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The Physics of the Circus - Weighbridge

The Marriage between Science and Art, enhancing the learning of Physics in New High School

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ABSTRACT

The New High School has caused great debates across the country since its implementation. The change in focus on learning, where content is exchanged for skills and abilities, the change in workload and available resources have always been a reason for distrust on the part of the school community, especially teachers and parents. The use of interdisciplinarity is the focus of this work, which involved first-year high school students and Basic Education teachers, with the support of a circus researcher. We analyze here the Weighbridge, a piece of equipment widely used in circuses all over the world. We use the contents of two training itineraries, which involve Physics and Circus, allied to Scientific Initiation and Research and Creative Writing to insert Physics contents within circus art. The result of this analysis is very interesting and shows the potential of interdisciplinarity in teaching, especially in New High School.

Keywords: Performing arts; Physics Teaching; New High School; Training Itineraries; Interdisciplinarity

Introduction

The fantastic journey that human beings undertook thousands of years ago gradually incorporated art and science, until both assumed a prominent place in modern life. Over the past centuries we have seen how these dimensions of knowledge and human sensitivity have come together and also distanced themselves, and we have noticed that often when art and science meet, a more than sublime image of life is presented.

We, teachers and enthusiasts of these dimensions of knowledge, present a brief study that deals with the encounter between PHYSICS and CIRCUS, between the laws of nature and some of the artistic feats. This work was built during a Formative Itinerary of the Puríssimo Coração de Maria High School, located in the city of Rio Claro - SP, more precisely in the itinerary "Reading the World through the Lens of Physics" in which we approach Physics in a different way , seeking to make it more palatable to students. An educational action that intends to present the Physical World to young people in a creative and practical way, while offering them greater contact with contemporary culture. In some way we agree with Richard P. Feynman when he says that "Poets complain that science takes away the beauty of the stars. But I can see them at night in the desert, and feel them. Do I see less or more?"

This study combined the expertise of Prof. doctor Marco Antonio Coelho Bortoleto, professor/researcher at UNICAMP, renowned scholar of Circus art; the experience of Professor Thércio Fábio Pontes Sabino, who practices "capoeira" and teacher of Physical Education and of the Training Route "Circus Practices" at Puríssimo School; the physicist, professor and pedagogical coordinator of the Puríssimo School, Huemerson Maceti, together with the Physics teachers of that institution and, also, high school students who attended the Itinerary "Reading the world through the lens of Physics", all of them 1st grade students of the "New High School".

On this occasion, we will deal with the study of the acrobatic modality "Weighbridge", discussing some physical concepts, such as speeds, accelerations, displacements, oblique throws, energy, power and angular momentum, which contribute to the understanding of the risky and charming artistic acts presented by circus artists.

The New High School, Formative Itineraries and the Puríssimo School

Law nº 13.415/2017 amended the Law of Guidelines and Bases of National Education (LDB) and established a change in the structure of secondary education. One of the changes concerned the workload, increasing the minimum time a student spends at school from 800 hours to 1,000 hours a year, until the present year, 2022. In addition, it defined a new, more flexible, curricular organization that includes a General Basic Qualification, based on the National Common Curricular Base (BNCC) and on the offer of "training itineraries", focusing on areas of knowledge and technical and professional qualification, which are aligned in the form of four "structural axes" – Scientific Research; Mediation and Sociocultural Intervention; Creative Processes and Entrepreneurship. This change aims to guarantee the provision of quality education to all young Brazilians, in addition to bringing schools closer to the complexities of the world of work and life in society.

"Training itineraries are the set of disciplines, projects, workshops, study centers, among other work situations, that students will be able to choose in high school" (MEC, 2017). The training itineraries can deepen the knowledge of one area of knowledge or even the knowledge of two or more areas. Also, according to the Ministry of Education (MEC), "The education networks will have autonomy to define which training itineraries they will offer, considering a process that involves the participation of the entire school community".

