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Evaluating Quality of Dance Movements in Bharatanatyam Through Kinematics and Statics

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ABSTRACT

Bharatanatyam, an ancient Indian Classical dance form, emphasizes the clean execution of steps with proper posture, usage of space, and energetic movements and thereby judges movements qualitatively. This paper aims to evaluate how kinematics/statics can determine the quality of a dance move in terms of 'Good' and 'Bad' movement quantitatively. The base hypothesis is that the dancer's body can be considered as a rigid body for easy analysis. Two movements- a one-dimensional jump and a two-dimensional jump- are performed, recorded with calibration sticks and analyzed using Tracker and JupyterLab. However, due to inconsistencies within acceleration due to gravity values this hypothesis can be disapproved. The main takeaways from the experiments were as follows. In the one-dimensional jump the 'Good' movement had a longer duration of free fall, a higher maximum vertical height (jumping 101% of the dancer's height), and a smaller horizontal displacement than the 'Bad' movement. The force exerted by the floor on the dancer in the 'Good' movement was five times the force exerted during the 'Bad' movement. In the two-dimensional motion, the 'Good' movement had a longer duration of free fall, a higher maximum vertical height (jumping 90% of the dancer's height), and a larger horizontal displacement than the 'Bad' movement. The force exerted by the floor on the dancer in the 'Good' movement was two times the force exerted during the 'Bad' movement. The value of spring constant in one dimensional motion is four times the value in two-dimensional motion.

Background

Bharatanatyam traces its origins to the ancient temples of Tamil Nadu in South India. Its roots can be found in the Natya Shastra, an ancient treatise on performing arts written by the sage Bharata Muni around 200 BCE to 200 CE. The name "Bharatanatyam" itself is derived from a combination of "Bha" (Bhava, meaning emotion), "Ra" (Raga, meaning melody), and "Ta" (Tala, meaning rhythm), encapsulating the essence of the dance form, which seamlessly blends these elements. It is a devotional dance characterized by expressive mime, elaborate hand gestures, and sculpturesque poses. Bharatanatyam encompasses three key facets: Nritta, representing pure dance and the presentation of rhythm through graceful body movements; Abhinaya, the art of facial expression; and Nritya, a combination of Nritta and Abhinaya (InsightsIAS).

During the initial years of a dancer's tutelage, the primary focus is on Nritta, and perfecting symmetric and geometrically appealing aesthetic poses and movements. Footwork is given prominence, with the beat or "taal" serving as the guiding factor for synchronization between rhythm and time. The meticulous practice of basic steps, rhythm, coordination, and discipline in Nritta is essential for developing a well-rounded and proficient Bharatanatyam dancer. Later, Nritya and Natya (Abhinaya) are highlighted to convey emotions and tell stories through facial expressions, transforming the performance into an immersive experience. A teacher or critic usually classifies a good dancer based on the accumulation of all three components of Bharatanatyam. They emphasize the clean execution of steps with proper posture and balance, usage of space, and graceful, energetic movements. A dancer can only recognize all the nuances of the art form after years of dedicated training.

Introduction

Usually Bharatnatyam dancers start learning Bharatanatyam at a very young age and are often intrigued by the science behind the art form. They wonder why squatting a little lower, bending a little further, and leaping a little higher made the dance look more aesthetically pleasing and how the dancers made the complex jumps, turns, and steps seem so easy. Eventually, many realize how directly related those concepts are to Bharatanatyam. The process of measuring the appeal of a dancer's Nritya and Natya is very subjective; however, the quality of Nritta depends on various physical factors such as time spent completing a movement, the initial and final velocity of the dancer, the torque and forces required for movements, and so on. Thus, this enables the use of various concepts in physics, such as Newton's laws of motion and the study of kinematics, to analyze, identify, and uncover the 'quality of the movement' performed. Understanding the mechanics behind the dance not only satisfies intellectual curiosity but also aids in injury prevention and enhances performance. For instance, recognizing the role of center of mass and balance can help a dancer avoid unnecessary strain on joints and muscles. Additionally, understanding the physics of rotational movements can improve the execution of spins and turns, making them more controlled and visually appealing.

This paper aims, firstly, to understand and analyze movements in Bharatanatyam through a physical lens. Thereafter, it aims to explain the dance movements and suggest ways to improve the quality of dance based on a purely physical aspect. It relates feedback often given by teachers such as "bend your knees more," "focus on maintaining balance through the core," "ensure your jumps are light and soft," or "jump higher" to its physical considerations. Through the physical understanding of the dance form, we can further appreciate the importance of the feedback given to dancers. This paper aims to add a solely physical and aesthetic dimension to the observation and analysis of the quantitative movements. However, it does not claim that a purely physical foundation is a replacement for training and learning the art form. Bharatanatyam is an extremely complex dance form that can only be perfected through years of rigorous and disciplined training. Physics only acts as another medium to evaluate the art form. The integration of scientific principles can enrich the dancer's understanding and execution, but the essence of Bharatanatyam remains deeply rooted in its cultural, spiritual, and emotional expression, which cannot be quantified solely by physical laws.

Exploring this is for the Bharatanatyam dance community, as the insights derived from this research could revolutionize the training and assessment processes. By introducing quality feedback systems, dancers could receive precise, objective evaluations of their Nritta, enabling more targeted improvements. This advancement could also inspire teachers to integrate scientific methodologies into their traditional assessment techniques, enhancing the accuracy and effectiveness of their feedback. Moreover, in an industry long dominated by subjective evaluations, this research could foster a paradigm shift in how a dancer's skill and performance quality are analyzed. This objective analysis could lead to standardized benchmarks for evaluating dancers, making the training process more consistent and transparent. Additionally, it could have broader implications, such as improving injury prevention strategies and optimizing performance techniques. Overall, this research has the potential to significantly impact the Bharatanatyam dance industry, providing valuable tools and insights that could elevate the art form to new heights.

Research Question and Hypothesis

The experimental question this research paper aims to answer is: "What are the quantifiable explanations for various movements in Bharatanatyam, and to what extent can we evaluate the quality of dance movements using kinematics and statics?" This research focuses on two core movements in Bharatanatyam: the 'tuck jump' and the 'side jump', which are further categorized as one-dimensional and two-dimensional movements, respectively. Both movements are analyzed from kinematics and statics perspectives.In this analysis, the body is assumed to act as a rigid body or a point mass, located at the center of mass. Additionally, the body is considered to function as a spring system, allowing for the calculation of the spring constant and the force exerted by the feet contributing to the dance movements. It is hypothesized that the spring constant k for the side jump will be approximately half of that for the tuck jump.

This paper aims to compare technically accurate movements, referred to as 'Good', with movements that include common Nritta errors made by Bharatanatyam dancers, referred to as 'Bad'', from a physical standpoint, and gather sufficient data to be able to distinguish between the two movements using only physical parameters. The paper follows the approach of the paper we are referencing (Ganesh et al., 2022) and improves upon the data collection process with by collecting data points at a higher rate and examines what the value of spring constant k would be in both one dimensional and two-dimensional movements.

Methods

The following measures and steps were undertaken to conduct the experiment to obtain, analyze and compare data.

