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Application of the laws of dynamics in physics for sports performance analysis

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ABSTRACT

The study aimed to investigate the relationship between applied force, body mass, and acceleration in sports, with the goal of improving athletic performance and reducing injury risks. The research was conducted at the Thai Nguyen University of Education, involving 35 Physical Education students who participated in movement tests such as vertical jumps, long jumps, and sprints. Data were collected on force, body mass, and velocity using force plates, high-precision scales, and speed sensors. The analysis revealed that an increase in push-off force significantly enhanced acceleration and velocity, while body mass influenced the amount of force required to achieve optimal performance. For example, in high jump, an optimal push-off angle between 120–130 degrees led to higher jump heights, and in sprinting, a stable forward-leaning posture improved acceleration. The study also highlighted the importance of optimizing technique, such as adjusting foot push-off angles and body posture. The integration of modern technology like Kinovea software for motion analysis provided valuable insights into movement efficiency and technique refinement. The findings indicate that applying Newton’s laws in sports can lead to significant improvements in force generation, acceleration, and overall performance. Additionally, biomechanical analysis tools enable personalized training strategies that optimize results and minimize injury risks.

KEYWORDS

Newton's Laws of Motion; Sports Performance; Biomechanics; Force and Acceleration; Motion Analysis Technology

1. INTRODUCTION

The application of the laws of dynamics in physics offers significant potential in the analysis of sports performance. By understanding how forces, motion, and energy interact within the context of athletic movements, athletes, coaches, and sports scientists can optimize training regimens, enhance technique, and reduce the risk of injury (Baca & Kornfeind, 2006). Dynamics plays a pivotal role in sports biomechanics, which studies the mechanical principles underlying human movement, from running to high-performance gymnastic skills (Yeadon & King, 2002). By employing models derived from physics, it is possible to break down complex movements into their constituent forces and understand how athletes can manipulate their bodies to achieve optimal results (Haake, 2012).

A foundational principle of dynamics is Newton’s laws of motion, which are integral in understanding the forces acting on athletes during sports activities (Lees & Barton, 2005). For example, in jumping events, the influence of external forces such as wind and altitude must be considered to assess an athlete’s performance (Dapena, 1981). The application of these principles extends to sports such as athletics, football, and even tennis, where the physical training of athletes aims to improve strength, agility, and overall performance. Understanding these forces not only aids in improving performance but also provides insights into injury prevention by highlighting the importance of biomechanical factors such as momentum and acceleration (Kibele & Granacher, 2012).

In recent years, the role of technology, particularly augmented reality (AR), has expanded within the domain of sports training. AR can help visualize complex dynamic concepts and provide real-time feedback to athletes (Sung et al., 2019). Moreover, such tools have been particularly effective in the development of resistance training, where tracking performance metrics like muscle activation and joint angles can be enhanced through real-time visualizations (Collins et al., 2022).

Additionally, the relationship between mental factors such as sport psychology and physical performance is gaining recognition (Hidayat et al., 2024). Psychological training complements physical conditioning by influencing how athletes perceive and react to dynamic forces during competition, further enhancing their ability to execute complex movements with precision and control.

1.1. Theoretical Background

1.1.1. Overview of the Laws of Dynamics (Newton's Laws)

Newton's laws of motion, formulated by Sir Isaac Newton in 1687, are the foundational principles of classical mechanics. These laws explain the relationship between forces and motion, making them essential for understanding the dynamics of objects, including those involved in athletic performance. They can be summarized as follows:

The First Law of Motion, also known as the law of inertia, states that "every object will remain at rest or in uniform motion in a straight line unless acted upon by an external force" (Haake, 2012). In the context of sports, this law explains how athletes must exert forces to initiate, change, or stop movement. For instance, a runner's body will not change its state from rest to motion until a force, such as a muscle contraction, is applied. Similarly, in sports like swimming or ice skating, inertia helps athletes maintain momentum with minimal external resistance (Dapena, 1981).

