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Analysis of Mechanical Principles of the Unbreakable Doll Performance at Tang Dynasty Night City

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Abstract: The unbreakable doll performance at Tang Dynasty Night City has become extremely popular, sparking a wave of enthusiasm online. In the performance, actors dressed in elegant Tang Dynasty attire appear as if they have stepped out of a historical painting, gracefully dancing on the unbreakable doll apparatus. Every gesture and expression exudes the unparalleled elegance of the Tang Dynasty. This paper primarily analyzes the mechanical principles behind the Tang Dynasty Night City's Unbreakable Doll Performance, starting with structural design to examine its mechanical principles and summarize its dynamic mechanical control mechanisms.

Keywords: Tang Dynasty Night City; Unbreakable doll performance; Mechanical principles; Structural design; Mechanical control

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1. Introduction

From the perspective of the unbreakable doll itself, its origins can be traced back to the Tang Dynasty, and possibly even earlier. The earliest recorded examples are the pointed-bottomed bottles unearthed at the Banpo Site in Xi'an and the tilting vessels from the pre-Qin period, whose balancing principles resemble those of the unbreakable doll, serving as its primitive form [1]. Additionally, the "Drunken Immortal Catcher" is the precursor to the unbreakable doll, a device used during the Tang Dynasty to encourage drinking. Like the unbreakable doll, it features a pointed bottom, wide mouth, and a shape that is narrower at the top and wider at the bottom, with a lighter head.

2. Structure and design features of the unbreakable doll device

2.1. Physical structure analysis of the device

The design of the unbreakable doll device in the Tang Dynasty's "City of Eternal Night" features a well-designed and unique physical structure. The base of the device is a hemispherical shell made of iron, with additional weights attached. This material not only possesses high strength, toughness, wind and sand resistance, and acid and alkali resistance, but also provides robust support for the entire device; Regarding mass and distribution, the total base mass is 250 kg, but the performer's weight is generally around 45 kg, ensuring the device's center of gravity is balanced. The installation method uses a T-shaped bracket to secure the device to the performer's body, allowing for unrestricted movement while preventing the performer from falling off the device. The selection of performers also follows a set of standards, such as a height below 163 cm and a weight not exceeding 50 kg. This design ensures better compatibility with the equipment's overall structure and weight distribution, resulting in a more perfect performance between the performer and the equipment, as shown in **Figure 1**.

Figure 1. On-site photo of the "Unbreakable Doll" at Tang Dynasty Night City

2.2. Basic design of static balance

The unique structure of the unbreakable doll, with its lightweight upper part and heavy lower part, enables it to achieve stable static balance. Under normal circumstances, the head of the unbreakable doll toy is a hollow structure with a smaller mass, while the lower half is a solid object in the form of a hemispherical base with a larger mass. The center of gravity of the entire toy is located at the center of the hemispherical base, resulting in a significant decrease in the center of gravity of the unbreakable doll toy. From a physics perspective, the stronger the stability of an object, the greater the extent to which its center of gravity lowers, enabling the wobbly toy to maintain balance in a stationary state. The use of a hemispherical base enhances operational stability because a single support point connects the hemispherical base to the ground, reducing friction during operation and allowing the device to run smoothly. Additionally, the hemispherical base can adjust its contact points, further facilitating stable operation [2].

3. Core mechanical principles of the unbreakable doll

3.1. The key role of the center of gravity distribution

In mechanics, an object's stability is related to the position of its center of gravity. Simply put, the lower the center of gravity, the higher the stability, primarily because a higher center of gravity makes it harder to deviate from the equilibrium position, and even harder to regain balance after tilting. The "unbreakable doll" device in the Tang Dynasty's Eternal City is based on this principle. Its upper body is relatively lightweight, while the base is stable. The entire lower body is hollow, and the upper body is a solid circular device, thereby placing the center of gravity within the circular base of the lower body, thereby lowering the center of gravity [3]. Compared to many other objects, due to differences in shape, structure, and material, the center of gravity may shift, and some objects may even have a higher center of gravity. Once subjected to external forces, they may sway or tip over. However, the "Unbreakable Doll" achieves stability under various external disturbances through its unique center of gravity design, thereby providing a stable foundation for the performer inside.

3.2. Dynamic mechanism of moment balance

When an external force causes the "unbreakable doll" to tilt, the moment generated by its gravitational force becomes the primary resisting force. According to physical principles, moment = force × distance along the direction. In the "unbreakable doll," the moment is primarily provided by gravitational force, and the distance along the gravitational force direction is the distance from the point of gravitational force application to the fulcrum.

When the self-righting object tilts, the center of gravity shifts away from the support point, generating a counteracting torque. This counteracting torque acts in the opposite direction of the external torque, causing the tilt, creating a tendency for the object to return to its initial state. Additionally, as the object tilts, the lever arm lengthens, and according to the torque formula, the counteracting torque increases. In other words, the more the object tilts, the stronger the tendency toward a balanced state. It is precisely this dynamic equilibrium torque system that ensures the self-righting toy can maintain an upright state for an extended period. Even under external force, the toy remains upright without tipping over.