1. Recorded videos of the 'Good' and 'Bad' movements for both motions at a normal recording speed on an IPhone 13 against a white wall. Measured horizontal and vertical distances from the dancer's body and used a bright colored sticky note on the center of the dancer's body (representative of dancer's center of mass), at the knees, and at the feet.
2. Recorded another video of a jump without crouching the knees to get a visual representation of free fall movement of the dancer without an extra force component contributed by crouching of the legs.
3. Upload the recorded video files onto 'Tracker' software (Brown et al., 2009) . Chose the start and end frame according to the duration of the movement and changed the frame rate to 30 fps.
4. Used the axis tool to mark X and Y position indicating time (in seconds) and vertical positions respectively. Set the origin as the point between the dancer's feet at the start of the movement.
5. Used calibration sticks- calibration stick A to measure horizontal distance (in meters) and calibration stick B to measure vertical distance (in meters) between the ground and highest position attained- to accurately track vertical and horizontal displacement of dancer.
6. Created a Point Mass 'A' indicating the dancer's center of mass and tagged its position for each frame of the video. Created point mass 'B' and 'C' at the knees and point masses 'D' and 'E' at the feet to analyze the contraction and expansion of the feet thereby acting as an extra force to the dancer.

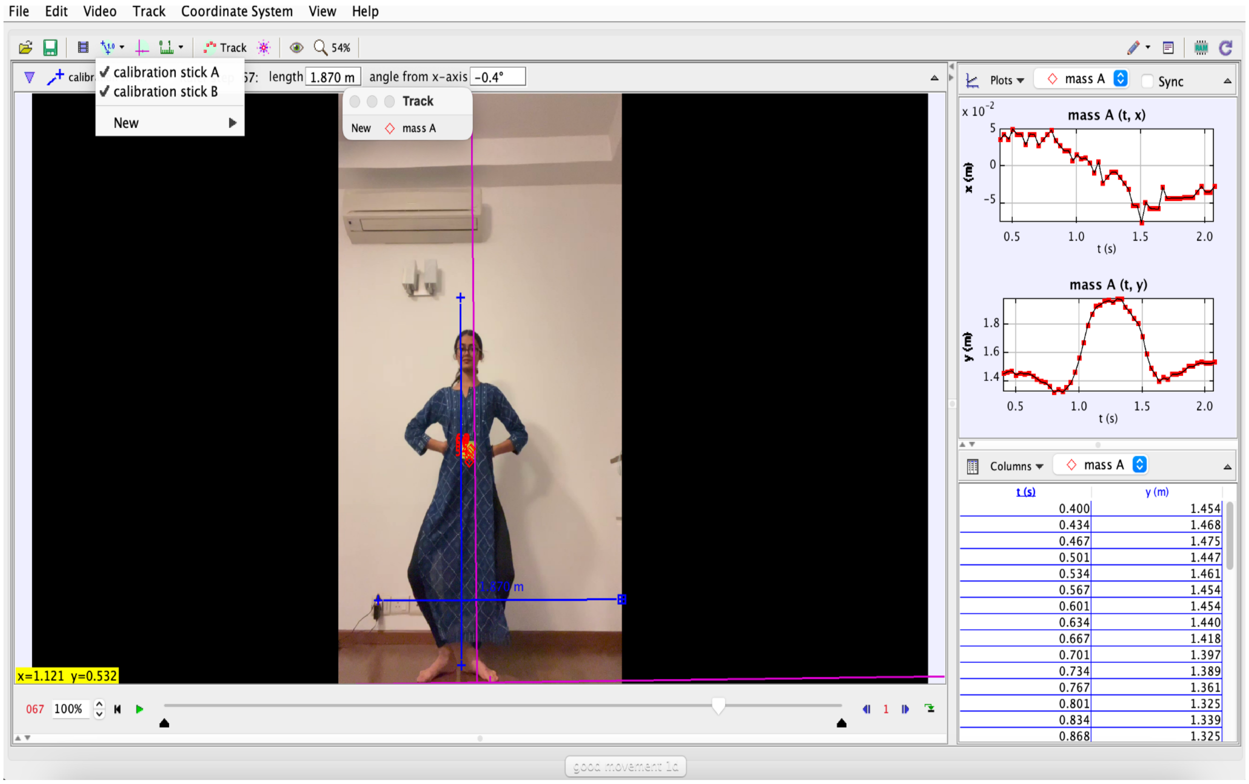

Figure 1. Graph generated on Tracker by manually tracking point mass A for Good movement in one-dimensional movement.

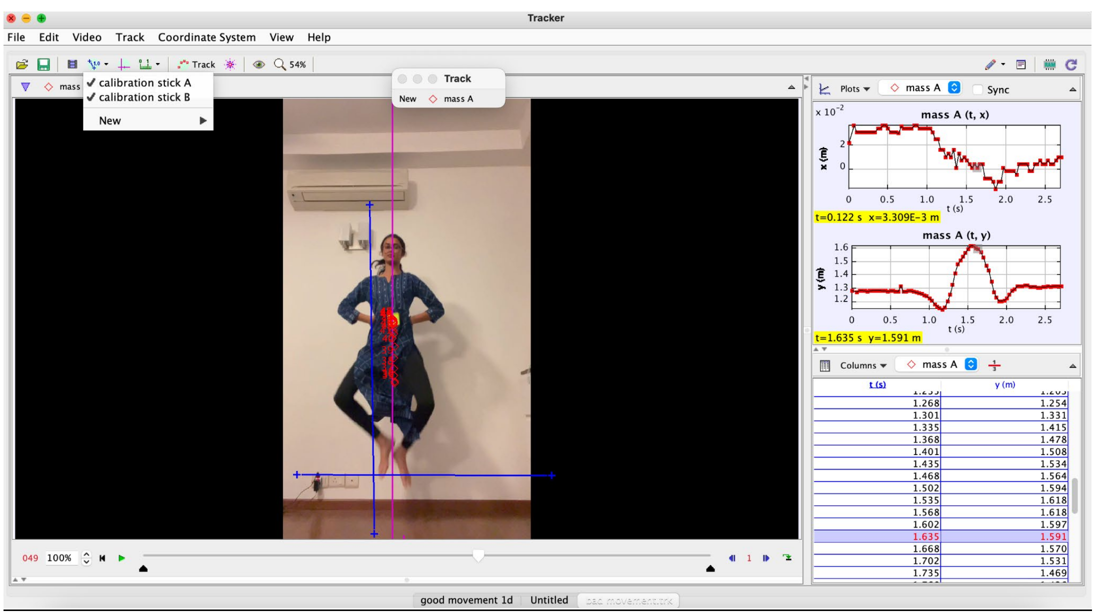

Figure 2. Graph generated on Tracker by manually tracking point mass A for Bad movement in one-dimensional movement.

