Using Newton's Laws to Determine the Quality of Bharatanatyam Dance Movements

Sidhya Ganesh[1] and Subramanian Ramachandran[#]

[1]Interlake High School, Bellevue, WA, USA
[#]Advisor

ABSTRACT

Bharatanatyam, an ancient Indian Classical dance form, places a heavy emphasis on dancers' body positioning and usage of space, categorizing movements as 'Good' or 'Bad' qualitatively. The present experiment investigated the extent to which statics/kinematics can be used to evaluate the quality of a Bharatanatyam dance movement. The declared hypothesis was that the dancer's body could be approximated as a rigid body/simple object, for analysis. Two Bharatanatyam movements, a one-dimensional jump, and a two-dimensional parabolic leap were each performed in a 'Good' and 'Bad' manner, recorded with calibration sticks in the background, and analyzed using Tracker. Inconsistencies within acceleration due to gravity values disproved the hypothesis. However, kinematics/statics comparisons between 'Good' and 'Bad' versions of both movements resulted in the following quantitative takeaways. In the one-dimensional movement, the 'Good' movement had a longer duration of free fall, a higher maximum vertical height, and a smaller horizontal displacement than the 'Bad' movement. The force exerted by the floor on the dancer was around 100 times the dancer's body mass in the 'Good' movement vs. only 72 times in the 'Bad' movement. In the two-dimensional 'Good' movement, the dancer vertically jumped 2.15% of their body height and horizontally jumped 16% of their body height. In the 'Bad' movement, the same values were 0.895% and 21%. Calculating torque during launch revealed that the launch leg in the 'Good' movement was closer to 90° than in the 'Bad' movement. The ratio of horizontal to vertical displacement was also 3 times lower for the 'Good' movement.

Introduction/Background

Background

Bharatanatyam is an ancient South Indian dance with origins tracing back more than 2000 years (*Bharatanatyam | Natyom*, n.d.). The complex form emphasizes three core elements of dance: Natya, Nritta, and Nritya. While Natya & Nritya combine the use of dramatic expressions and storytelling to make performances impactful, Nritta is composed of the pure dance steps of Bharatanatyam (InsightsIAS, 2018). When judging the quality of a Bharatanatyam Dancer, Nritta is highly valued, as it is centered around the effective and precise use of the dancer's body to represent various geometrically aesthetic postures. The first 4-5 years of every Bharatanatyam dancer's journey go into perfecting Nritta, as it is the sole focus to generate a technically accurate dancer. Nritya & Natya are later emphasized through complex pieces that add storytelling to an underlying Nritta base, to help the dancer elevate their performances.

When any critic is asked what makes an ideal Bharatanatyam dancer, their response always includes the fact that the dancer must have sharp and clean technique, with precise control over their body and their usage of space. However many dancers tend to spend several years training and still do not master their Nritta, with movements that aren't aesthetically appealing to a seasoned Bharatanatyam professional. Many Bharatanatyam teachers spend decades training deeply in the dance form before gaining the expertise to recognize small flaws in their students' Nritta.

Introduction

The process of measuring the appeal of a dancer's Nritya and Natya is extremely subjective, however, the analysis of a dancer's Nritta is based on the placement of their body in space, the time spent completing motions, and more physical cues. This raises the question of whether the quality of a dancer's Nritta can be measured and analyzed using objective mechanisms. In Physics, different types of motion can be analyzed, and resulting trends can be determined using a combination of Newton's Laws of Motion and the study of kinematics. This sets up the environment for an interesting exploration into the applications of kinematics and statics in Bharatanatyam and raises the question of whether analyzing Nritta through a physical lens can derive beneficial insights regarding the quality of the movement performed.

It is important to note that this paper is an attempt to explain dance movements through physics, and the takeaways are not prescriptive, but descriptive. For example, teachers usually make remarks such as – "jump higher", "bend your knees sooner", and "focus on jumping to the side as far as you can". These pieces of feedback are extremely beneficial to dancers, and this paper solely seeks to add a purely physical/aesthetic dimension of quantitative observations. Dance is an art form that can only be learned and perfected through repeated practice and solid training. Physics is just one more lens to view dance through, and this paper does not claim that it is a replacement for training and tutelage.

Research Question & Hypothesis

In this research paper, two core Nritta movements in Bharatanatyam will be analyzed. One of these movements is a tuck-jump which can be approached as a one-dimensional movement. The second movement is a side leap, which is one step in a group of jumps called the Payudhal Adavus. This movement can be approached as a two-dimensional movement. This movement is very similar to a Pas de Chat in Ballet. Both movements will be analyzed from a kinematics and statics standpoint in hopes of answering the following experimental question: To what extent can we evaluate the quality of a Bharatanatyam movement using kinematics/statics? The underlying hypothesis is that the dancer's body can be approximated as a rigid body or a simple object (point mass) while analyzing the movement..

The exploration of this question is crucial to the Bharatanatyam dance industry as the insights derived from this research may open the doors to automated quality Nritta feedback & training for dancers in the future. It may also trigger changes in the approach taken by teachers themselves to judge dancers' movements. Most of all, in an industry that has always emphasized subjective feedback, this research may generate a paradigm shift in the manner of analyzing the fragments that determine a dancer's skill and quality of performance. This paper will compare ideal and technically accurate movements, labeled as 'Good' movements, with movements that combine some of the most common Nritta errors Bharatanatyam dancers make, labeled as 'Bad' movements, from a physical standpoint. It will start by highlighting the methodical data collection and experimentation process and then outline the limitations of the research, key takeaways, and possible future considerations/applications.

Methods

To conduct this experiment, the following seven steps were completed to obtain and analyze data:

1. Videotaped 'Good' and 'Bad' movements at normal recording speed, with calibration tape measures in the background, and an easy-to-see sticky note on the center of the dancer's body (representative of the dancer's center of mass).
2. Uploaded video files to Tracker software and changed frame rate to 60 fps and added X (time) & Y (vertical position) axis setting the origin as the point between the dancer's feet at the start of the movement.