The Puríssimo Coração de Maria School, located in the city of Rio Claro - SP, is an institution maintained by the Congregation of the Sisters of the Immaculate Heart of Mary - ICM Education and Social Assistance Network, which develops an education based on the basic principles of the Guidelines and Bases of School Education and in the Educational Project prepared by the Pedagogical Sector of the Congregation, whose foundations are the teachings of its founder, Bárbara Maix, ensuring students the opportunity to develop potentialities that enable them to exercise a more just and fraternal citizenship. With more than 113 years of tradition, the Puríssimo School is committed to the transformation of human beings – and this means that students learn to relate the knowledge built in the classroom with everyday life.

The High School Pedagogical Coordination of the Puríssimo Coração de Maria School defined, through consultation with the students, the itineraries to be offered in the year 2022. In a "menu" of Itineraries presented to the students, our students could choose between Initiation and Scientific Research , Laboratory Practices (Physics, Chemistry and Biology), Immunology and Public Health, Protagonism and Life Project, Sustainable World, Creative Writing, Entrepreneurship and the New World of Work, My Finances, Leadership and Volunteering (Maker), offered in partnership with the Poliedro Teaching System, in addition to the itineraries Reading the World with the Lens of Physics and Circus Practices, of authorship by school teachers. For the year 2023, this "menu" was expanded, including other training itineraries that permeate the four structuring axes, in addition to propaedeutic itineraries, of deepening, accompanied by simulations. Some of the Itineraries are common to all students and others form the "diversified part", where the student makes his choice between several offered, according to his tastes and aptitudes.

The work presented here was carried out based on these last two itineraries, grouping circus art with the Physical analysis of one of the most used equipment in riding arenas around the world, the Báscula, and joined Scientific Investigation and Creative Writing in the making of this article, with focus on a group of first grade high school students.

In addition to the changes in the curricular matrix, the entire teaching methodology was reassessed, using the Active Learning Methodologies in the itineraries. The evaluation process was also modified. Our High School Assessment Process is plural and, in fact, procedural. For the analysis of the students' scores, we took into account Official Tests, Laboratory Practices and "Maker" Activities, Simulations, Daily Procedures, Various Evaluative Activities, Textual Production, Social Projects, Scientific Olympics, Puríssimo Junior Company, Sports, Arts. In this way, the student is seen as a unique human being in training, with skills and abilities that can be improved, without leaving aside their identity.

This work is the result of this set of factors, which led the students, aged 15 years, to research and write an article that deals with Physics and Circus, but more than that, which requires methodology, commitment, deepening and self-knowledge, which led them to have contact with researchers and which led them to see beyond appearances, applying physical knowledge in art, without losing the beauty of art itself.

Acrobatics with the Weighbridge

The Weighbridge is a device similar to a playground seesaw, which was incorporated into the classical circus repertoire over two centuries ago (DUPRAT, BORTOLETO, 2007). By means of the Weighbridge, circus performers are launched into the air and can perform various acrobatics, landing on the ground or on the bodies of other acrobats (BUSSE, 1991). The countless shows that incorporated the Weighbridge reveal the courage, a preparation of many years for the acrobats to be able to withstand the impact of this activity on their bodies and also to control their emotions and thus offer a quality and safe artistic performance (FEDEC, 2010). The flights, even if for a few moments, that the Weighbridge´s acrobats perform provide countless opportunities for the physics teaching[1].