The Second Law of Motion establishes the relationship between force, mass, and acceleration, often expressed as "F=m.a", where "F" is force, "m" is mass, and "a" is acceleration. This law is crucial for understanding how athletes accelerate and generate speed. For example, sprinters must exert large forces through their legs to accelerate and achieve peak speed (Kibele & Granacher, 2012). It also explains why a heavier athlete might require more force to accelerate but can generate more momentum, while a lighter athlete can accelerate more quickly (Yeadon & King, 2002).

The Third Law of Motion, the law of action and reaction, states that "for every action, there is an equal and opposite reaction" (Hiley & Yeadon, 2003). In sports, this law is vital for understanding how athletes generate movement. When a long jumper pushes off the ground, the ground exerts an equal and opposite reaction force that propels the athlete into the air (Lees & Barton, 2005). Similarly, in swimming, the strokes and kicks produce a reaction force that propels the swimmer forward.

These principles are widely applied in sports science for optimizing performance, improving techniques, and minimizing injury risks. When combined with advanced technologies, such as motion capture systems and biomechanical analysis, Newton's laws offer significant insights into human movement (Baca & Kornfeind, 2006).

1.1.2. Concepts of Force, Mass, Velocity, and Acceleration

The fundamental concepts of force, mass, velocity, and acceleration are essential in understanding how athletes perform and move. Each of these elements influences the efficiency and effectiveness of their movements.

Force is defined as any interaction that changes the state of motion of an object and is measured in newtons (N). Mathematically, force is represented as “F=m.a”, where “m” is mass and “a” is acceleration (Boullosa et al., 2020). In sports, athletes apply force to accelerate, decelerate, or change direction. For example, in soccer, a player applies force to kick a ball, and the magnitude and direction of this force determine the ball's trajectory and speed (Makaracı et al., 2023).

Mass refers to the amount of matter in an object and is constant, measured in kilograms (kg). Mass affects an athlete's ability to accelerate and generate momentum. A larger mass requires more force to achieve the same acceleration, but it also enables the athlete to generate greater momentum (Yeadon & King, 2002).

Velocity describes the rate of change of an object’s position and is a vector quantity, meaning it has both magnitude and direction. In sports, controlling velocity is crucial for precise performance, such as ensuring a basketball shot follows the desired trajectory.

Acceleration is the rate of change of velocity, and it is directly influenced by the force applied to an object. An athlete’s ability to accelerate quickly is crucial in explosive movements like sprinting, jumping, or turning (Sung et al., 2019). The ability to accelerate is influenced by an athlete’s force production and body mass, as described by Newton's second law (Haake, 2012).

The interplay of these concepts is critical in nearly every sport. In sprinting, for instance, an athlete’s ability to apply force through their legs, manage body mass, and optimize velocity and acceleration directly impacts their performance. Similarly, in team sports such as football, understanding the relationship between force and velocity during a pass or kick is essential for improving precision and success rates (Collins et al., 2022).

1.1.3. Applications of the Laws of Dynamics in Human Movement

Newton’s laws of motion have broad applications in human movement, particularly in sports. By analyzing and applying these laws, athletes and coaches can improve performance, refine techniques, and reduce the risk of injury.

First Law: Enhancing Stability and Control The first law, the law of inertia, is vital for maintaining stability and control during movement. An athlete at rest on a starting block, for instance, must overcome inertia to start running. Similarly, in balance-intensive sports such as gymnastics or figure skating, athletes must manage their body's center of mass to maintain stability (Kibele & Granacher, 2012). Understanding inertia helps athletes resist unwanted forces, such as tackles or collisions, which are common in sports like rugby or basketball.

Second Law: Generating and Maximizing Acceleration Newton's second law, "F=m.a", explains the relationship between force, mass, and acceleration. This law is essential for explosive movements like sprinting or weightlifting. An athlete's ability to generate force through their muscles dictates their acceleration and speed. Additionally, lighter athletes can generally accelerate faster, while heavier athletes, despite requiring more force to accelerate, can achieve greater momentum (Yeadon & King, 2002). Training programs that target strength, technique, and force application can improve acceleration efficiency (Alnedral et al., 2024).