3. Overlayed Tracker's calibration sticks on the existing tape measures in the video so that horizontal and vertical displacement could be tracked accurately.
4. Created a Point Mass on the software and tracked it by manually clicking on the center of the sticky note for each frame of the video.

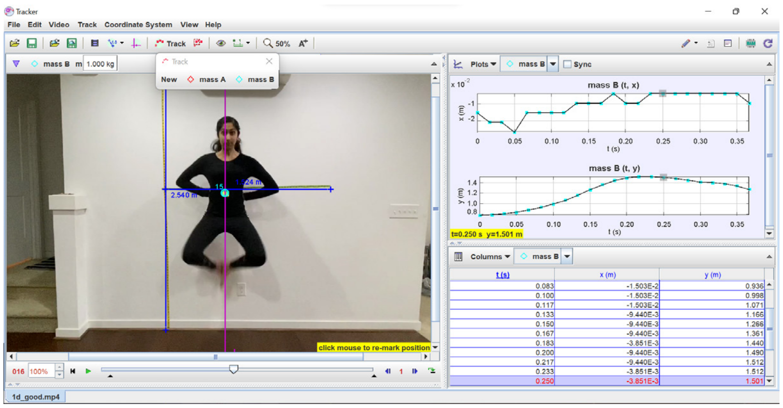

Figure 1. Graph generated by manually tracking mass B (point mass), for 'Good' one-dimensional movement.

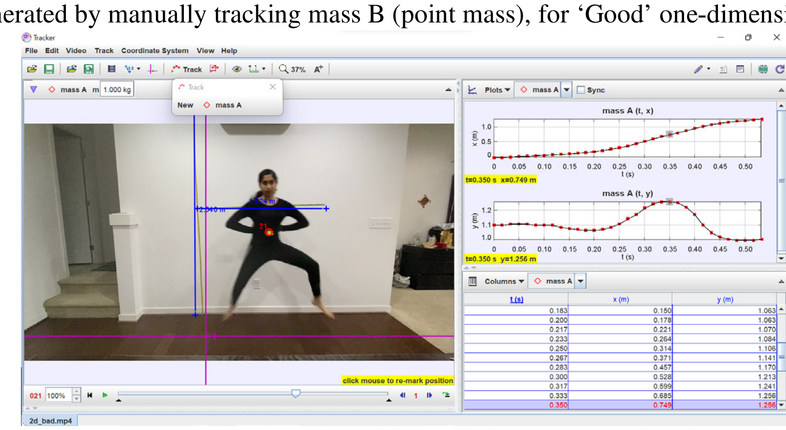

Figure 2. Graph generated by manually tracking mass B (point mass), for 'Bad' two-dimensional movement.

5. Transferred the horizontal and vertical position vs. time data, presented in Figures 1 and 2, onto Excel to manipulate variables to produce velocity vs. time and vertical position vs. horizontal position graphs. The velocity vs. time graphs were derived by setting the graph's X values to the averages of each set of two time intervals and setting the Y values to the instantaneous slope of the position vs. time graph between those two intervals. The slope was found by dividing the change in position by the change in time. For example, taking y as position and t as time, the slope was calculated with the following equation: $(y_2-y_1)/(t_2-t_1)$. It is important to note that all time values should be measured in seconds and all position values in meters.
6. Utilized Newton's laws & kinematics equations to derive insights from the data and seek differentiated trends between the 'Good' and 'Bad' movements. For analysis, one of the key steps was to designate what the different phases of the dancer's movement should be labeled. Starting off, the **launch phase** is when the dancer's lower limbs are still in contact with the ground, where a normal force and the force of gravity act on the dancer. The next phase is the **free fall phase**, where all parts of the dancer's body are out of contact with the ground. This phase can be broken up into two subparts, the first of which is where the dancer's lower limbs are still retracting close to the dancer, where the dancer's center of mass may change as a result. The second of which is where the dancer's legs are tucked in the same position, where the center of mass is approximated to stay the same.
7. Used the free fall of a tennis ball to verify the experimental accuracy of the methodology outlined above. The procedure and takeaways from this step are explained below.

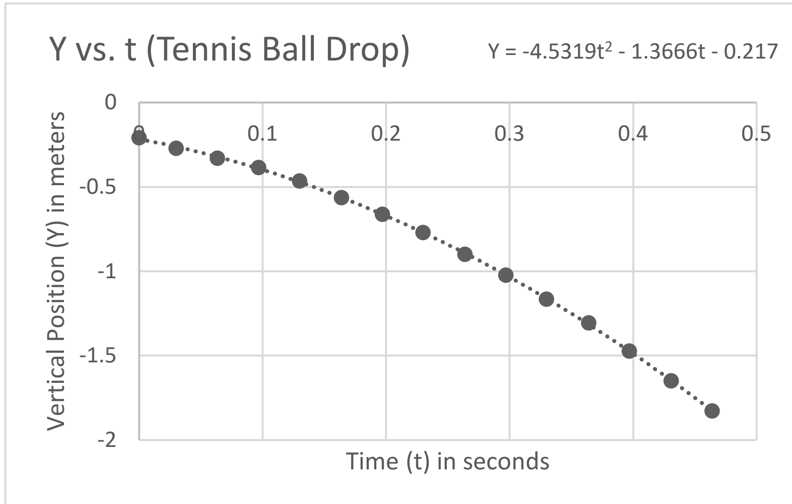

Figure 3. Vertical Position vs. Time graph for a tennis ball drop performed using the aforementioned procedure.