7. Divided the data into three different stages. The first stage included the period from the launch phase till the moment when the legs just leave the ground where normal force and gravitational force act on the dancer. The second stage included the period the dancer was in the air which can be divided into two phases- the period when the dancer moves in the positive y direction and reaches the highest vertical position, and the return to the ground as a free fall. Lastly the third stage included the point from when the feet just touch the ground again until the body is at the lowest position.
8. Transferred the horizontal and vertical position vs time data, as shown in Figures 1 and 2 onto JupyterLab to produce graphs for Displacement vs Time, Velocity vs Time, Acceleration vs Time, and Force vs Time for each stage for the good and bad movements. Reversed engineered the data in the reference paper (Ganesh et al., 2022) using Web Plot Digitizer and computed the graphs for the Displacement vs time to be compared with the published results. Based on this, we formed a comprehensive comparison between the reference paper and the data collected in our experiments.
9. Used the free fall of a tennis ball to verify the accuracy of the methodology outlined above and to calculate the value of acceleration due to gravity. Calculated the value of acceleration due to gravity using the following equation:
$$y = ut + \frac{1}{2}gt^2$$
Calculated the value of g or acceleration due to gravity to be 9.12 ms^{-1}.
10. Considered the body to be constituted of a spring to explain the motion of the tuck jump and side jump and calculated the value of spring constant from the equation: $F = -ky$, where F is spring force and y is the position of the body in vertical direction. Hypothesized value of k to be close to half for the side jump as of its value for tuck jump.
11. Utilized Newton's laws & kinematics equations to derive insights from the data and seek differentiated trends between the 'Good' and 'Bad' movements.

Results and Findings

The one dimensional and two-dimensional movements were analyzed separately on the basis of time, position, and acceleration of the 'Good' and 'Bad' movements and the force exerted by floor on dancer during the launch phase.

One-Dimensional Motion

Comparison and Contrast of Vertical Movements

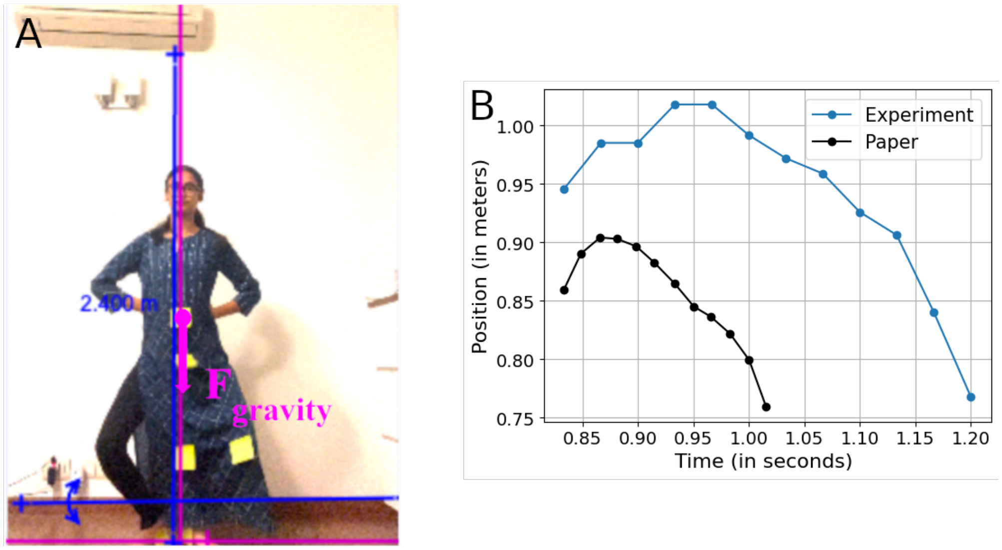

Figure 3. Free body diagram and Vertical Position vs Time graph for the comparison of ‘Good’ one -dimensional movement during the free fall phase. As seen in 3A, $F_{gravity}$ is the force due to gravity that acts on the dancer. In 3B, we see a graphical representation and comparison of the dancer’s vertical displacement over the time between the data from the ‘Experiment’ and the data from the reference ‘Paper’.

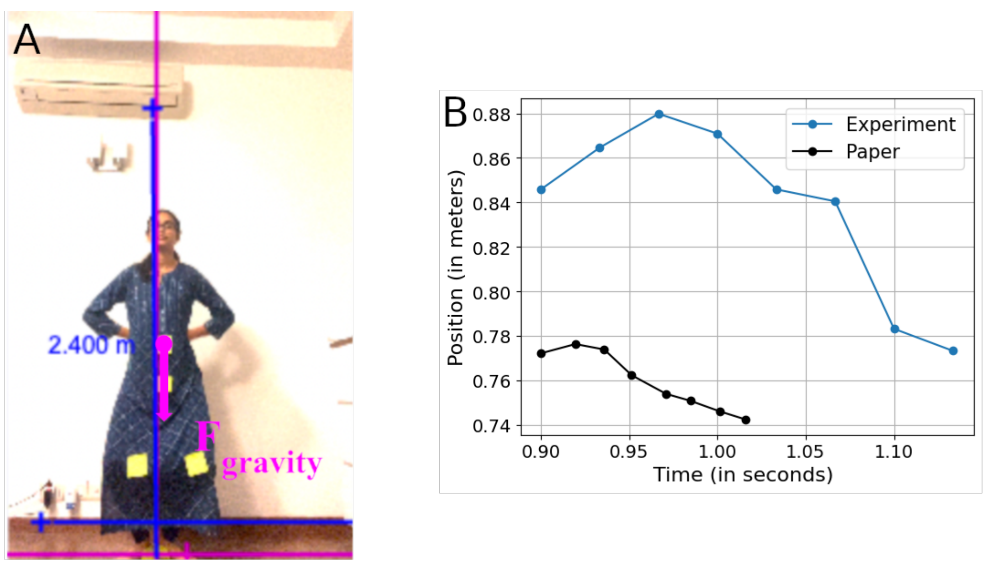

Figure 4. Free body diagram and Vertical Position vs Time graph for the comparison of ‘Bad’ one -dimensional phase during the free fall phase. As seen in 4A, $F_{gravity}$ is the force due to gravity that acts on the dancer. In 4B we see a graphical representation and comparison of the dancer’s vertical displacement over the time between the data from the ‘Experiment’ and the data from the reference ‘Paper’.

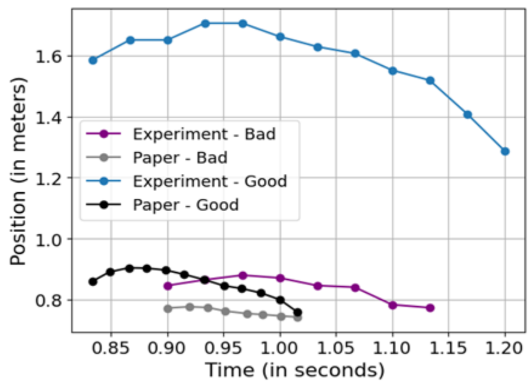

Figure 5. Vertical Position vs Time graph showing stark comparison between both 'Good' and 'Bad' one dimensional movement during the free fall phase. This is an aggregation of both figures 3B and 4B in the same plot for clarity.

Time: Through the analysis of Figure 3B and 4B we can calculate flight time for both the 'Good' and 'Bad' movements. For the 'Good' movement the free fall phase had a total flight time of 0.184 seconds for the reference paper and a total flight time of 0.4 seconds for the experiment (as seen in Figure 3B). The time taken from the maximum height till the end of the free fall is approximately 0.233 seconds. Whereas for the 'Bad' movement the free fall phase had a total flight time of 0.117 seconds for the reference paper and a total flight time of 0. 234 seconds for the experiment (as seen in Figure 3B). The time taken from the maximum height till the end of the free fall is approximately 0.130 seconds. As seen in Figure 5, the dancer remains in the air for a longer period in the 'Good' movement as compared to the 'Bad' movement in both cases. In our experiment, the flight time for the 'Good' movement is almost twice the flight time in the 'Bad movement'.

