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A5_3 Are the Boots a Lie?

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Abstract

An investigation is described regarding the spring constant of the material used to create the boots worn by the leading character in the game ‘Portal’. Within the game, the boots allow the character to fall from any height without injury. It is found that such ‘long-falls’ are not possible with the depicted boot design. A spring constant of 1.19 x 10^6 Nm^{-1} would allow a user to survive an impact of 20 ms^{-1} without experiencing soft tissue related injuries.

Introduction

Featured within the video game ‘Portal’, made by the Valve Corporation [1], is a set of boots whereby the wearer is able to fall from any height without injury. If such boots were plausible in reality they could have a variety of applications, from recreational to military uses. An investigation is performed into the spring constant required for the material used in the heel of the shoes so that the wearer may land unharmed. The boots in question are depicted in Figure 1.

Two factors need be considered when determining whether the fall would have led to an injury or fatality. If the deceleration provided by the spring is too great, fatal soft tissue damage may be caused. Secondly, if the material has not allowed for sufficient energy dissipation, the impact may be transferred to the body and result in injury or death. The spring constant must be large enough to prevent the heel of the foot colliding with the ground but should not be so large that the deceleration is intolerable. Furthermore, the spring constant must allow the ball of the foot to touch the floor when standing in the boots. If this is prevented, walking whilst wearing the boots would prove challenging and the whole design would be unfeasible.

The required material properties would depend on the mass of the wearer. In light of this, three masses are considered: the typical masses of an adult female, an adult male, and a child. Within the game the boots are in the possession of an adult female. The feasibility of the actions shown in ‘Portal’ should be based on the result of calculations using this mass.

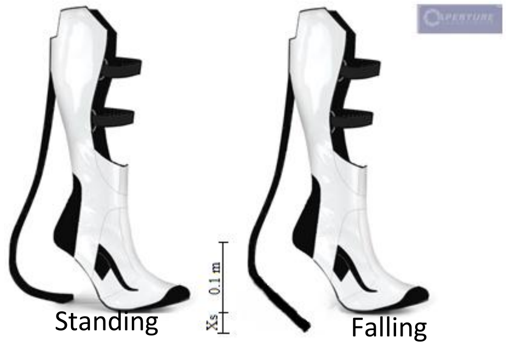

Figure 1 – An image of the boots used in the game ‘Portal’ [2] with the heel position shown for standing and for falling. Measurements used in the calculation are also included.

Theory

The spring constant is henceforth referred to as the *k* value. This value may be calculated by equating the elastic potential energy stored in the spring and the kinetic energy of the falling wearer. This is shown in Equation (1):

$$mv^2 = 2kx^2, \qquad (1)$$

where *m* is the mass of the person, *v* is their velocity, *x* is the compression, and the factor of two is included to account for the two boots. The compression is the sum of X_S and 0.1 m (see Figure (1)). Equation (2) may be used to determine the value of X_S:

$$X_S = \frac{mg}{2k}, \qquad (2)$$

Where *g* is the acceleration due to gravity and all other variables are as previously defined. The use of Equation (2) ensures that the ball of the foot may always reach the floor when standing. Equation (2) can be substituted into Equation (1), using the relationship $x = X_S + 0.1$, and expanded to give Equation (3). This may then be rearranged to produce Equation (4).

$$mv^2 = \frac{(mg)^2}{2k} + 0.2\,mg + 0.02\,k \tag{3}$$

$$0.02\,k^2 + m(0.2\,g - v^2)k + \frac{(mg)^2}{2} = 0 \tag{4}$$

Equation (4) can then be solved through use of the quadratic formula.

$$k = \frac{m(v^2 - 0.2g) \pm \sqrt{m^2(0.2g - v^2)^2 - 0.04(mg)^2}}{0.04} \tag{5}$$

Equation (5) is solved to calculate *k*. For the wearer to survive any fall *k* must be calculated for terminal velocity. Any air density variation with altitude has been neglected. Equation (6) shows the calculation used to determine the terminal velocity for each of the three considered masses.

$$v_{term} = \sqrt{\frac{2mg}{C_D \rho A}} \tag{6}$$

In Equation (6) v_{term} denotes the terminal velocity, C_D the drag coefficient (assumed as 1.2 [3]), A the surface area presented to the air when falling (assumed to be 0.15 m^2), and ρ the density of air (1.225 kg m^{-3}).

Results and Conclusion

Upon investigation, it was shown that the subtraction of the root in equation (5) produced k values that were not physically valid, peaking at a low velocity. From this point onwards, only k values calculated with the addition of the root shown in equation (5) are considered.

Figure 2 shows the k values required for the three weights considered, over a range of velocities up to terminal velocity. It is seen that, as the velocity increases, the required spring constant becomes very large. To compensate for the large k, equation (2) requires the X_S value to be small in order to allow the wearer to stand. To highlight this, X_s is calculated for a female falling at terminal velocity and found to be 18.3 μm.

As seen in Figure 3, the large spring constant of the heel results in considerable deceleration upon impact with the floor. The human body can withstand a shock deceleration of 100g with trauma [4], it is therefore assumed that a shock deceleration of 25g is survivable without soft tissue damage. It is clearly demonstrated by figure 3 that the deceleration is sufficiently large that a fall from terminal velocity is unsurvivable for a man, woman, or child. However, an impact at a velocity of ~20 ms^{-1} is potentially possible without soft tissue damage.

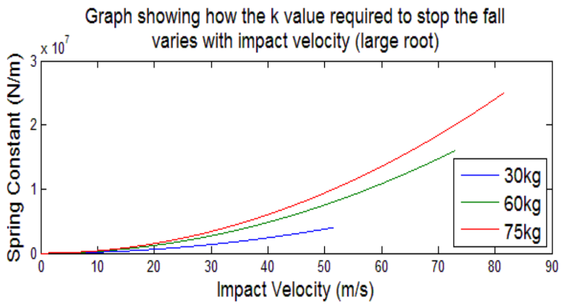

Figure 2: A graph of the calculated *k* value at each velocity for the masses of a man (red), woman (green), and child (blue).

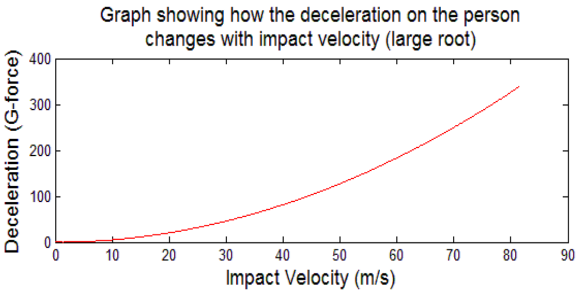

Figure 3: A graph of the deceleration caused by the *k* value at each velocity. This is not mass dependent.

For the boots to have an effect the wearer must always land on their feet. Energy losses from impact have been neglected in the calculation. For a greater degree of physical accuracy this should be included. Significant damping is also required to prevent the wearer accelerating upwards post impact.

In conclusion, while it is possible that the wearer could be protected from harm when falling at ~20 ms^{-1}, a fall from any height is not possible as shown in the game. Further investigation could perhaps be performed into the possibility of having a larger value of X_s and a smaller value of k.

References

[1] http://www.thinkwithportals.com/about.php, 2011, Valve Corporation, accessed on 14/10/14

[2] http://forum.hon.garena.com/showthread.php?31476-ITEMS-Warp-Boots-or-Portal-Boots, accessed on 15/10/14

[3] Oteh U., Mechanics of Fluids, 2008, USA, AuthorHouse, page 395

[4] http://en.wikipedia.org/wiki/G-force, accessed on 12/11/14