To evaluate the quality of the analysis, it is important to test the same procedure with a simple object/rigid body as well. A tennis ball is the ideal simple object because it approximates well as a point mass, which aligns with the hypothesis we are making for the dancer being a rigid body where the center of mass is easily located.
Equation 1: One-dimensional kinematic equation applicable to situations with constant acceleration.

$$\mathbf{y}_{\boldsymbol{f}}(t) = \mathbf{y}_{\mathbf{i}} + \mathbf{v}_{\mathbf{o,y}}t + \frac{1}{2}\mathbf{a}_{\mathbf{y}}t^2$$

The acceleration due to gravity (g) value of the tennis ball during its free fall was calculated by fitting the data from Figure 3 to Equation 1 and multiplying the coefficient of the t^2 term by two. In addition, the ball was dropped from rest, so the starting vertical velocity was zero. The g value derived was -9.06 m/s^2. When the error margins and uncertainty for the ball drop data were calculated, it was found that g was equal to -9.06 $m/s^2 \pm 0.69$, setting the lower bound as -8.37 m/s^2 and the upper bound at -9.75 m/s^2. The percentage inaccuracy was 7.6%, which can be lowered with careful data collection, particularly at higher speeds. This inaccuracy is important to note, as it reflects the fact that if the ideal scenario did not have metrics that perfectly matched the desired g value of -9.81 m/s^2, the acceleration due to gravity, or the specific numbers reflected by the rest of the movements in this paper may not be completely accurate either. While the difference between -9.81 m/s^2 and -9.75 m/s^2 is to be noted, if other values in this paper also have such a difference, it wouldn't be too large of a concern. This is because in the context of this paper, the objective of deriving ratios and broader conclusions/trends that differentiate 'Good' movements from 'Bad' movements, trumps the objective of making very specific numeric observations.

Results & Findings

One-Dimensional Motion

Comparing and Contrasting the Vertical Movement in both Datasets

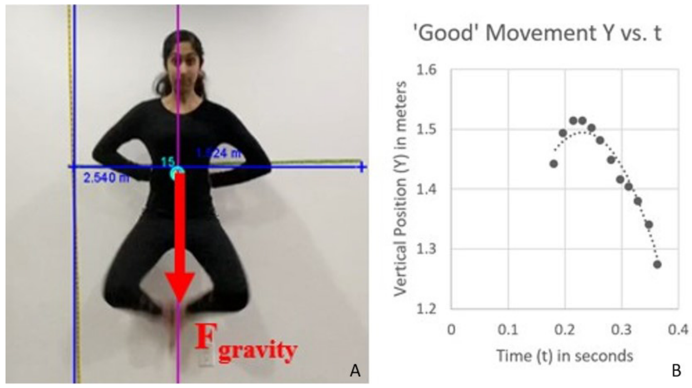

Figure 4. Free Body Diagram & Vertical Position vs. Time graph for the 'Good' one-dimensional movement's free fall phase. As seen in 4A, $F_{gravity}$ represents the force due to gravity acting on the dancer, and 4B is a graphic representation of the dancer's vertical displacement over time.

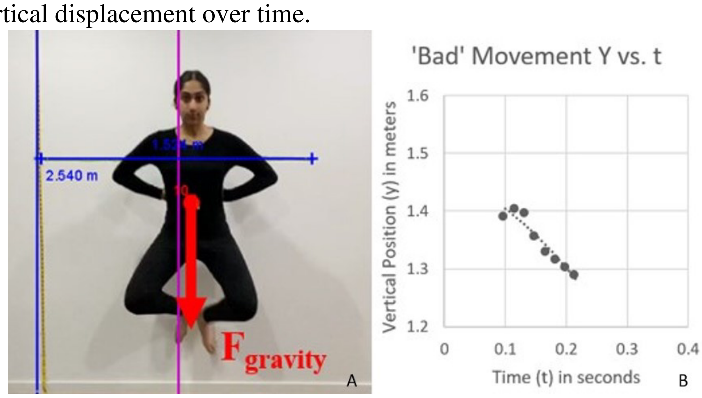

Figure 5. Free Body Diagram & Vertical Position vs. Time graph for the 'Bad' one-dimensional movement's free fall phase. As seen in 5A, $F_{gravity}$ represents the force due to gravity acting on the dancer, and 5B is a graphic representation of the dancer's vertical displacement over time.

Time: The total time of the free fall phase was 0.184 seconds for the 'Good' movement (as seen in Figure 4B), and 0.117 seconds for the 'Bad' movement (as seen in Figure 5B).

Height: Analysis of Figures 4B and 5B also reveals the following findings on the dancer's vertical displacement. In the free fall phase of the 'Good' one-dimensional movement, the distance from the initial y position at the start of the free fall, to the maximum height of the parabolic trajectory, is 0.072 ± 0.001 meters. When divided by the height of the dancer, this value as a percentage of the dancer's height is 4.29 ± 0.06%. In addition, the total vertical distance covered during both the launch and free fall phases (0.726 meters) is 43.3 ± 0.1% of the dancer's height. In contrast, in the free fall phase of the 'Bad' one-dimensional movement, the distance from the initial y position at the start of the free fall, to the maximum height of the parabolic trajectory, is 0.013 ± 0.001 meters. When divided by the height of the dancer, this value as a percentage of the dancer's height is 0.78 ± 0.06%. In addition, the total vertical distance covered during both the launch and free fall phases (0.359 ± 0.001 meters) is 21.4 ± 0.1% of the dancer's height. Thus, the dancer's vertical displacement in the 'Good' movement was more than two times the dancer's displacement in the 'Bad' movement.

Acceleration due to Gravity: Calculating the acceleration due to gravity in any of the datasets for the free fall phase, would have to be calculated using only a couple of data points from each dataset. The reason why, is that there is a leg motion that needs to be considered in both the one-dimensional and two-dimensional movements, where the dancer bends their legs towards the middle of the free fall phase. 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. In Figures 4B and 5B, there are only two to three data points that can be plotted which fit these requirements. When the data from Figures 4B and 5B are converted to vertical velocity vs. time graphs, the g values predicted by the slopes of the linear lines of best fit are inaccurate.

