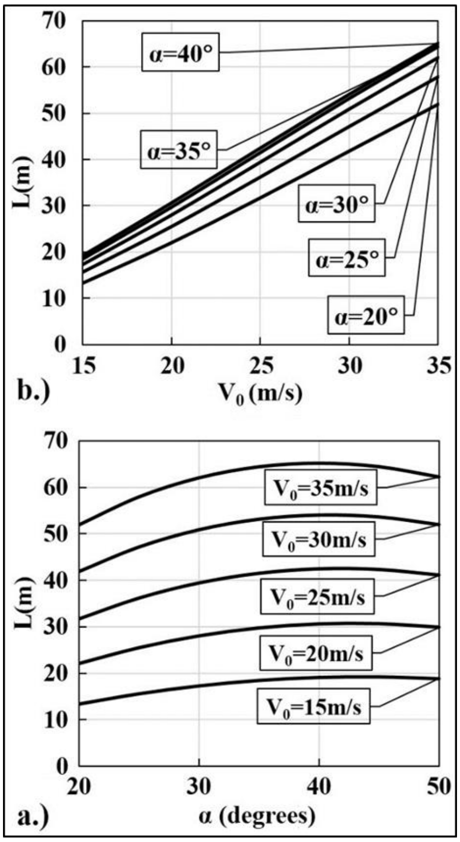


**Fig 2:** a) The dependencies of the range L on the starting angle α for different values of $V_0$. b) The dependencies of L on the starting velocity $V_0$ for different values of α.

We see that the increase of α from 20° to 40° increases the range by 8.5-13.2 m depending on the value of $V_0$ (Fig. 2 a). For large $V_0$ the range achieves its maximum value when the starting angle is about 41°. The increase of $V_0$ from 20 m/s to 35 m/s increases the range by 30.0-35.0 m in an almost linear manner (Fig. 2 b).
At the next step, we studied how the kick's range through the still air depends on altitude H. Using our program, we have calculated how the range of a goal kick launched at 45° depends on the starting velocity of the kick $V_0$ and the altitude.

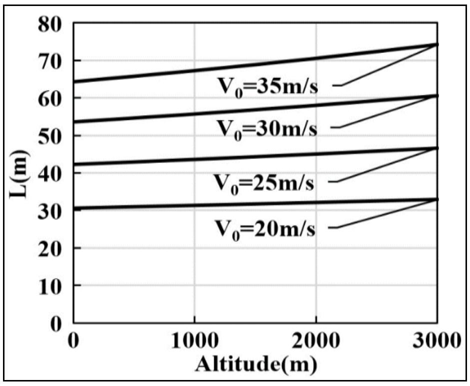


**Fig 3:** The dependencies of the range of a goal kick on the altitude (α=45°).

Fig. 3 shows that the calculated graphs have an almost linear character: for $V_0$=20 m/s the range L increases only by 2.3 m when the altitude increases from 0 m to 3000 m, while for $V_0$=30 m/s such an increase is about 7 m and it is about 9.7 m for $V_0$=35 m/s. A rough approximation for goal kicks is, that a ball that carries about 50 m through the air at sea level will carry about 1.6-2.2 m further with each 1000 m increasing of altitude.
When there is a wind, the speed of the air over the ball is changed and there is an additional force on a ball. This force depends on the speed of the ball and is approximately proportional to the speed of the wind [6]. It is clear that a tail wind will increase the range of a kick and head wind will decrease a range. Fig. 4 shows how the range L of a goal kick depends on the ball's starting velocity and the speed of the wind. Here we also see almost linear graphs, where the effect of a wind increases when the initial velocity of the ball increases. For a goal kick at sea level with $V_0$=30 m/s, a rough approximation is that the range is increased or decreased by 2 m for each meter per second of the wind. For $V_0$=35 m/s the range will be increased or decreased by 2.3 m for each meter per second of the wind.