3.3. Physical essence of stable equilibrium

Stable equilibrium refers to a system that, after being subjected to minor disturbances, raises its center of gravity and automatically tends to return to its original equilibrium posture from the equilibrium position. The unbreakable doll amusement facility in Tang Dynasty Night City operates in a state of stable equilibrium. If it is deflected by an external force, the raised center of gravity increases the gravitational potential energy of the system. However, since matter always seeks the state of minimum energy, the unbreakable doll automatically swings back to its initial position under the influence of gravity, lowering the center of gravity and reducing the gravitational potential energy of the system [4]. The physical essence is shown in **Table 1** below.

Table 1. Physical essence of stable equilibrium

Balance type	Definition	Features	Examples
Stable equilibrium	After being disturbed, the center of gravity of the object rises, and it can automatically return to its original position.	Low center of gravity, tendency to recover after disturbance	Wobble device
Unstable equilibrium	After being disturbed, the center of gravity of the object lowers, and it cannot return to its original position.	High center of gravity, prone to tipping over after disturbance	Upright pencil
Equilibrium at random	After being disturbed, the height of the center of gravity of the object remains unchanged, and it can balance at its new position.	Center of gravity height remains unchanged, no tendency to recover after disturbance	Sphere on a horizontal surface

4. Mechanical formula and data analysis for the stability of the wobble doll

4.1. Calculation formula

The stability of the wobble doll can be quantified and analyzed using the resistance moment formula:

$$M_{扶} = W \cdot GM \cdot \sin\alpha \quad (1)$$

In equation (1), W is the total weight of the roly-poly toy (including the performer and the base); GM is the "center of stability height" (the distance from the center of gravity G to the "center of stability M," which is the intersection of the extension line of the supporting force and the axis of the roly-poly toy); α is the tilt angle (the angle between the line connecting the center of gravity and the fulcrum and the vertical direction).

When the disturbance torque M (gan) generated by external forces equals M (fu), the roly-poly toy reaches a new state of equilibrium (tilted but not falling over). If M (gan) > M (fu), the roly-poly toy will fall over.

4.2. Experimental analysis

We selected a Da Tang unbreakable doll and designed different hemispherical radii and masses to analyze the height of the center of gravity of the weight and the angle of overturning. Through experiments, we investigated the factors affecting the stability of the unbreakable doll. The data is shown in **Table 2** below.

Table 2. Experimental data analysis

Number of experiments	Hemisphere radius (m)	Hemisphere mass (kg)	Height of center of gravity of heavy object (m)	Overturning angle α (°)
1	0.4	35	0.5	30
2	0.6	35	0.5	45
3	0.8	35	0.5	60
4	0.4	20	0.5	25
5	0.4	60	0.5	50
6	0.6	35	0.7	35
7	0.6	35	1.0	25

Based on the above data analysis, it can be concluded that the larger the hemisphere radius, the greater the overturning angle α (e.g., from 0.4 m to 0.8 m, α increases from 30° to 60°), and the better the stability (more difficult to overturn). The greater the mass of the hemisphere, the larger the overturning angle α (e.g., from 20 kg to 60 kg, α increases from 25° to 50°), and the stronger the stability. The higher the center of gravity of the heavy object, the smaller the overturning angle α (e.g., from 0.5 m to 1.0 m, α decreases from 45° to 25°), and the poorer the stability (more prone to overturning).

5. Dynamic mechanical control in live performances

5.1. The mechanism of active force generation by performers

In the performances at Tang Dynasty Night City, performers actively generate force using various parts of their bodies, particularly by exerting force through the waist to drive the movement of the rest of the body, transferring the force to their support structures. This allows the force generated by the movement of a specific body part to regulate the stability and swing amplitude of the seesaw mechanism.

For example, when a performer uses their flexible waist to achieve graceful, fluid left-to-right swaying movements, this functions as a fulcrum in a lever system, accurately transmitting force all the way to the lower body. This enables the teeter-totter structure to move in a rhythmic, rhythmic manner according to the performer's movements. However, this is no easy feat, as performers must endure significant hardships and overcome numerous obstacles. The most common challenge is damage to the hips, as prolonged friction and pressure from equipment can cause numerous wounds on the hip bones. On the other hand, maintaining a stable center point is also extremely difficult; any misstep can disrupt the stability of the unbreakable structure and compromise the performance's quality.

5.2. Strategies for maintaining dynamic balance

Performers typically maintain movement stability by controlling their body posture, a process that can be described using a time function. When the unbreakable doll prop tilts due to external forces or its own swinging motion, the performer can promptly detect the imbalance and adjust their position and posture to control angular velocity. For example, if the system shifts to the left during oscillation deviation, the performer must promptly shift their position to the right, thereby generating an opposite angular velocity to counteract the unsteady prop's leftward deviation trend, ultimately achieving re-balance [5]. In this process, the sliding friction angle plays a balancing role. Due to the sliding between the semicircular base plate and the ground, the position of the supporting force shifts slightly. The dancer must sensitively perceive this change and adjust their posture in real-time to compensate. Through repeated adjustments and adaptation, the dancer can maintain the relative stability of the wobble doll prop's performance, thereby presenting an awe-inspiring performance to the audience.

6. Conclusion

In summary, the Tang Dynasty Night City wobble doll performance achieves high stability through its "light top, heavy bottom" structural design, torque balance mechanism, and hemispherical base support. Its mechanical principles can be quantified using the resistance torque formula, and experimental data validates the influence of key parameters (radius, mass, center of gravity height) on stability.

Disclosure statement

The authors declare no conflict of interest.

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