Position: Through the analysis of Figure 3B and 4B we can calculate the vertical displacement of the dancer from the launch phase to the maximum height as well as from the maximum height until the end of the free fall phase for both the 'Good' and 'Bad' movements.

While considering the 'Good' movement: for the experimental data, the displacement from the initial position of free fall to the maximum height is approximately 0.121meters (in 0.137 seconds) while for the reference paper the displacement is 0.074 meters. The total vertical distance covered for the experimental data is 0.638 meters (in 0.3 seconds) whereas for the reference paper the distance covered is 0.726 meters. In the experiment, the total distance covered is 38.1% of the dancer's height. In the paper, the total distance covered is 43.3% of the dancer's height. As seen in Figure 3B in the experiment the maximum height attained according to the marker at the center of mass of the dancer is 1.706 meters which is 101.8% of the dancer's height. Whereas in the reference paper the maximum height attained according to the marker at the center of mass of the dancer is 1.517 meters which is 90.4% of the dancer's height.

In contrast, while considering the 'Bad' movement: for the experimental data, the displacement from the initial position of free fall to the maximum height is approximately 0.042 (in 0.067 seconds) meters while for the reference paper the displacement is 0.013 meters. The total vertical distance covered for the experimental data is 0.414 meters (in 0.234 seconds) whereas for the reference paper the distance covered is 0.359 meters. In the experiment, the total distance covered is 24.7 % of the dancer's height. In the paper, the total distance covered is 21.4% of the dancer's height. As seen in Figure 3B in the experiment the maximum height attained according to the marker at the center of mass of the dancer is 1.475 meters which is 87.9% of the dancer's height. Whereas in the reference paper the maximum height attained according to the marker at the center of mass of the dancer is 1.302 meters which is 77.6% of the dancer's height.

There is more total vertical displacement in the 'Good' movement in comparison to the 'Bad' movement. The time taken for the dancer to reach its maximum height from the launch phase as well as the time taken for the body from the maximum height till end of free fall phase is longer for the 'Good' movement than for the 'Bad' movement. In comparison to the data points in the paper, the flight time and maximum height are higher for the experimental data in the 'Good' and 'Bad' movements.

<u>Acceleration:</u> While calculating the acceleration due to gravity, only a few data points should be considered. To calculate the most accurate results for acceleration, only the data points where the dancer's legs are continuously bent should be considered. This is because the location of the center of mass of the dancer's body may be shifting if the dancer is changing their leg position.

Comparison and Contrast of Horizontal Movements

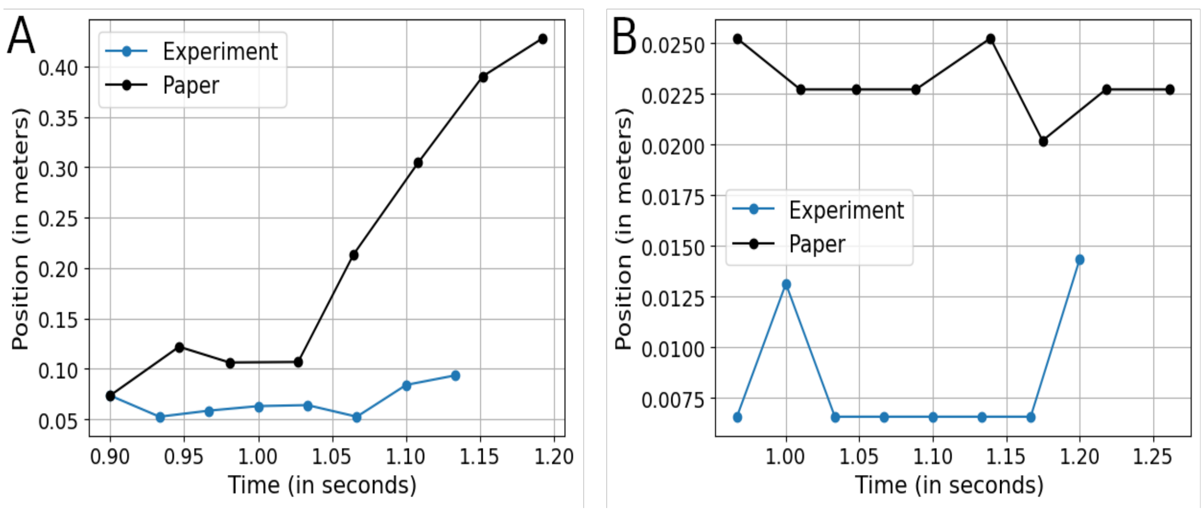

Figure 6. Horizontal Position vs Time graphs for the free fall phase of one-dimensional movement. Figure 6A shows the dancer's horizontal position vs time for the 'Good' movement and Figure 6B shows the dancer's horizontal position vs time for the 'Bad' movement.

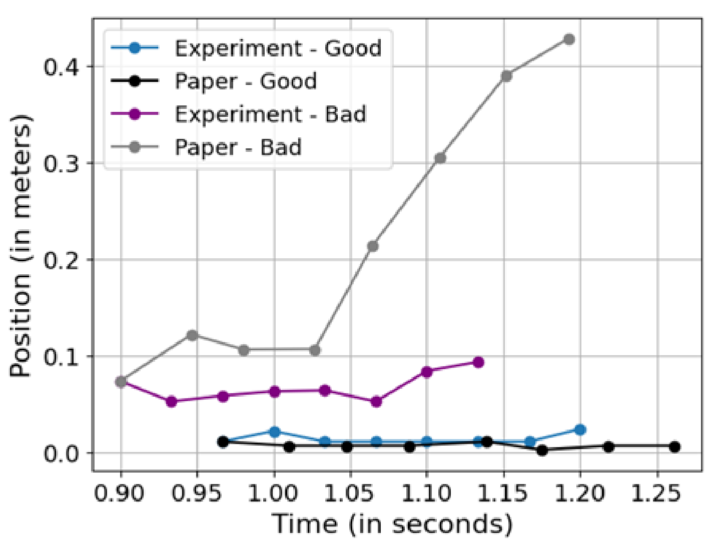

Figure 7. Horizontal Position vs Time graph showing stark comparison between both 'Good' and 'Bad' one dimensional movement during the free fall phase. This is an aggregation of both figures 3B and 4B in the same plot for clarity.

As seen in Figure 6A, representing the 'Good' movement: for the experiment the spread of the horizontal position during the free fall phase is between 0.011 and 0.022 meters and for the reference paper the spread is between 0.033 and 0.042 meters. Thus, there is barely any displacement in the horizontal position of the dancer in the 'Good' movement. Approximately, an average displacement of 0.016 meters.

As seen in figure 6B, representing the 'Bad' movement: for the experiment the spread of the horizontal position during the free fall phase is between 0.058 and 0.093 meters and for the reference paper the spread is between 0.043 and 0.079 meters. Thus, there is more displacement in the horizontal position of the dancer in the 'Bad' movement. Approximately, an average displacement of 0.075 meters. The difference in the horizontal displacements in the 'Good' and 'Bad' movements can clearly be seen in Figure 7.