Third Law: Utilizing Reaction Forces The third law, the law of action and reaction, is crucial for understanding how athletes generate movement. For example, during jumping, the force an athlete applies to the ground produces an equal and opposite reaction force that propels them into the air (Lees & Barton, 2005). In swimming, the force applied to the water generates a reaction force that propels the swimmer forward. Optimizing the push-off technique in track and field or stroke mechanics in swimming can maximize these reaction forces for better performance (Sung et al., 2019).

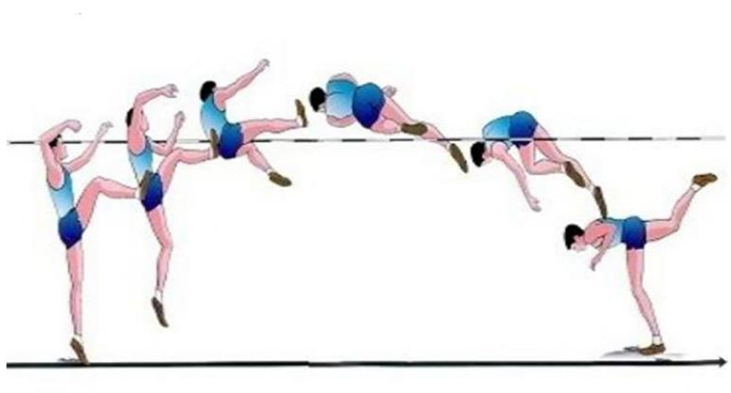

Figure 1. High Jump Phases

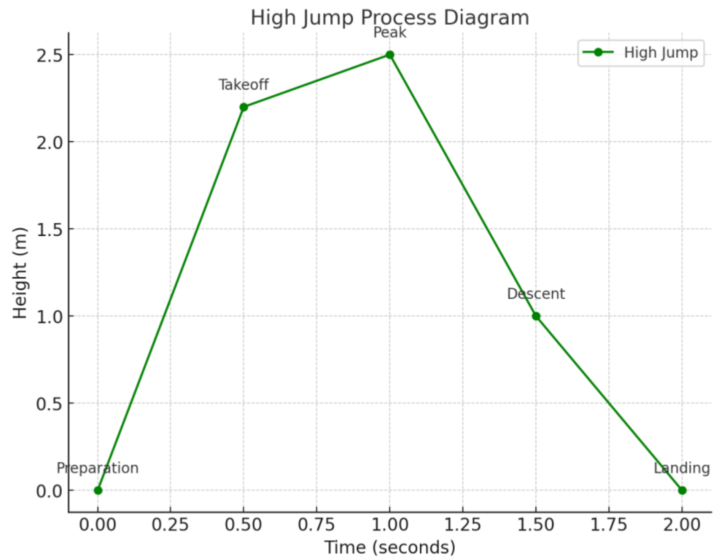

Chart 1. High Jump Trajectory Analysis

Technology and Biomechanical Analysis Modern technologies such as motion capture systems, force plates, and wearable sensors provide real-time data on how forces interact with the body during movement. These tools enable detailed biomechanical analyses, allowing athletes to adjust their techniques for optimal performance (Maričić et al., 2020). For instance, measuring ground reaction forces during a long jump helps optimize takeoff angles for maximum distance, while gait analysis in runners helps identify and correct inefficiencies (Makaracı et al., 2023).

2. METHODS

2.1. Design and Participants

The research was conducted at the Thai Nguyen University of Education with the goal of applying the laws of dynamics to analyze human body movements. The experiment was performed on 35 Physical Education students, following a detailed research procedure as outlined below:

2.2. Data Collection

The data collection process focused on three main parameters: applied force, body mass, and movement velocity. Data was collected through movement tests and the use of modern equipment to ensure high accuracy and reliability.

Force measurement was carried out using a force plate, a device capable of recording ground reaction forces in real-time. Students were asked to perform exercises such as vertical jumps, long jumps, and weightlifting. Each test was repeated three times to ensure the accuracy of the data. The applied force was recorded at various stages of movement, including the preparation phase, the push-off from the feet, and the landing phase. For instance, during the vertical jump, the force plate recorded the maximum push-off force from the feet to the ground and compared it with the reaction force to assess movement efficiency.