Comparing and Contrasting the Horizontal Movement in both Datasets

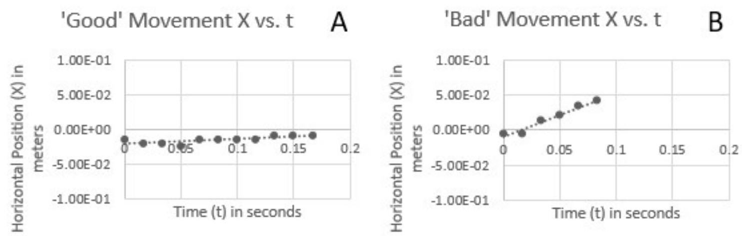

Figure 6. Horizontal Position vs. Time graphs for the launch phase of the one-dimensional movement. Figure 6A represents the dancer's horizontal position vs. time in the 'Good' movement's launch phase, and Figure 6B represents the dancer's horizontal position vs. time in the 'Bad' movement's launch phase.

As seen in Figure 6A, the horizontal spread of the data points from the 'Good' movement is 6 ± 1 mm, meaning the dancer's starting and final horizontal positions during the launch phase are approximately 5-7 millimeters away from each other. As seen in Figure 6B, the horizontal spread of the data points from the 'Bad movement is 47 ± 1 mm, meaning the dancer's starting and final horizontal positions during the launch phase are approximately 46-48 millimeters away from each other.

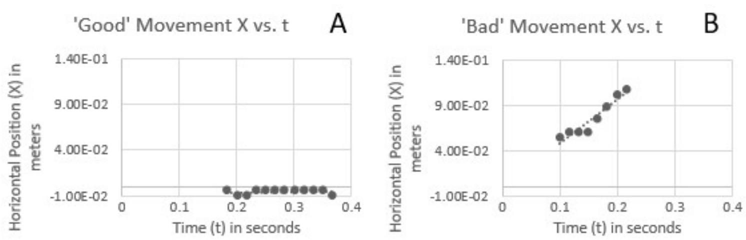

Figure 7. Horizontal Position vs. Time graphs for the free fall phase of the one-dimensional movement. Figure 7A represents the dancer's horizontal position vs. time in the 'Good' movement's free fall phase, and Figure 7B represents the dancer's horizontal position vs. time in the 'Bad' movement's free fall phase.

As seen in Figure 7A, the horizontal spread of the data points from the 'Good' movement is 6 ± 1 mm, meaning the dancer's starting and final horizontal positions during the free fall phase are approximately 5-7 millimeters away from each other. As seen in Figure 7B, the horizontal spread of the data points from the 'Bad' movement is 54 ± 1 mm, meaning the dancer's starting and final horizontal positions during the free fall phase are approximately 53-55 millimeters away from each other.

Calculating the Impulse during the Launch Phase

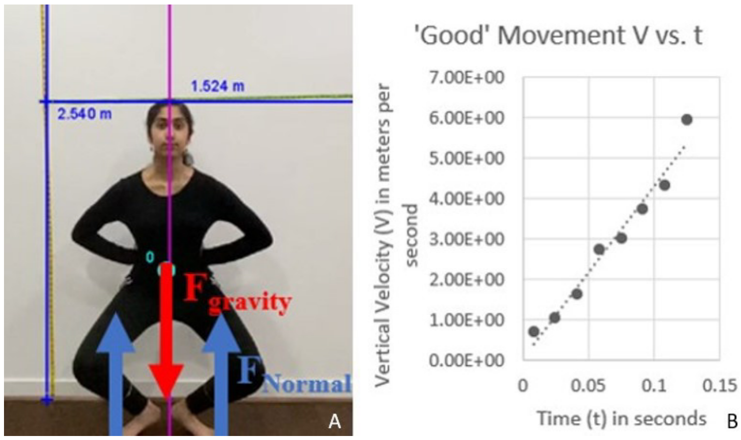

Figure 8. Free Body Diagram & Vertical Velocity vs. Time graph for the 'Good' one-dimensional movement's launch phase. As seen in 8A, $F_{gravity}$ represents the force of gravity acting on the dancer's center of mass while F_{Normal} represents the Normal contact force acting on the dancer's feet. 8B is a graphic representation of the dancer's change in vertical velocity over time.

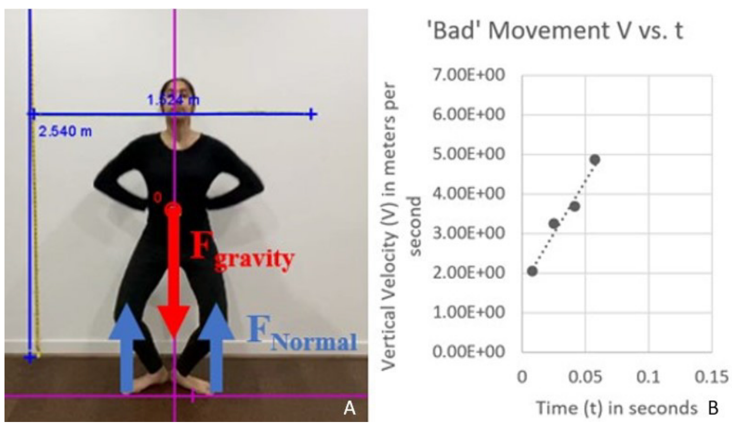

Figure 9. Free Body Diagram & Vertical Velocity vs. Time graph for the 'Bad' one-dimensional movement's launch phase. As seen in 9A, $F_{gravity}$ represents the force of gravity acting on the dancer's center of mass while F_{Normal} represents the Normal contact force acting on the dancer's feet. 9B is a graphic representation of the dancer's change in vertical velocity over time.

Utilizing the change in velocity that can be derived from Figures 8B and 9B, the change of momentum of the dancer can be calculated. The last two points from each dataset are taken to find the net force exerted on the dancer by the floor.