Impulse Calculations in the Launch Phase

We can calculate the change in momentum using the change in velocity to find the net force exerted on the dancer by the floor. We use the Impulse- momentum theorem equation to calculate the value of the force. The equation is as follows:

$$F\Delta t = m\Delta v$$

For the 'Good' movement, the mass ($m = 47.0\ kg$) of the dancer, along with the change in velocity ($\Delta v = 0.83 m/s$), and the time ($\Delta t = 0.033\ seconds$) over which the velocity increased, can be plugged into the equation to get the net force (F) Newtons exerted by the floor on the dancer as:

$$F(0.033) = 47(0.83)$$
$$\Rightarrow F = \frac{47(0.83)}{0.033}$$
$$\Rightarrow F = 1182N$$

Similarly, for the 'Bad' movement, the mass ($m = 47.0\ kg$) of the dancer, along with the change in velocity ($\Delta v = 0.16 m/s$), and the time ($\Delta t = 0.033\ seconds$) over which the velocity increased, can be plugged into the equation to get the net force ((F) Newtons exerted by the floor on the dancer as:

$$F(0.033) = 47(0.16)$$
$$\Rightarrow F = \frac{47(0.16)}{0.033}$$
$$\Rightarrow F = 227N$$

Thus, we can conclude that in the 'Good' movement the force exerted by the floor on the dancer is more than it is in the 'Bad' movement. In the 'Good' movement the force is approximately 25 times the mass of the dancer whereas in the 'Bad' movement it is only 5 times the mass of the dancer. Hence the force exerted in the 'Good' movement is 5 times the force exerted in the 'Bad' movement. Now, if we were to consider the dancer's body as a rigid spring, using these values of force and maximum height attained we can calculate the value of spring constant 'k' using the equation:

$$F = -ky$$

For the ‘Good’ movement the value is calculated as:

$$k = \frac{1182}{1.704}$$
$$k = 693\ N/m$$

For the ‘Bad’ movement the value is calculated as:

$$k = \frac{227}{1.475}$$
$$k = 153\ N/m$$

Two-Dimensional Motion

Comparison and Contrast of Vertical Movements

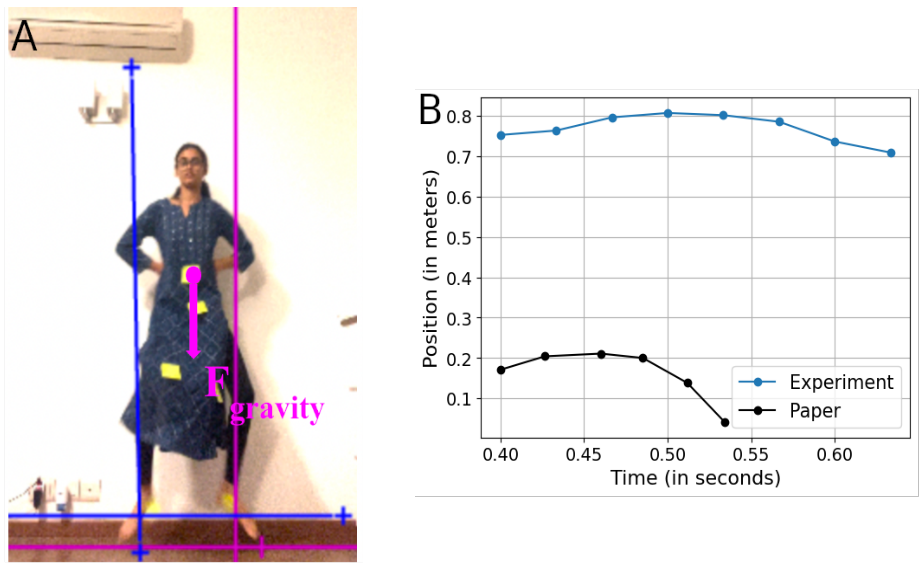

Figure 8. Free body diagram and Vertical Position vs Time graph for the comparison of ‘Good’ two -dimensional movement during the free fall phase. As seen in 8A, F_{gravity} is the force due to gravity that acts on the dancer. In 8B we see a graphical representation and comparison of the dancer’s vertical displacement over the time between the data from the ‘Experiment’ and the data from the reference ‘Paper’.

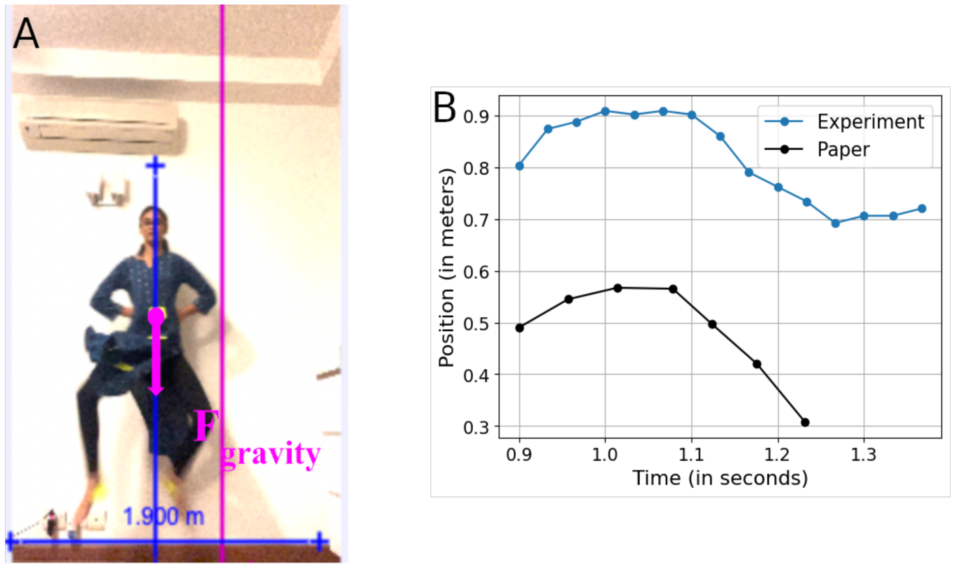

Figure 9. Free body diagram and Vertical Position vs Time graph for the comparison of 'Bad' two -dimensional phase during the free fall phase. As seen in 9A, F_{gravity} is the force due to gravity that acts on the dancer. In 9B we see a graphical representation and comparison of the dancer's vertical displacement over the time between the data from the 'Experiment' and the data from the reference 'Paper'.

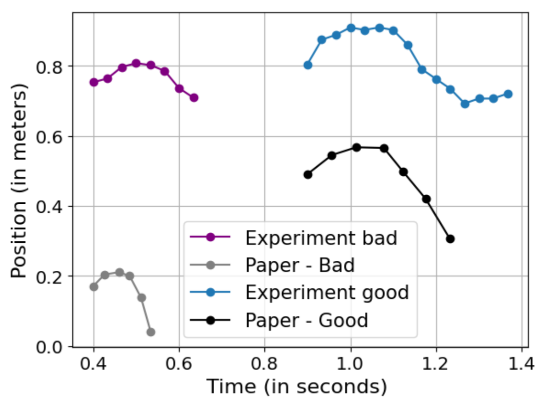

Figure 10. Vertical Position vs Time graph showing stark comparison between both 'Good' and 'Bad' two dimensional movements during the free fall phase. This is an aggregation of both figures 3B and 4B in the same plot for clarity.