For the present study, we analyzed the scale number called "Scandinavian Boards" presented at the "40th Festival Mondial du Cirque de Demain" (Paris, 2019)[2], one of the most important circus meetings in the world. The images were visualized via Youtube, copied and worked on using Microsoft Paint software, showing that there is no need for expensive software to work with the analyses, being possible to carry them out in practically all schools in the country.

https://cirque-cnac.bnf.fr/fr/acrobatie/propulsion/la-bascule

[2] https://www.cirquededemain.paris/en/presentation/history

Dimension Analysis

Image 1 – Dimensions and Energy Involved

Image 1 provides us with some interesting input data. Comparing the size of the circus artist, estimated at 1.60 m, we can estimate the elevation of his body around 3.20 m, making his head reach almost 5 meters in height. This would already be frightening, not to mention the natural nervousness of a public presentation, the intense lighting above them and the small landing area on the Weighbridge, an "equal-armed balance", which was studied by the mathematician, philosopher, Greek physicist, engineer, inventor and astronomer Archimedes, over 2,200 years ago. We see here the evolution of its use, so present in our lives in mechanical equipment and in our own bodies. We noticed that the artists achieve incredible control of their bodies!

Kinematics

Let's look at some surprising data! To reach this height, the body must be thrown off the ground with a velocity easily calculated by Torricelli's equation:

$$V^2 = Vo^2 + 2a.\Delta S$$

Being "V", the final velocity of the artist, at the highest point of the trajectory (V = 0), "Vo" is the velocity at the exit of the flight, "a" is the acceleration of gravity (we can assume without major errors that the = g = - 10 m/s²) and "ΔS" is the height reached, that is, 3.2 m. Thus, we have:

$$0^2 = Vo^2 + 2(-10)3.2$$

$$0 = Vo^2 - 64$$

$$Vo^2 = 64$$

$$Vo = 8\,m/s\,(28.8\,km/h)$$

Note that this happens in a very short time interval (elevation of the bascule from the ground to its maximum point), which lasts around 0.4 seconds. The acceleration of the throw is given by:

$$a = \frac{\Delta V}{\Delta t}$$

By considering "ΔV" the artist's velocity variation, that is 8 m/s and Δt is the time interval elapsed to reach that velocity (0.4 s), we can write

$$a = \frac{8}{0.4}$$

$$a = 20\,m/s^2$$

That's right, twice the acceleration of gravity applied to the acrobats' bodies. Let's assume that the artist has a mass of 60 kg. This data is important for the calculation of forces and their moments and energies involved in the process.

Dynamics

Image 2 – Forces at the time of throwing

Image 2 illustrates the forces that act on the artist's body at the time of throwing. In this case, we have the Weight force (P = m.g = 600 N) and the Normal force (N), caused by the balance on the athlete's foot, perpendicular to the plane (hence the name "normal", which means perpendicular). The resultant Force is calculated by Newton's Second Law, developed by the brilliant English physicist in 1666:

$$\overrightarrow{F_R} = m\vec{a}$$

Since the Resultant Force points upwards, we have:

$$F_R = N - P$$

$$N - P = ma$$

$$N = P + ma$$

$$N = 600 + 60x20$$

$$N = 1{,}800N$$

Thus, the force acting on his legs during the 0.4 s time interval is equivalent to 3 times his weight (It is as if the athlete were, momentarily, 180 kg).

After a significant increase in the pressure exerted on two legs, he takes off and becomes available to gravity, which causes him to decelerate by 10 m/s every second, until he stops and starts to fall, increasing his speed again until he touches the ground with the same speed with which he was thrown upwards. To reduce the impact on the knees, the artist slightly flexes the legs when landing, increasing the stopping time and thus decreasing the acceleration and, consequently, the force on the legs.

The duration of the artist's flight can be calculated using the equation of spaces, developed by Galileo Galilei around 1630:

$S = So + Vot + \frac{at^2}{2}$,

where S stands for space (position), V stands for velocity and a stands for acceleration (gravity).

As the ascent time is equal to the descent time, let's calculate the fall of this circus artist from a height of 3.2 m (image 1). Calculating the fall, we adopt the initial position (So) as being zero, the final one (S) equal to 3.2 m and the initial velocity (Vo) zero at the highest point, which facilitates the calculations:

$$3.2 = \frac{10t^2}{2}$$

$$t^2 = 0.64$$

$$t = 0.8s$$

We note, then, that the acrobat takes 0.8 seconds to go up and another 0.8 seconds to come down, totaling 1.6 seconds in the air. That's the small amount of time available for him to perform different stunts!