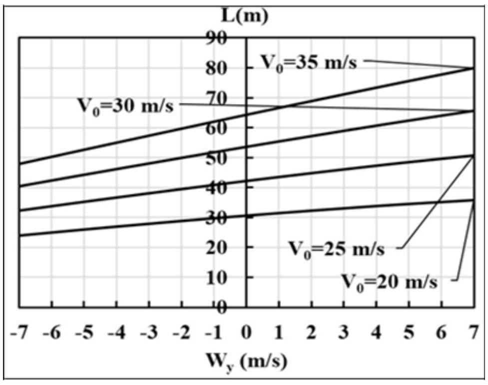


**Fig 4:** The dependencies of the range of a goal kick on the altitude (α=45°).

Crosswinds of moderate strength or less do not affect the range of soccer balls very much. However, they can deflect their trajectory quite considerably. The deviation traces out the curved path because of natural drag effects which reduce the duration of the flight [7].
Our calculations show that each meter per second of a side wind displaces the flight of a goal kick launched at 45° with $V_0$=30 m/s approximately by 1 m (see Fig. 5). For $V_0$=35 m/s the displacement will be about 1.5 m.

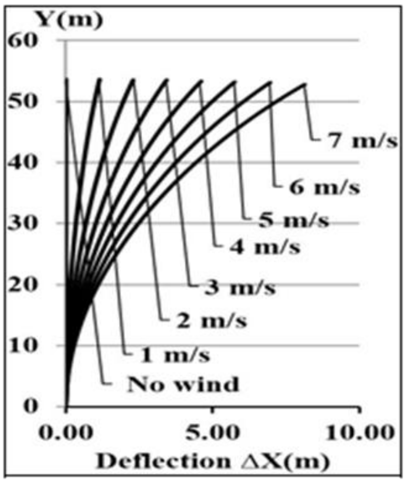


**Fig 5:** Top view of trajectories of a goal kick deflected by a side wind. ΔX is the displacement of the ball along the OX axis ($V_0$=30 m/s, α=45°).

At high altitudes wind effects become weaker: for example, the deflection of a goal kick with $V_0$=30 m/s and α=45° caused by a crosswind with Wx=7 m/s at 3000 m altitude becomes 6.92 m against 8.06 m deflection at sea level. Besides altitude there is another factor affecting the air density - the temperature. All our trajectories were calculated for the temperature T=15 °C which corresponds to sea level standard temperature 288.15 K.
Air density depends on temperature T and may be calculated using the following formulas:
$\rho=p/(R_{specific}\cdot T)$, where $p\approx p_0\cdot \exp(-gMh/R_0/T_0)$ - absolute pressure, $R_{specific}$ - 287.058 J/(kg·K), T - absolute temperature (K), $p_0$=101.325 kPa - sea level standard atmospheric pressure, g=0.9806 m/s$^2$ - earth-surface gravitational acceleration, M=0.0289644 kg/mol - molar mass of dry air, h(m) - altitude, $R_0$=8.31447 J/(mol·K) - ideal (universal) gas constant, $T_0$=15 °C = 288.15 K - sea level standard temperature.
In our program the temperature together with the ball's mass, the ball's cross-sectional area, the ball's diameter and aerodynamical coefficients is an external parameter and may be changed using a special interface. But there is also a rough approximation: the air density decreases when temperature increases and a 5 °C temperature increase is approximately equivalent to a 150 m increase of altitude which cannot be neglected especially if there is a side wind.

## 4. Conclusions
In this paper, a computational study of the three-dimensional equations describing the motion of a soccer ball through the air is presented. Excellent agreement is demonstrated between our results and numerical, analytical and experimental results published in the reliable scientific papers.
Based on our analysis we make rough approximations and recommendations for athletes and coaches:

1. For starting velocities lying between 20 m/s and 35 m/s, the range of a goal kick started at 45° will be increased by about 0.7-2.2 m with each 1000 m increase of altitude depending on the starting velocity;
2. At sea level each increase of the head/tail wind by 1 m/s will decrease/increase the range of such a goal kick by about 0.8-2.3 m depending on the starting velocity;
3. The trajectory of such a goal kick will be deflected by about 0.5-1.5 m for each meter per second of a crosswind depending on the starting velocity.
4. Air density decreases when temperature increases. The increase of temperature by 5 °C at sea level is approximately equivalent to the increase of altitude by 150 m.

Our program helps sportsmen and coaches understand and predict the effects of wind and altitude on the trajectory of a soccer ball. Players who are aware of altitude's and wind's effect on aerodynamics could have an advantage over those who don't. They will be able to better predict a trajectory of a football during a game and occupy better positions.

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