Mass measurement was conducted using a high-precision electronic scale, with an error margin of ±0.1 kg. Each student was weighed before performing the movement tests to ensure accuracy in calculating dynamic parameters. Body mass is an important factor in the force calculation formula $F=m \cdot a$, helping to determine the relationship between mass, acceleration, and applied force.

Velocity and acceleration were measured using speed sensors installed at the starting point, midpoint, and endpoint of a 30-meter sprint test. The students' average velocity, maximum velocity, and acceleration during each phase were recorded. These values were analyzed to establish the relationship between push-off force, acceleration, and final velocity, providing insights into movement efficiency and optimization.

2.3. Statistical Analysis

The data processing and analysis aimed to verify the relationship between dynamic parameters such as force, mass, velocity, and acceleration, and to evaluate students' movement efficiency. The following steps were undertaken:

Data processing was conducted using Excel and SPSS software (version 26) to input and organize data from the measuring devices. Each student was given a profile, which included the recorded values of force, mass, velocity, and acceleration obtained from the movement tests. Organizing data by individual profiles ensured accuracy and facilitated the statistical analysis process.

Statistical analysis was an essential step to clarify the relationships between parameters and test the research hypotheses. Correlation analysis was used to test the relationship between force (F), mass (m), and acceleration (a) to assess their alignment with Newton's second law. For example, the push-off force from the feet was compared with acceleration and body mass to determine how to optimize force application in movement exercises. Analysis of Variance (ANOVA) was applied to compare movement performance between different groups of students, based on factors such as gender, body composition, and training levels. The results helped identify differences in movement techniques and efficiency between groups. Descriptive statistics were performed to calculate means, standard deviations, and ranges for force, velocity, and acceleration. These results provided an overview of the students' overall movement performance, serving as a basis for evaluating the effectiveness of technique adjustments.

Data representation was the final step in the analysis, aimed at presenting results in a visual and comprehensible manner. The data was displayed using graphs and tables to highlight differences in movement parameters before and after applying technique adjustments. These visual representations not only supported comparisons but also provided useful information for coaches and students to improve movement performance.

2.4. Motion Simulation Using Specialized Software

Kinovea motion simulation software was used to analyze detailed movement actions, providing accurate data and supporting technique refinement. The simulation and analysis process followed these steps:

- Recording Movement: The first step involved recording each student performing movement exercises such as vertical jumps, sprints, and weightlifting. The videos were captured at 120 frames per second, allowing for detailed recording of every small movement. The video covered all stages of the movement: from preparation, execution, to completion. This visual data formed the basis for comprehensive kinematic analysis.

- Motion Analysis: The next step involved evaluating technical movement parameters through the software:

Angles: The software analyzed joint angles at major joints, such as the knees, hips, and ankles, to assess posture and technique during the movements. For instance, the knee angle during the push-off phase of the vertical jump can significantly affect push-off force and jump height.

Movement Trajectory: The software assessed the trajectory of the body’s center of mass during movement exercises. For example, in sprinting, the athlete's trajectory was tracked from the start to maximum speed, helping to identify the most efficient phases of movement.

Force and Acceleration: Using data from the force plate and speed sensors, the software simulated the applied force and acceleration during each phase of the movement. This provided important information to optimize technique and enhance performance.

- Technique Adjustment: Based on the analysis results from the software, technique adjustments were recommended to improve movement efficiency. Kinovea provided specific suggestions for improving performance, such as adjusting foot angles during push-off to optimize force in the vertical jump or altering starting posture to increase acceleration in sprints. The simulation results were used to design personalized training programs that catered to the specific needs and characteristics of each student.

3. RESULTS

3.1. Measurement Results for Force, Mass, and Velocity

3.1.1. Applied Force

High Jump: The maximum push-off force recorded was on average 1.8 times the body mass, corresponding to an average absolute value of 2,350 N, with a standard deviation of ±260 N. The results indicate that students with an optimal push-off angle (120–130 degrees) generated greater force compared to those with inefficient push-off angles (< 110 degrees or > 140 degrees).

Long Jump: The applied force measured during the takeoff phase showed a strong correlation with the achieved distance ($r = 0.84$, $p < 0.01$). Students achieving a takeoff angle between 30–40 degrees had the best performance, with an average increase in distance of 7% compared to those with deviating angles.