Image 3 – Distance between weighbridges

Based on this other image, we can estimate the lateral distance between the weighbridges as being 1.6 m (practically the height of one of the athletes) and we can also consider the length of the weighbridge as being something close to 3.2 m (image 16). In this way, we can calculate the diagonal distance between one plank and another:

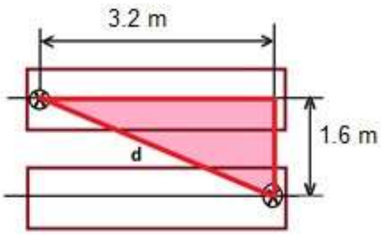

Image 4 – Triangulation

We can calculate the distance d using the Pythagorean Theorem:

$$d^2 = 3.2^2 + 1.6^2$$

$$d^2 = 10.24 + 2.56$$

$$d^2 = 12.8$$

$$d \cong 3.6m$$

This is the distance between one point and another, when they change positions between the weighbridges.

Image 5 – Change of position between the weighbridges

Although it seems simple to the viewer, this feat is incredible, as the artist needs to direct his body to another point. Note that in jumps, artists usually go upwards, which in itself is already complex, since the inclination of the board must be considered, which would direct the artist's body to another location (figure 6). Note in the image above that the body of the acrobat that is on the board is inclined, so that he can maintain his balance on the surface that is also inclined.

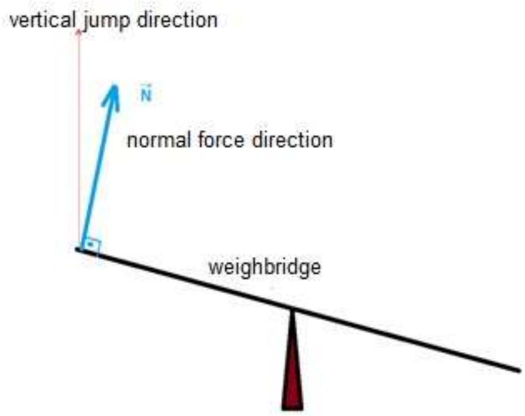

Image 6 – Vertical jump vector control

Now imagine that, in addition to this control, the artist has to create a vector directed to another plane, aiming to reach the weighbridge on the side:

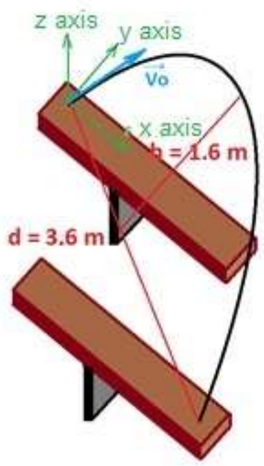

Image 7 – Jump between weighbridges

The athlete's directional control is amazing! We can see that he directs the forces on his feet in order to get the exact vector that takes him to the landing point. This means that he has to control the direction and magnitude of this vector. Let's bring this image to a plane and verify this data:

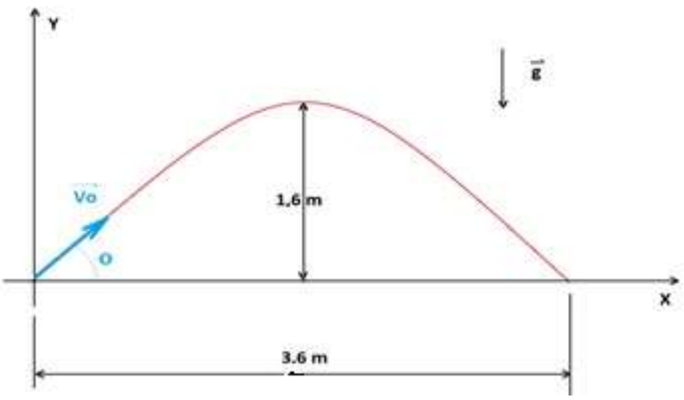

Image 8 – Oblique Launch

Considering the ascent, we have on the y axis:

$$Vy^2 = Voy^2 + 2a.\Delta S$$

$$0^2 = Voy^2 + 2(-10)6$$

$$0 = Vo_y{}^2 - 32$$

$$Voy^2 = 32$$

$$Voy = 5.7\, m/s$$

This is the speed on the y axis only. The rise time is also calculated by:

$$S = So + Vot + \frac{at^2}{2}$$

$$1{,}6 = \frac{10t^2}{2}$$

$$t^2 = 0.32$$

$$t = 0.57s$$

Since the ascent time is equal to the descent time, the flight time will be twice the ascent time, that is, 1.14 s. In the x axis the velocity is constant, since there are no forces present. Thus, the athlete's speed on the x axis is given by:

$$Vx = \frac{\Delta S}{\Delta t}$$

$$Vx = \frac{3.6}{1.14}$$

$$Vx = 3.16\, m/s$$

With these two values, the velocity vector can be calculated:

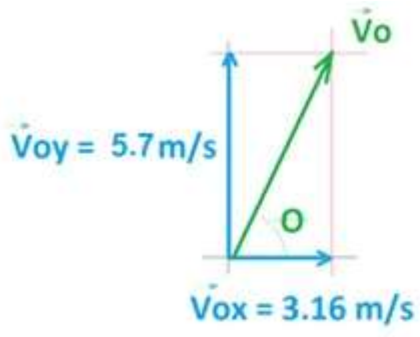

Image 9 – Velocity vector

The vector $\vec{V}$o can be calculated by the Pythagorean Theorem:

$$V_o{}^2 = 5.7^2 + 3.16^2$$

$$V_o{}^2 = 32.49 + 9.98$$

$$V_o^2 = 42.47$$

$$V_o = 6.5\, m/s\, (23.5\, km/h)$$

The jump angle θ can be calculated by any trigonometric relations (sine, cosine or tangent), since we have the three sides of the right triangle. Therefore, the angle θ is given by:

$$tg\theta = \frac{5.7}{3.16}$$

$$tg\theta = 1.8$$

θ = 61°

That's right, on another plane, different from jumping on the same scale! But why was the height lower than in the vertical jumps? Because of Energy!

When the acrobat jumps, propelled by the weighbridge, he transforms Kinetic Energy (speed) into Gravitational Potential Energy (height). Let's analyze the vertical leap. The athlete's Energy at the highest point is just Gravitational Potential Energy (Epg) given by:

$$Epg = mgh$$

Based on our previous calculations:

$$Epg = 60x10x3.2$$

$Epg = 1{,}920J$

When the acrobat describes a parabola, he has at the highest point Kinetic ($Ec=mv^2/2$) and Gravitational Potential ($Epg=mgh$) energies:

$$E = Ec + Epg$$

$$E = \frac{m{v_{ox}}^2}{2} + mgh$$

$$E = \frac{60x3.16^2}{2} + 60x10x1{,}6$$

$E =$ **1,260 J**

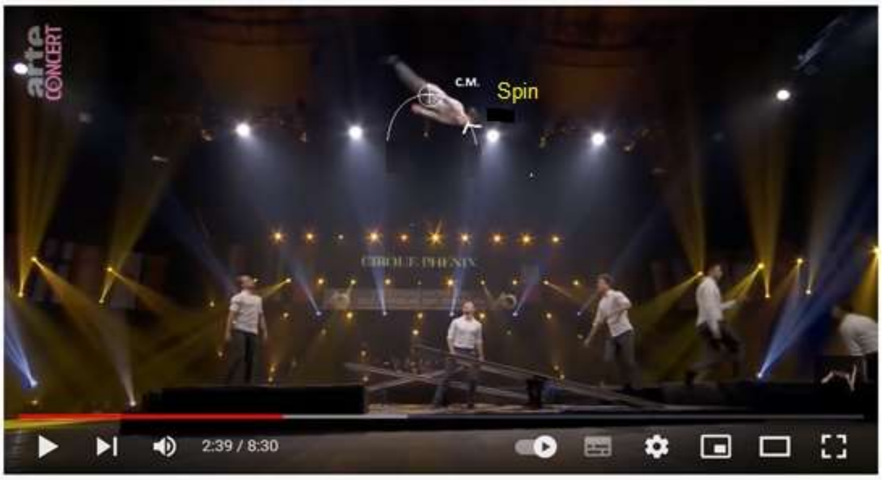

Image 10 - Rotation around the center of mass

In the previous image, it can be seen the artist spinning his body during the jump. It can also be noticed that his body is stretched out (in an extended position as they colloquially say). What is the reason for this choice? This is due to the Moment of Inertia!

When it is spinning, the body has kinetic energy associated with rotation (in addition to translation, since we have an oblique launch). There is a quantity, called Moment of Inertia, which acts in this case. This quantity depends on how the mass of the body is distributed in relation to the axis of rotation. The moment of inertia, represented by the letter I, depends on the body and the axis around which the rotation is being performed, that is, its value only has meaning if it is specified in relation to which axis of rotation the body spins. With that, representing m its mass and r its distance from the axis of rotation, the formal definition of moment of inertia for an isolated particle is:

$$I = mr^2$$

In the case of the human body, the calculation of the Moment of Inertia is a little more complex, but the idea is the same. It is used for the calculation of rotations, when it is applied a Torque or Moment of a force.

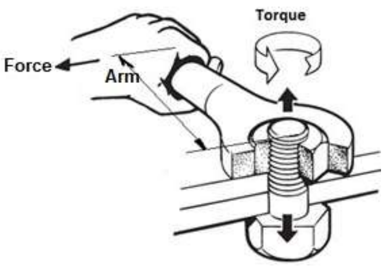

Image 11 – Torque or Moment of a Force

Torque can be calculated by multiplying the force applied, perpendicular to the axis of rotation, by the distance between the force application point and the "pivot point". It is a vector quantity, which can be expressed in a simplified way (scalar) by:

$$\tau = F.d$$

The analogue of Newton's Second Law (F_R=m.a) for rotations is given by:

$$\tau_R = I.\alpha,$$

where τ_R is the resultant torque, I is the moment of inertia and α is the angular acceleration of the body. Thus

$$\alpha = \frac{\tau_R}{I}$$

The smaller the moment of inertia, the greater the angular acceleration (increase in rotation) and the greater the moment of inertia, the smaller the angular acceleration (decrease in rotation).

Remembering that the moment of inertia is given by I=mr², it can be noticed that the greater the distance r, related to the athlete's center of mass (navel), the greater the moment of inertia, therefore the lower the rotation and vice versa. That's why the acrobat stretches his body, to reduce the rotation and have a better control of the action.

Image 12 – Double spin

In another moment, the artist does a double spin in the air. To be able to accomplish this feat, his body must acquire a greater rotation, therefore a greater value for his angular acceleration (α). For this, he shrinks his body, decreasing the distance to the center of mass and, consequently, decreasing the moment of inertia.

Image 13 – Balance and Levers

By the way we see another acrobat running between the weighbridges, not interfering with the stunts. At opportune moments, this artist steps exactly on the support points of the weighbridges. Since the distance is zero, there is no Torque, which causes no rotation.

We can also observe two artists on opposite sides of the weighbridge, in balance. But how is that possible if they both have the same mass?

The fact is that they are located at different distances from the support point. With a greater distance, the artist at the bottom achieves a greater torque, remaining in that position, with the board touching the ground.