Equation 2: Impulse-Momentum theorem

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

For the 'Good' movement, the mass (m = 50.0 kg) of the dancer, along with the change in velocity (Δv = 1.65 m/s), and the time (Δt = 0.167 seconds) over which the velocity increased, can be plugged into Equation 2 to get the net force (F) Newtons exerted by the floor on the dancer:

$$F(0.167) = 50.0(1.65) \rightarrow F = \frac{50.0(1.65)}{0.167} \rightarrow F = 5000 \pm 0.1 \text{ N}$$

The same process can be performed on the 'Bad' movement as well, plugging the mass (m = 50.0 kg) of the dancer, along with the change in velocity ($\Delta v = 1.20$ m/s), and the time ($\Delta t = 0.066$ seconds) over which the velocity increased, into Equation 2 to get the net force (F) Newtons exerted by the floor on the dancer:

$$F(0.066) = 50.0(1.20) \rightarrow F = \frac{50.0(1.20)}{0.066} \rightarrow F = 3590 \pm 2\ \text{N}$$

This reveals that in the 'Good' movement, the net force exerted by the floor was 100 times the dancer's body mass, while in the 'Bad' movement the same force was only 71.8 times the dancer's body mass.

Two-Dimensional Motion

Comparing and Contrasting the Vertical Movement in both Datasets

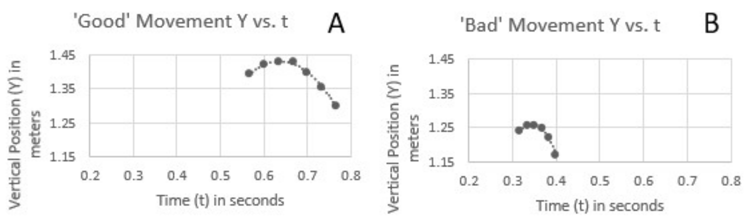

Figure 10. Vertical Position vs. Time graphs for the free fall phase of the two-dimensional movement. Figure 10A represents the dancer's vertical position vs. time in the 'Good' movement's free fall phase, and Figure 10B represents the dancer's vertical position vs. time in the 'Bad' movement's free fall phase.

Observation of Figures 10A and 10B indicates that the 'Good' movement has a higher maximum vertical height reached compared to the 'Bad' movement. In addition, the steeper change in the vertical position in the 'Bad' movement indicates the shorter time over which the free fall phase took place compared to the 'Good' movement.

In the 'Good' movement, the distance between the dancer's starting vertical position at the start of free fall, and the highest position reached, is 0.036 ± 0.001 meters which is 2.15 ± 0.024% percent of the dancer's body height. In the 'Bad' movement, the distance between the dancer's starting vertical position at the start of free fall, and the highest position reached, is 0.015 ± 0.001 meters which is 0.895 ± 0.013% percent of the dancer's body height.

Comparing and Contrasting the Horizontal Movement in both Datasets

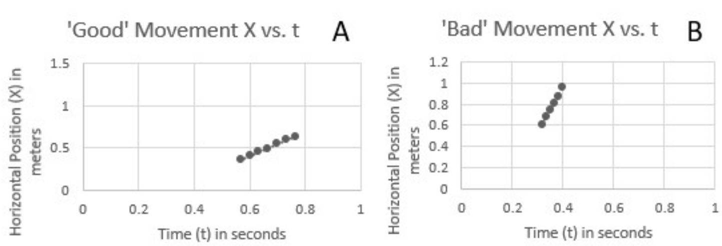

Figure 11. Horizontal Position vs. Time graphs for the free fall phase of the two-dimensional movement. Figure 11A represents the dancer's horizontal position vs. time in the 'Good' movement's free fall phase, and Figure 11B represents the dancer's horizontal position vs. time in the 'Bad' movement's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

Observation of Figures 11A and 11B indicates that the 'Good' movement has a higher horizontal distance reached compared to the 'Bad' movement. In addition, the steeper change in the horizontal position in the 'Bad' movement indicates the shorter time over which the free fall phase took place compared to the 'Good' movement. While the

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'Good' movement features a change of 0.274 ± 0.001 meters in 0.200 seconds, the 'Bad' movement features a change of 0.357 ± 0.001 meters in 0.083 seconds.

In the 'Good' movement, the distance between the dancer's horizontal position at the start of free fall, and the final horizontal position reached at the end of free fall, is 0.274 ± 0.001 meters which is 16.3 ± 0.1% percent of the dancer's body height. In the 'Bad' movement, the distance between the dancer's horizontal position at the start of free fall, and the final horizontal position reached at the end of free fall, is 0.357 ± 0.001 meters which is 21.3 ± 0.072% percent of the dancer's body height.

Relationship between Vertical & Horizontal Distance Covered

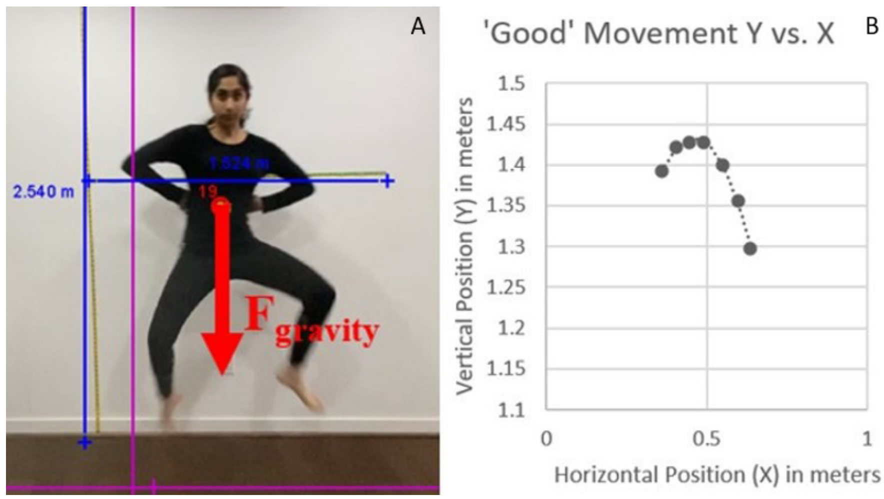

Figure 12. Free Body Diagram & Vertical Position vs. Horizontal Position graph for the 'Good' two-dimensional movement's free fall phase. As seen in 12A, $F_{gravity}$ represents the force of gravity acting on the dancer's center of mass. 12B is a graphic representation of the dancer's vertical position vs. horizontal position during the movement.