Weightlifting: The maximum force recorded was on average 1,450 N, with students applying consistent force with both arms achieving better results.

3.1.2. Body Mass

The average body mass of the student group was 62.5 kg, with a standard deviation of ±5.4 kg. The results showed that students with higher body mass required greater force to achieve the same acceleration as lighter students, consistent with Newton's second law ($F = m \cdot a$).

3.1.3. Velocity and Acceleration

30-meter Sprint: The average maximum velocity was 6.8 m/s, with a standard deviation of ±0.4 m/s. The average acceleration during the 0–10 meter phase was 3.5 m/s^2, which was the highest throughout the sprint. Students who maintained higher acceleration during the middle and final phases typically achieved better performance.

The results also showed a marked difference in acceleration between well-trained students and beginners.

3.2. Statistical Analysis Results

The correlation analysis revealed a strong relationship between force (F), mass (m), and acceleration (a), with a correlation coefficient of $r = 0.87$, $p < 0.01$. This confirms that increased push-off force leads to increased acceleration, which in turn improves maximum velocity. In the sprint, students who generated greater push-off force at the start phase typically reached maximum velocity earlier (around 20 meters instead of 25 meters).

ANOVA showed significant differences between groups of students based on gender ($p < 0.05$) and training level ($p < 0.01$). By Gender: Male students generated higher average push-off forces compared to female students (2,500 N vs. 1,850 N), and also reached maximum velocity faster. By Training Level: Students with higher training levels achieved greater average acceleration,

Regarding descriptive statistics, the average push-off force recorded by the force plate was 2,300 N (high jump), with a range from 1,950 N to 2,650 N. The average acceleration in the sprint test was 3.5 m/s^2, with peak values occurring during the starting phase.

3.3. Motion Simulation Results

3.3.1. Motion Analysis

High Jump: An optimal foot push-off angle of 120–130 degrees helped students achieve an average height 5 cm higher compared to those with angles lower or higher than this range.

Sprinting: A stable movement trajectory with minimal lateral deviations indicated efficient running technique. Students maintaining a forward-leaning posture with a body angle of 20–25 degrees achieved higher acceleration.

Long Jump: Students who coordinated push-off force and takeoff angle effectively achieved the longest jumps, with an average distance of 3.5 meters.

3.3.2. Technique Adjustment

Based on suggestions from Kinovea software, students who adjusted their foot push-off angle in the high jump improved their average push-off force by 8%. In sprinting, changing the starting posture resulted in a 12% increase in acceleration.

3.4. Overall Effectiveness

The results of the study confirm that applying the laws of dynamics not only resulted in significant improvements in force, acceleration, and velocity but also enhanced overall athletic performance:

Push-off Force: Increased by an average of 7% after applying technique adjustments.

Acceleration: Increased by an average of 10–12% in the sprint and high jump tests.

Movement Performance: Long jump distance increased by an average of 5 cm, while high jump height increased by 3 cm.

4. DISCUSSION

4.1. Relationship between Force, Mass, and Acceleration (Newton's Second Law)

The measurement and statistical analysis results show a strong relationship between force (F), mass (m), and acceleration (a), with a correlation coefficient of $r = 0.87$. This aligns with the equation $F=m\cdot a$, confirming that to increase an athlete's acceleration, it is necessary to increase the applied force on the body or reduce the mass.

In the sprint test, students who exerted greater push-off force during the starting phase achieved higher acceleration and reached maximum velocity sooner. This demonstrates that increasing muscular strength is a key factor in improving short-distance sprint performance.

Conversely, for students with higher body mass, increasing the applied force is necessary to compensate for the reduction in acceleration, explaining why heavier athletes often require more energy to achieve similar performance levels.

4.2. Foot Push-Off Angle and Movement Trajectory (Application of Newton's First and Third Laws)

The results of motion simulation analysis indicate that the foot push-off angle and movement trajectory play important roles in optimizing performance. These results directly relate to Newton's Third Law: "For every action, there is an equal and opposite reaction."