Image 14 – Different moments of the spin

In this other image, we observe that the artist shrinks his body at the exit of the jump, while the other artist has his body stretched to reduce the rotation and control the descent. This is often used in ballet, ornamental jump, artistic gymnastics and martial arts such as Aikido, Judo and Jiu-Jitsu. The control of the torque, the moment of inertia, as well as the position of the center of mass, allows the person to control the spin, make less effort and provide us with great spectacles.

Image 15 – Aikido technique known as Kotegaeshi, which causes the body to rotate through twisting the wrist (Professor Huemerson - 1st Dan – Aiki Kaizen/ Rio Claro)

Image 16 – Positioning along the plank

In another moment of the presentation, an athlete lies down on the board. With that, his body is arranged along the board, with his head very close to the balance point of the weighbridge and his feet very far apart. With the application of a force on the opposite side of the weighbridge, caused by the landing of the fellow artist, the body is lifted in different distances, in the same time interval. In this way, the speed of the feet becomes greater than the speed of the head, causing a controlled rotation of the athlete around his center of mass.

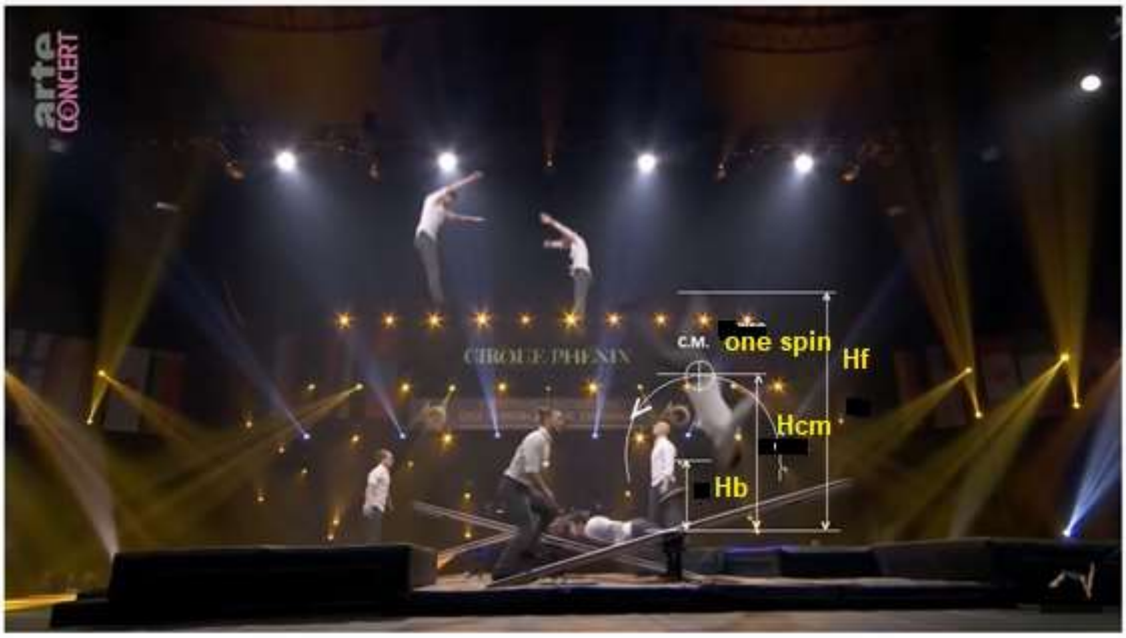

Image 17 – Spin of the athlete who was lying down

Angular Momentum and Rotation

We know that objects rotate, from an electron to a galaxy, passing through gears, pulleys, wheels, athletes... We have seen that torque (τ) is a fundamental quantity in this rotation, as well as the moment of inertia of the body (I).

In the rotation movement, we observe that the bodies can rotate in different situations, as with the propellers and the body of a helicopter, which uses the tail propeller to cause a compensation of this rotation and thus remain stable.