<u>Time:</u> Through the analysis of Figure 8B and 9B we can calculate flight time for both the 'Good' and 'Bad' movements. For the 'Good' movement the free fall phase had a total flight time of 0.332 seconds for the reference paper and a total flight time of 0.467 seconds for the experiment (as seen in Figure 8B). The time taken from the maximum height till the end of the free fall is approximately 0.27 seconds. Whereas for the 'Bad' movement the free fall phase had a total flight time of 0.134 seconds for the reference paper and a total flight time of 0. 233 seconds for the experiment (as seen in Figure 9B). The time taken from the maximum height till the end of the free fall is approximately 0.167 seconds. As seen in Figure 5, the dancer remains in the air for a longer period in the 'Good' movement as

compared to the ‘Bad’ movement. Thus, in the experiment the flight time for the ‘Good’ movement is almost twice the flight time in the ‘Bad movement’.

<u>Position:</u> Through the analysis of Figure 8B and 9B we can calculate the vertical displacement of the dancer from the launch phase to the maximum height as well as from the maximum height until the end of the free fall phase for both the ‘Good’ and ‘Bad’ movements.

While considering the ‘Good’ movement: for the experimental data, the displacement from the initial position of free fall to the maximum height is approximately 0.176 (in 0.233 seconds) while for the reference paper the displacement is 0.125 meters. The total vertical distance covered for the experimental data is 0.34 meters (in 0.27 seconds). In the experiment, the distance from initial position of free fall to maximum height covered is 10.5% of the dancer’s height. In the experiment the maximum height attained according to the marker at the center of mass of the dancer is 1.524 meters which is 90.9% of the dancer’s height .Whereas in the reference paper the maximum height attained according to the marker at the center of mass of the dancer is 0.951 meters which is 56.7% of the dancer’s height.

In contrast, while considering the ‘Bad’ movement: for the experimental data, the displacement from the initial position of free fall to the maximum height is approximately 0. 092 meters (in 0.1 seconds) while for the reference paper the displacement is 0.067 meters. The total vertical distance covered for the experimental data is 0. 192 meters (in 0. 167 seconds). In the experiment, the distance from initial position of free fall to maximum height covered is 5.487% of the dancer’s height. In the experiment the maximum height attained according to the marker at the center of mass of the dancer is 1.353 meters which is 80.7% of the dancer’s height. Whereas in the reference paper the maximum height attained according to the marker at the center of mass of the dancer is 0.353 meters which is 21.1% of the dancer’s height.

Thus, the total vertical displacement is more in the ‘Good’ movement in comparison to the ‘Bad’ movement. The time taken for the dancer to reach its maximum height from the launch phase as well as the time taken for the body from the maximum height till end of free fall phase is more for the ‘Good’ movement than for the ‘Bad’ movement. In comparison to the data points in the paper, the flight time and maximum height are higher for the experimental data in the ‘Good’ and ‘Bad’ movements.

Comparison and Contrast of Horizontal Movements

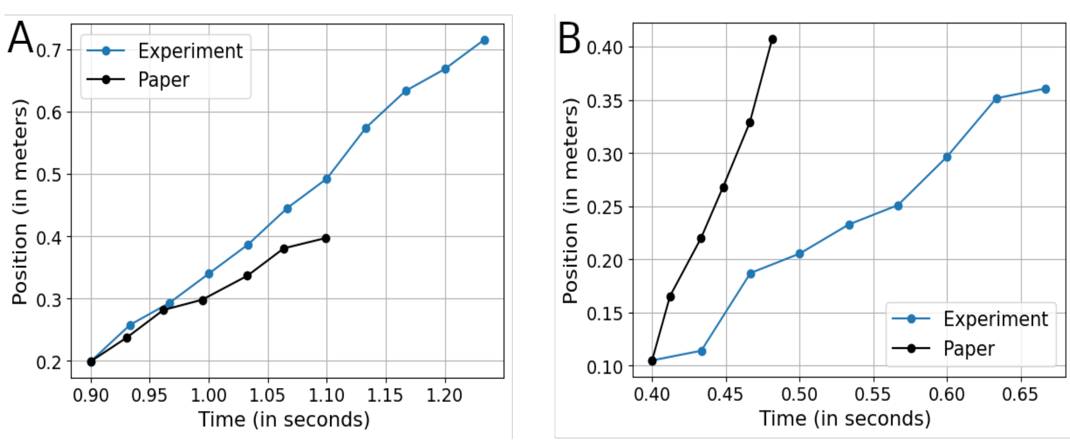

Figure 11. Horizontal Position vs Time graphs for the free fall phase of two-dimensional movement. Figure 11A shows the dancer’s horizontal position vs time for the ‘Good’ movement and Figure 11B shows the dancer’s horizontal position vs time for the ‘Bad’ movement.

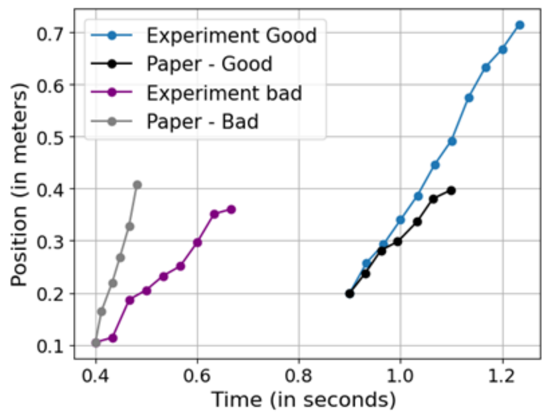

Figure 12. Horizontal Position vs Time graph showing stark comparison between both 'Good' and 'Bad' two dimensional movements during the free fall phase. This is an aggregation of both figures 3B and 4B in the same plot for clarity.

As seen in Figure 11A, representing the 'Good' movement: for the experiment the spread of the horizontal position during the free fall phase is between 0.199 and 0.715 meters which is a total of 0.516 meters. In the paper the displacement during the free fall phase is 0.27 meters. Thus, there is a large displacement in the horizontal position of the dancer in the 'Good' movement. There is approximately a total displacement of 0.704 meters throughout the entire movement.

As seen in figure 11B, representing the 'Bad' movement: for the experiment the spread of the horizontal position during the free fall phase is between 0.104 and 0.360 meters which is a total of 0.256 meters. In the paper the displacement during the free fall phase is 0.3 meters. Thus, there is lesser displacement in the horizontal position of the dancer in the 'Bad' movement. Approximately, there is a total displacement of 0.29 meters.

The difference in the horizontal displacements in the 'Good' and 'Bad' movements can clearly be seen in Figure 12. The horizontal displacement is significantly more in the 'Good' movement compared to the 'Bad' movement. In addition, the change in the horizontal position in the 'Bad' movement takes place in a shorter period over which the free fall phase took place compared to the 'Good' movement.