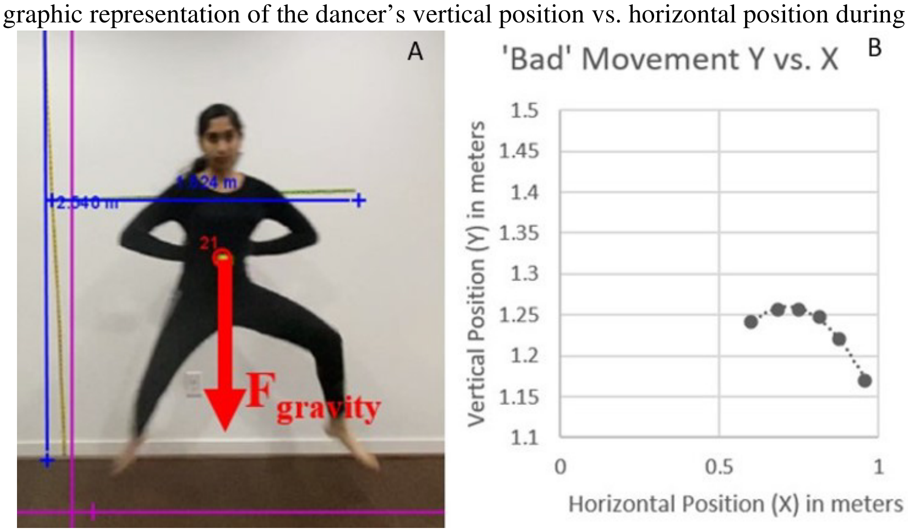

Figure 13. Free Body Diagram & Vertical Position vs. Horizontal Position graph for the 'Bad' two-dimensional movement's free fall phase. As seen in 13A, $F_{gravity}$ represents the force of gravity acting on the dancer's center of mass. 13B is a graphic representation of the dancer's vertical position vs. horizontal position during the movement.

From a purely visual standpoint, the parabolic path taken by the dancer in the 'Good' movement, as shown in Figure 12B, is much steeper and has a higher vertex as opposed to the 'Bad' movement, as shown in Figure 13B.

The ratio of the horizontal distance traveled to the vertical distance traveled from the moment of being airborne to the maximum height in the 'Good' movement, expressed as a percentage is 761 ± 11%. In the 'Bad' movement, this same percentage is 2380 ± 40%.

Rotational Motion and Torque Considerations

The comparison of the 'Good' and 'Bad' movements can prove extremely beneficial in terms of torque as well. In the two-dimensional motion movement being considered, certain rotational motion considerations add to the analysis of the dancer's movement. Because the axis of rotation for the dancer is the initial point from which they start leaping (the foot's point of contact with the floor), and the force of gravity acts downwards, there is a torque that is causing the dancer as a point mass to rotate around the axis of rotation. The following equation can be utilized to calculate torque for the 'Good' and 'Bad' movements.

Equation 3: Torque Equation

$$T = F \times r \sin\theta$$

The following free body diagrams can be created by overlaying force vectors on frames from the dancer's movements. The only two forces we will consider here are $F_{gravity}$ (force of gravity) and F_{Normal} (Normal force).

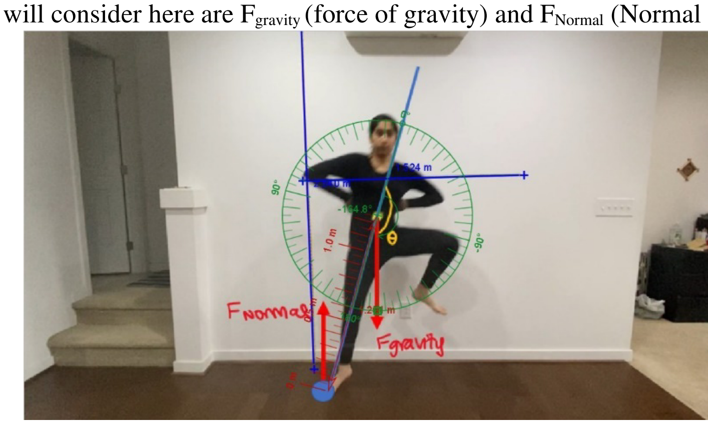

Figure 14. Free Body Diagram of the launch phase for the dancer's 'Good' two-dimensional movement, overlayed with a protractor and ruler to enable torque calculations. $F_{gravity}$ represents the force of gravity acting on the dancer's center of mass while F_{Normal} represents the Normal contact force acting on the dancer's foot.

By plugging the distance from the axis of rotation to the dancer's center of mass (r = 1.251 meters), measured in Figure 14, the force being exerted at the dancer's center of mass (F = 490.5 Newtons), and the angle between the center of mass and the axis of rotation (θ = 195.2°), into Equation 3, the torque can be calculated.

$$T = 490.5 \times 1.251 \times \sin(195.2) \rightarrow T = -161 \pm 0.450 \text{ Newton Meters}$$