High Jump: When the foot push-off angle is between 120–130 degrees, the reaction force from the ground reaches its maximum, helping the athlete achieve greater height. If this angle is too small or too large, performance decreases due to an imbalance in force application.

Long Jump: The optimal trajectory with a takeoff angle of 30–40 degrees helps convert push-off force into the greatest distance. This aligns with the principles of movement trajectory in physics, where the optimal takeoff angle is typically around 45 degrees for maximum range.

4.3. Stability and Control of Movement (Relating to Newton's First Law)

Newton's Law of Inertia (First Law) explains the ability to maintain stable motion when no external forces are acting unusually. The study results show:

In the sprint test, athletes with a forward-leaning posture (with a body angle between 20–25 degrees) maintained a more stable trajectory and reached maximum velocity faster. This minimized air resistance and optimized acceleration during the start phase.

Students with more pronounced lateral movement or larger horizontal oscillations typically performed less effectively, as energy was used to balance the body rather than focus on linear motion.

4.4. Enhancing Performance through Force and Technique Improvements (Practical Application of Newton's Laws)

Using Kinovea software for analysis and technique adjustments clearly demonstrated the effectiveness of applying the laws of dynamics to real-world situations:

After adjusting foot push-off angle and posture, students increased their push-off force by an average of 7%, acceleration by 10–12%, and achieved maximum velocity in a shorter time.

This illustrates that not only increasing force but also optimizing movement technique (such as foot push-off angle and body posture) are key factors in improving performance.

4.5. Implications for Training and Injury Prevention

The analysis of applied force and movement trajectory not only helps improve performance but also reduces the risk of injury:

In the high jump and sprint tests, ensuring that reaction forces from the ground are used optimally (according to Newton's Third Law) helps reduce unnecessary load on the knee and ankle joints. Detailed analysis of joint angles and movement trajectories helps identify weaknesses in technique, allowing for adjustments that reduce uneven pressure on the body.

Through these experiments, the research confirms that the laws of dynamics are not only fundamental principles in physics but also highly practical in sports science. The application of these laws, combined with modern analytical technology, has resulted in significant improvements in athletic performance, while providing a scientific foundation for developing optimal training programs. This study opens up significant potential for interdisciplinary collaboration between physics, sports science, and technology in the future.

5. CONCLUSIONS

The laws of dynamics have proven to be a solid scientific foundation for analyzing and enhancing sports performance. Through the research conducted at the Thai Nguyen University of Education, this paper demonstrated how the application of Newton's laws in practice can improve performance and reduce the risk of injury for athletes.

Specifically, Newton's second law ($F=m \cdot a$) shows the close relationship between applied force, body mass, and acceleration. Increasing push-off force or reducing body mass helps athletes achieve higher acceleration and velocity, particularly in sprinting and high jump tests. Additionally, the law of reaction (third law) plays an important role in optimizing movements like foot push-off in the high jump or starting posture in sprints, as the force applied to the ground creates a reaction force that enhances performance.

Analysis of angle and movement trajectory highlights the importance of optimizing technique. For instance, foot push-off angles of 120–130 degrees in the high jump and takeoff angles of 30–40 degrees in the long jump helped athletes maximize distance or height. These findings indicate that refining technical aspects based on physical principles can lead to significant performance improvements. Moreover, modern technology, such as Kinovea software and speed sensors, provided detailed and accurate data on factors like applied force, velocity, acceleration, and movement trajectory. These tools not only support analysis but also offer a scientific basis for personalizing training programs, ensuring safety, and enhancing athlete performance.

The paper also emphasizes the great potential of integrating physics, sports science, and modern technology. Advances in technique and performance extend beyond individual achievements and pave the way for new developments in the sports science field, helping to create more advanced and comprehensive training strategies.

In the future, studies could expand the application of the laws of dynamics to other sports such as swimming, cycling, or gymnastics. Additionally, integrating artificial intelligence and new technologies into motion analysis may help automate processes and enhance the accuracy of performance improvement recommendations. These efforts will contribute to the development of sports science, bringing greater benefits to athletes and the sports industry as a whole.

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AUTHOR CONTRIBUTIONS

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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