Impulse Calculations in the Launch Phase

We can calculate the change in momentum using the change in velocity to find the net force exerted on the dancer by the floor. We use the Impulse- momentum theorem equation to calculate the value of the force. The equation is as follows:

$$F\Delta t = m\Delta v$$

For the 'Good' movement, the mass ($m = 47.0\ kg$) of the dancer, along with the change in velocity ($\Delta v = 0.18 m/s$), and the time ($\Delta t = 0.033\ seconds$) over which the velocity increased, can be plugged into the equation to get the net force (F) Newtons exerted by the floor on the dancer as:

$$F(0.033) = 47(0.18)$$
$$\Rightarrow F = \frac{47(0.18)}{0.033}$$
$$\Rightarrow F = 257N$$

Similarly, for the 'Bad' movement, the mass ($m = 47.0\ kg$) of the dancer, along with the change in velocity ($\Delta v = 0.13 m/s$), and the time ($\Delta t = 0.033\ seconds$) over which the velocity increased, can be plugged into the equation to get the net force (F) Newtons exerted by the floor on the dancer as:

$$F(0.033) = 47(0.13)$$
$$\Rightarrow F = \frac{47(0.13)}{0.033}$$
$$\Rightarrow F = 185N$$

Thus, we can conclude that in the 'Good' movement the force exerted by the floor on the dancer is more than it is in the 'Bad' movement. In the 'Good' movement the force is approximately 6 times the mass of the dancer whereas in the 'Bad' movement it is only 3 times the mass of the dancer. Hence the force exerted in the 'Good' movement is 2 times the force exerted in the 'Bad' movement. Now, if we were to consider the dancer's body as a rigid spring, using these values of force and maximum height attained we can calculate the value of spring constant k using the equation:

$$F = -ky$$

For the 'Good' movement the value is calculated as:

$$k = \frac{257}{1.525}$$
$$k = 168\ N/m$$

For the 'Bad' movement the value is calculated as:

$$k = \frac{185}{1.353}$$
$$k = 136\ N/m$$

Animation Of Motion

To be able to visualize the data we collected in the data collection process, animations for each of the 'Good and 'Bad' 1D and 2D movements were created. Below are three frames from the 2D motions:

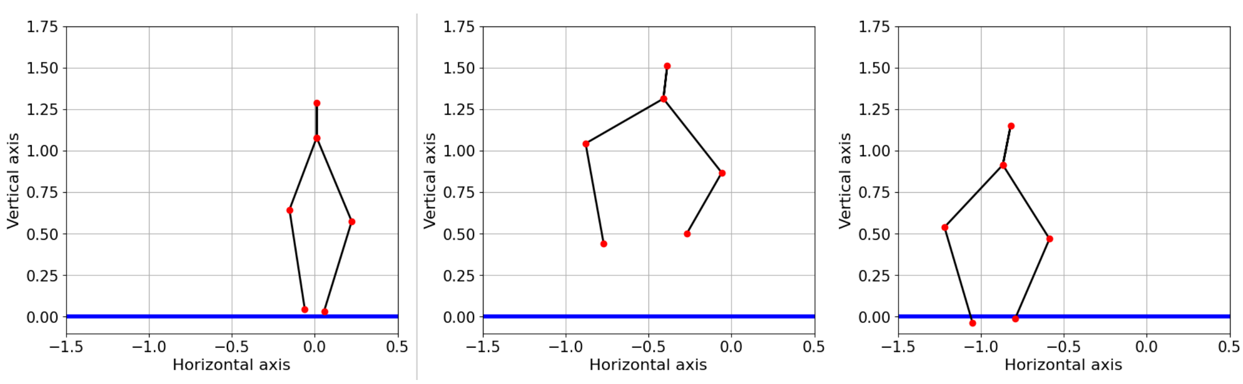

Figure 13. It shows three frames of the animation of the 2D 'Good' motion jump.

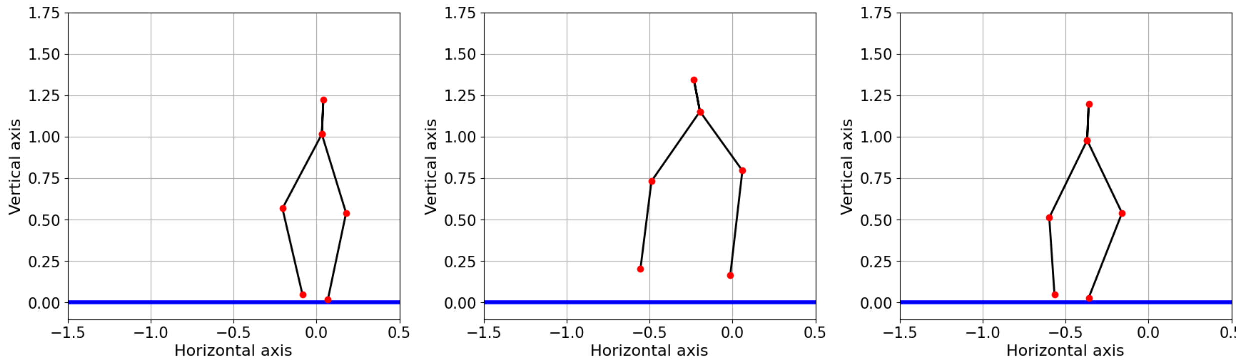

Figure 14: It shows three frames of the animation of the 2D 'Bad' motion jump.

The rest of the animations can be viewed at https://github.com/metalcycling/bharatanatyam for not only the 2D but also the 1D motion.

Discussion

Key Outcomes

The main takeaways regarding an ideal movement in Bharatanatyam were as follows:

One-Dimensional Motion

Firstly, while comparing the vertical motion for both the 'Good' and 'Bad' movements, we can conclude that the total flight time taken is longer for the 'Good' movement than the 'Bad'. Not only is the period for the free fall phase longer but also for the launch phase. This signifies that dancers should bend their knees more to be able to jump at a higher height and stay in the air for a longer period in order to have a technically 'ideal' movement that is aesthetically pleasing. Moreover, in the 'Good' movement the maximum height attained according to the marker at the center of mass of the dancer is 1.706 meters which is 101.8% of the dancer's height. On the other hand, the maximum height attained according to the marker at the center of mass of the dancer for the 'Bad' movement is 1.475 meters which is 87.9% of the dancer's height. In the 'Good' movement the total distance covered in the motion is approximately 38.1% of the dancer's height and in the 'Bad' movement it is only 24.7 % of the dancer's height. Hence, we can conclude that for a movement to be 'ideal' the dancer must attain a higher maximum height (around 80-90% of their height according to the center of mass) and should aim to cover around 35-40% of their body height in their jump. Covering a lower maximum height and lower total distance around 20-25% of the dancer's height would result in a lack of technical and aesthetic skill of the movement.

While comparing the horizontal movement in both the datasets, the average displacement for the 'Good' movement was approximately 0.016 meters. While for the 'Bad' movement it was 0.075 meters which is almost 5 times the displacement in the 'Good' movement. Thus, we can conclude that the dancer minimizes any horizontal movement during the launch phase; to perform a technically correct movement and the dancer should attempt to make their jump as purely vertical as possible. This helps maintain the technical aspect as well as an aesthetic aspect as symmetry of the motion is maintained which shows the true skill of a dancer.