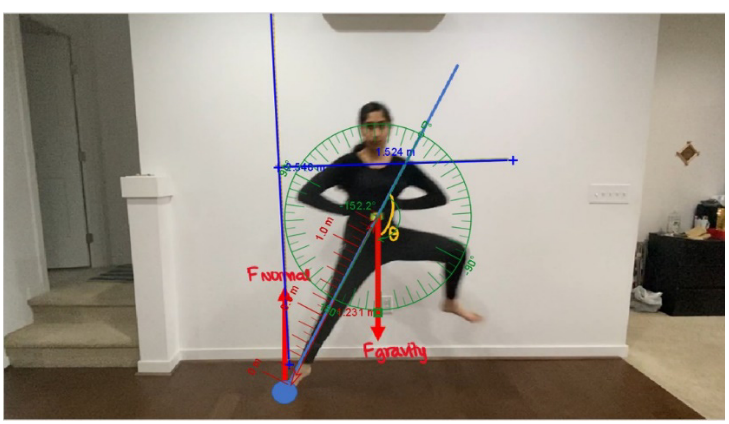

Figure 15. Free Body Diagram of the launch phase for the dancer's 'Bad' two-dimensional movement, overlayed with a protractor and ruler to enable torque calculations. $F_{gravity}$ represents the force of gravity acting on the dancer's center of mass while F_{Normal} represents the Normal contact force acting on the dancer's foot.

The above diagram is for the 'Bad' movement, and by plugging the distance from the axis of rotation to the dancer's center of mass (r = 1.231 meters), measured in Figure 15, the force being exerted at the dancer's center of mass (F = 490.5 Newtons), and the angle between the center of mass and the axis of rotation ($\theta = 207.8°$), into Equation 3, the torque can be calculated.

$$T = 490.5 \times 1.231 \times \sin(207.8) \rightarrow T = -282 \pm 0.790 \text{ Newton Meters}$$

The negative sign on both torque values calculated indicates that the body is trying to rotate clockwise, as typical physics conventions include counterclockwise as positive.

Discussion

Key Outcomes & Takeaways

The key takeaways, in regards to what makes a dancer's movement "ideal", are below.

One-Dimensional Motion

Firstly, comparing and contrasting the vertical movements in the 'Good' and 'Bad' one-dimensional movements, led to the conclusion that the 'Good' movement had a longer launch phase than the 'Bad' movement. As a result, the free fall phase of the 'Good' movement was also longer, giving the dancer more airtime. In the context of dance, this indicates that dancers should bend their legs to have a longer rise period during their launch, to adhere to the structure of the "ideal" movement better. In addition, the 'Good' movement's vertical position vs. time graph had data points in a parabolic shape, which was a trend unseen in the 'Bad' movement. This insight is critical, as in the future if this research is used to build an automated Machine Learning Movement Quality rater, the trend within the data points is a key indicator of a 'Good' movement. The next finding was that, during the 'Good' movement, the dancer covered 43.3% of their total body height during the free fall phase, as opposed to only 21.4% in the 'Bad' movement. In the context of dance, this indicates that dancers should aim to cover around 40-45% of their body height in their jump. Covering only around 20 percent would indicate that they are lacking in the technical performance of the movement.

Comparing and contrasting the Horizontal movement in both datasets resulted in two findings. The first was that the horizontal displacement of the dancer during the launch phase in the 'Bad' movement was around 8 times the displacement in the 'Good' movement. This indicates that the dancer should aim to minimize any horizontal movement during the launch phase, to perform a technically correct movement. The second finding was that the horizontal displacement of the dancer during the free fall phase of the 'Bad' movement was 10 times the displacement of the dancer in the 'Good' movement. Once again, this indicates that a dancer should attempt to make their jump as purely verticalaspossible.

Lastly, analyzing the launch phase of the dancer in both the 'Good' and 'Bad' movements resulted in the following result. In the 'Good' movement, the force acting on the dancer by the floor was 100 times the dancer's mass, versus only 71.8 times the dancer's mass in the 'Bad' movement. This indicates that a dancer should attempt to maximize the force acting on them by the floor, and as a result, they have to exert more pressure on the ground while launching. Pushing on the floor with both legs will result in a closer to ideal movement than launching in a light-footed manner.

Two-Dimensional Motion

Firstly, comparing and contrasting the vertical movement in both datasets resulted in the takeaway that the dancer covered 2.15% of their body height in the 'Good' vertical jump and only 0.895% of their body height in the 'Bad' vertical jump. This indicates that the dancer should aim to maximize their vertical distance covered during this specific movement, to perform it accurately. Combining these results with the ones derived from the horizontal movement investigation results in the conclusion that although both vertical and horizontal distance must be covered, the dancer should prioritize jumping high enough instead of focusing on moving a large horizontal distance.

Secondly, comparing and contrasting the horizontal movement in both datasets resulted in the following takeaways. Firstly, the 'Good' movement was less horizontal distance covered, in a greater amount of time than the 'Bad' movement. While the dancer covered a horizontal distance of 16.3% of their body height in the 'Good' movement, they covered 21.3% in the 'Bad' movement. This indicates that the dancer should aim to jump high enough to be airborne for as long of a time as possible and control their horizontal movement.

In addition, in the 'Good' movement, the percentage that the horizontal distance covered of the vertical distance covered was 761%. In the 'Bad' movement, this same percentage was 2380%. This indicates that a dancer needs to cover a horizontal distance of around 7-8 times their vertical distance, to produce a perfect parabolic jump. The dancer must also be careful not to move too far horizontally, 20-30 times as far as their vertical movement, as that would result in a technically incorrect step.

Lastly, from a Rotational Motion standpoint, there was a greater torque acting on the dancer in the 'Bad' movement than in the 'Good' movement. This indicates that a 'Good' performance of this movement requires a smaller torque being exerted by the dancer. Because the distance from the axis of rotation to the dancer's center of mass, and the force being exerted at the dancer's center of mass stayed constant across both movements, the angle is the main changed variable. This indicates that the dancer needs to launch more upright, to reduce the angle from their axis of rotation, thus lessening the torque exerted on them, to model the 'Good' movement.

Future Applications & Expansion of Research

This research provided insights into how the graph of a dancer's movement and the application of kinematics can be used to judge the movement's quality. While this specific research pertained to only one dancer's movement, in the future with the addition of several more movements, larger amounts of data can open up the opportunity to utilize machine learning. With the use of machine learning, when a user inputs their movement video into the software, they will be able to receive an automated analysis of how well they performed the movement. This will increase the applications of this research to a broader audience, and also make the analysis process more accessible due to automation.