Analyzing this situation and making an analogy with the translational movement, in the rotational movement there is something that does not vary which we call angular momentum (L). In the case of acrobats, we have seen that a body that is rotating can have its speed altered if the moment of inertia of the body is altered, shrinking or stretching the body.

Another explanation that can be used is that this effect is guaranteed by “conservation of angular momentum”. So we can write the angular momentum as

$\vec{L} = I\vec{\omega}$,

where I is the Moment of Inertia and ω is the angular velocity of the body. As $I = mr^2$ and ω=v/r, we have:

$$L = \frac{mr^2 v}{r}$$

$$L = mvr$$

By considering that p is the linear moment given by p = mv

$\vec{L} = \vec{r} x \vec{p}$

The equation shows that the angular momentum, in addition to depending on the angular velocity ω, has the same direction as the angular velocity that can be defined by the right hand rule, since it is a vector product.

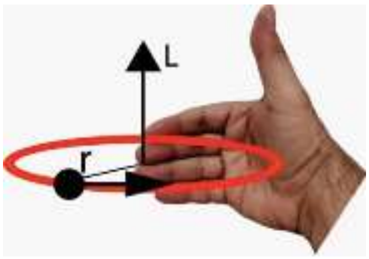

Image 18 – "Right Hand Rule"

Let's think about rotational motion. Once rotation is taking place, if no net torque acts on the body, angular momentum will be conserved. Thus, there is a close relationship between the distance r and the speed of the spin, and these are inversely proportional to each other, something that is very interesting.

Estimation of Energy Expenditure during the Presentation

Based on what was seen earlier, we can estimate that a circus acrobat like this consumes about 2000 J per jump. One calorie corresponds to 4.18 J, therefore, with each jump, about 478 cal (≈ 0.5 kcal) is consumed.

Each jump lasts about 2 seconds and they intersperse the jumps. Considering the small pauses between the jumps and those of the show itself, we can say that each one of them jumps every 5 seconds, on average, during 7 minutes of presentation, which totals around 80 jumps per acrobat. Thus, just for this show, the energy consumption would be 80 x 0.50 = 40 kcal, in just 7 min (420 seconds).

The power is given by:

$$Pot = \frac{\Delta E}{\Delta t}$$

$$Pot = \frac{40{,}000cal}{420s}$$

$$Pot \cong 100\frac{cal}{s}$$

If we take into account the 7 artists who participate in this scale number, the consumption will be 280 kcal, in 7 minutes!

And, we still have the previous body warm-up, the horizontal movement, the brain activity that certainly added more energy expenditure. Incredible, formidable bodies that require a lot of fuel and special preparation!

If the calculations seem complicated, imagine training your body to exhaustion so that it controls everything with such perfection. After all, a small error in this type of acrobatic modality can result in a serious accident. This really is a SHOW!

Final Considerations

The learning of physical concepts can be enhanced with the analysis of interdisciplinary problems, among them, those involving sports practices or, as in this case, circus art. The study that we have just presented proved to be very motivating for the students and also aroused their curiosity about the circus. We have seen that science education (in physics in this case) is fully compatible with education in culture.

We understand, therefore, that the teaching of Physics needs to adapt to the new times and to be consistent with the new model of secondary education. The role of the teacher is, among many others, that of enchanting the student. Topics such as superheroes, circus, martial arts, among many others, can serve as bridges for efficient learning and for the enchantment of young minds.

Finally, it seems to us that this partnership between the University and Basic Education has also proved to be very productive, bringing students closer to the academic environment and to new proposals for work and learning. Certainly, Puríssimo Coração de Maria School will continue its cooperation with the Faculty of Physical Education at UNICAMP, with the Circus Research Group (CIRCUS); with the São Paulo State University (UNESP), through the Scientific Initiation Program for Secondary Education and with the Engineering Nucleus of the University Center of the Hermínio Ometto Foundation - FHO, organizations that together seek to contribute to quality education.

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