From analyzing the launch phase, we can conclude that in the 'Good' movement the force exerted by the floor on the dancer is more than it is in the 'Bad' movement. In the 'Good' movement the force is approximately 25 times the mass of the dancer whereas in the 'Bad' movement it is only 5 times the mass of the dancer. Hence the force exerted in the 'Good' movement is 5 times the force exerted in the 'Bad' movement. We can hypothesize that due to the force being greater in the 'Good' movement, the dancer is able to attain a higher height as compared to the 'Bad' movement. Hence a dancer must aim to bend lower and maximize the force acting on them by the floor by exerting maximum pressure on the ground while launching into the free fall phase. Hence, a firmer movement will result in the 'ideal' movement rather than a light-footed manner lacking energy and power.

Two-Dimensional Motion

Firstly, while comparing the vertical motion for both the 'Good' and 'Bad' movements, we can conclude that the total flight time taken is longer for the 'Good' movement than the 'Bad'. Not only is the period for the free fall phase longer but also for the launch phase. The total time taken in the 'Good' movement was 0.467 seconds and 0.233 seconds for the 'Bad' movement which is almost half the time taken in the 'Good' movement. A similar conclusion can be made that the dancers should bend their knees more to be able to jump at a higher height and stay in the air for a longer period to have a technically 'ideal' movement. Moreover, in the 'Good' movement the maximum height attained according to the marker at the center of mass of the dancer is 1.524 meters which is 90.9% of the dancer's height. On the other hand, the maximum height attained according to the marker at the center of mass of the dancer is 1.353 meters which is 80.7% of the dancer's height. This indicates that the dancer should aim to maximize their vertical distance covered during the jump to perform it accurately.

While comparing the horizontal movement in both the datasets, there is approximately a total displacement of 0.704 meters throughout the 'Good' movement. Whereas for the 'Bad' movement there is a total displacement of 0.29 meters. Hence, we can conclude that while maintaining the dancer's vertical position the dancer must also focus on covering horizontal distance while being airborne for a more technical and skilled 'ideal' motion. However, the dancer must prioritize jumping higher than the horizontal distance covered.

From analyzing the launch phase, we can conclude that in the 'Good' movement the force exerted by the floor on the dancer is more than it is in the 'Bad' movement. In the 'Good' movement the force is approximately 6 times the mass of the dancer whereas in the 'Bad' movement it is only 3 times the mass of the dancer. Hence the force exerted in the 'Good' movement is 2 times the force exerted in the 'Bad' movement. We can hypothesize that due to the force being greater in the 'Good' movement, the dancer is able to attain a higher height as compared to the 'Bad' movement. Hence a dancer must aim to bend lower and maximize the force acting on them by the floor by exerting maximum pressure on the ground while launching into the free fall phase. Hence, a firmer movement will result in the 'ideal' movement rather than a light-footed manner lacking energy and power. Using the analysis of the spring constant for the 'Good' we can notice that the value of k for the one-dimensional motion is almost 4 times the value of $k$for the two-dimensional motion. We can hypothesize that this is due to the fact that both the legs are used in the one-dimensional motion and hence more force is exerted on the feet by the floor as compared to in the two-dimensional motion.

Conclusion

It is important to understand that learning and teaching Bharatanatyam include more than simply the physical analysis of Nritta, in addition to the conclusions made in this work. It takes more than just comprehending the body's geometric constraints and the mathematically perfect ratios through Physics that dancers aim for to evaluate Bharatanatyam. A dancing instructor's or mentor's involvement is essential in helping to put these physical concepts into reality. On the flip side of the quantitative analysis the qualitative way to judge the art form uses parameters such as facial expressions and body language, hand and eye movements, costume and presentation, choreography (technical nuances), selection of the music piece and so on. A dancer has employed physics to its best advantage when they can effectively repeat a motion in the intended way and produce visually beautiful movements. This method of assessing dance, which combines qualitative and quantitative techniques, is a useful complement to the way Bharatanatyam is now practiced. It might even open the door for future research that is primarily applicable to technical aspects of the dance such as Nritta.

The results of the experiment show that kinematics and statics can be used to evaluate Bharatanatyam movements to a considerable degree. Kinematic analysis, motion graphs, and data manipulation were used to obtain numerous important insights that can help dancers improve their technical accuracy. Additionally, the study offered helpful numerical benchmarks that dancers can utilize to reach the "perfect" movement, which is a remarkable advancement in a dance style that has historically been evaluated using qualitative metrics. A drawback of this research, though, is that it only looked at two motions, whereas Bharatanatyam uses a variety of moves. More research on a wider range of motions is required to ascertain whether the quality of Bharatanatyam movements can be reliably assessed using these techniques. Thus, while the paper shows promise, a comprehensive evaluation would require more extensive testing.

This experiment has also called into question the concept that some parts of a dancer's body can be roughly modeled as a rigid body or a basic item. The dancer's center of mass appears to change as they move, which makes it incorrect to characterize their body as a rigid structure, according to the inconsistent results of the calculation of the gravitational constant g from data points gathered throughout the dancer's movement. When the data was restricted to a single stage of the dance, during which the dancer's body and legs maintained a constant position, more precise outcomes were achieved. This result suggests that when analyzing a dancer's movements physically, the dancer's body cannot be approximated as a rigid object.

Future Applications and Expansion

The conclusions and analysis from the research provide helpful insights into how a dancer’s movement’s quality can be judged using Newton's laws and kinematics and statics. Although only two movements- which are the one-dimensional jump and two-dimensional jump- have been considered in this research paper, many more movements such as the spins, jumps on toes and so on can be analyzed to further judge the quality of the dance form altogether. Larger amounts of data also open the opportunity to use machine learning making the analysis process more widespread, accessible and automated.

Additionally, the analysis from the research can be applied to many other fields that incorporate such leg movements and jumps like sports such as basketball, volleyball and athletics. These sports require a comprehensive analysis of motion performed, height attained and so forth to decipher the quality of performance and ways to improve upon the skill. It could even serve beneficial in physical therapy relating to these movements.

Apart from Bharatanatyam and sports the analysis can be used in various other dance forms especially Indian dance forms. For example, in art forms like “Kathak” and Ballet that involve spins, Newton’s laws can be used to calculate angular momentum and rotational torque to gain insights to these movements. The analysis can also be used in dance forms such as “Kuchipudi” and “Odissi” that require jumps and bending leg movements. Moreover, movements in the neck and waist can be analyzed aside from merely leg movements as they are an integral part of many Indian classical dance forms.

Both the launch and landing phase of the movements can be investigated further. This is because disciplines like dance and gymnastics involve specific landing techniques, such as bending the knees or executing a minor rebound. Analyzing these distinct landing methods would be a valuable criterion for assessing the quality of a movement.

In the future, data collection can be improved and refined by collecting data points at a higher rate or using a different method altogether to reduce the jittery motion of the dataset. However, the existing data collection process serves as a useful method to gain insights about a general trend in the movements of the dancers. Furthermore, since the research question addresses Bharatanatyam in its entirety, it is essential to analyze movements involving rotations and a broader range of motions to provide a comprehensive evaluation of how Physics applies to Bharatanatyam. Comparing the same movement across different styles reveals significant variations in the criteria for assessing the performance quality. Although the movements examined in this research are relatively simple and applicable to most

Bharatanatyam styles, future studies that incorporate different movements or hand gestures must carefully consider and adhere to the specific characteristics of each style.

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