Additionally, these research findings are not only beneficial for dancers and dance enthusiasts, but also for key stakeholders in many sectors of sports, such as basketball and volleyball players. This is due to the prevalence of vertical jumps in these sports, where the height jumped by the player often determines better or worse sports performance (Áragón-Vargas & Gross, 1997).

Considering the future expansion of this research, one interesting topic arises in the investigation of the launch phase of both the one-dimensional motion datasets for 'Good' & 'Bad' motion. While considering the R values for both linear lines of best fit for vertical velocity vs. time, both datasets have a high linear correlation. While both graphs display close to constant acceleration, the conclusion of constant acceleration cannot be drawn because the dancer's muscles can be compared to a Simple Harmonic Motion oscillator. The real acceleration is thus non-constant and dependent on the compression and flex of the dancer's body. This may be an interesting topic to research and further explore in detail.

One more exciting aspect of the movements investigated might be their landing phase. This is because dance, gymnastics, and other types of movements have defined ways of landing, such as bending one's legs or performing a small rebound jump. In terms of judging the quality of a movement, this would be a helpful additional factor to analyze.

Aside from Bharatanatyam, one more imminent ancient dance form from India is Kathak. Kathak includes a massive amount of spins in each performance, so applying Newton's laws and conservation of angular momentum to better judge the quality of dancers' spins would be interesting. Further opportunities lie in tracking other parts of dancers' bodies such as their neck (used a lot in Bharatanatyam), and even waist/hips (often used in a dance style native to India called Odissi), to better judge the quality of movements.

In the future, to make the data collection process more accurate and minimize error margins, a stress sensor can be employed. Placing a stress sensor on the ground would enable a better picture of the pressure exerted by the dancer on the floor as they launch and land. This would be conducive to better mathematical modeling, and when applied to more dancers this would all combine to create a richer grove of meaningful data.

For the one-dimensional movement, there is a good approach to implement in the future to gain close to accurate values for the acceleration due to gravity. Starting off, the Y vs. t graph for the free fall must be divided into two phases; rise and fall. By creating two separate graphs for these phases and selecting the y-intercepts of the graphs manually (the y-intercepts would be the starting vertical position), extrapolation of the collected data points can be used to analyze the movement as if the dancer was tossed in the air with a starting velocity, from a height y_0.

In addition, because the research question refers to Bharatanatyam as a whole, movements that involve rotations and more varieties of motion need to be analyzed to provide a more solid reply on the application of Physics to Bharatanatyam. There are also many different styles of Bharatanatyam, such as Kalakshetra, Melattur, and Pandanallur, which are just a few of them (Waghmare, 2022). When comparing the same movement across different styles, the metrics for how ideal the performance of the movement is, change greatly. While the movements in this research are quite simple and thus apply to most styles of Bharatanatyam, if future research involves other movements or the addition of hand movements, styles must be strictly considered and respected.

Conclusion

Aside from all the findings in this paper, it must be noted that in both learning and teaching Bharatanatyam, there are a lot more elements aside from the physical analysis of Nritta, there is another side of the coin when it comes to judging the quality of Bharatanatyam. Physics only explains the geometric limitations of the body, and the mathematically ideal ratios dancers may aim to achieve, but a dance teacher/guide is the one who makes the physics work out correctly. When a person repeats a motion in the manner desired, and when the movement appears appealing in terms of the quality of dance, they have attained their optimal physics. This method to evaluate dance is appropriate and may be used in conjunction with existing qualitative analysis within current Bharatanatyam establishments or may even open up doors for a future with mainly quantitative analysis for technical movements such as Nritta.

This experiment has proven that we can evaluate the quality of a Bharatanatyam movement using kinematics/statics to a moderately large extent. The use of kinematics & motion analysis through graphs and manipulation led to several beneficial insights that can be applied to help dancers improve their technical accuracy. The investigation also provided helpful quantitative benchmarks for dancers to keep in mind to move in the 'ideal' manner, which is an exciting development as Bharatanatyam has mostly been seen as a dance form that is qualitatively analyzed. However, one factor reducing the extent of this experimental claim, is that the investigation tested only two specific movements, and there are a vast array of movements within Bharatanatyam. To gain an accurate answer on whether we can evaluate the quality of a Bharatanatyam movement, we need to perform experiments on more movements to measure whether we can gain as beneficial insights and takeaways as we did with this experiment. Thus, we can evaluate the quality of a Bharatanatyam movement using kinematics/statics to a moderately large extent.

The underlying hypothesis that some aspects of the dancer's body can be approximated as a rigid body, or a simple object, has been disproved by this experiment. This is due to the inconsistencies derived while finding the g value for the dancer using data points from throughout their movement. More accurate values were derived when the data points were from solely a single portion of the dancer's movement, where their legs and body were in a constant position. This indicates that the dancer's center of mass shifts over time as they complete their movement and thus their body cannot be approximated as a rigid body or a simple object while analyzing the movement physically.

Limitations

Firstly, in this experiment, most of the data processed and presented had an acknowledgment of instrumental uncertainty but lacked error propagation through standard deviation. Although the instrumental uncertainties provided an upper limit to the uncertainty in each datapoint, in the future expansion of this research this limitation may be better reduced with the use of multiple trials, so that error propagation can be implemented.

In addition, in certain sections, such as the impulse & force calculations for the launch phase in the one-dimensional motion, the errors appear to be very small at this stage. The reason why is that the error calculations are based solely on instrumental error considerations. In the future, trying to replicate these movements may result in higher error margin calculations. However, to minimize the errors, there need to be strict guidelines as to how to complete the jumps. Despite these guidelines, the dancer's muscles cannot be fully controlled as many external variables are playing into how the movement is performed and how accurately it can be replicated.

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