The Effect of Ballet-Based Training on the Lower Limb Kinematic Characteristics of the Take-off Phase in the Toe Loop Jump of Female Figure Skaters

Yueqi Li

School of Music and Dance, Shenzhen University, 518000, Shenzhen, Guangdong, China

Keywords: Ballet-Based Training; Figure Skating; Toe Loop Jump; Take-off Phase; Lower Limb Kinematics; Knee Flexion; Hip Flexion; Pelvic Tilt; Markerless Motion Capture; Statistical Parametric Mapping (SPM1d)

Abstract: To address the need for enhanced technical precision and kinetic chain efficiency in the take-off phase of the toe loop jump among female figure skaters, this study investigated the effects of ballet-based training using a rigorous kinematic analysis framework. Twelve amateur skaters (aged 11–15 years) capable of performing a single-revolution toe loop jump were recruited and assigned to an experimental group ($n = 6$; ≥12 months of structured ballet training) or a control group ($n = 6$; minimal or no ballet exposure) based on training history. Off-ice standardized take-offs were captured using the OpenCap markerless motion capture system, and joint angle trajectories for bilateral knees, hips, and pelvic tilt were analyzed via Statistical Parametric Mapping (SPM1d) to characterize intergroup differences in movement patterns. The analysis revealed that ballet-trained skaters exhibited significantly greater left knee and hip flexion and larger pelvic tilt excursions, reflecting increased lower-limb loading capacity, deeper center-of-mass lowering, and more coordinated sequencing of joint extension. These findings support the conclusion that ballet-based and floor-control training contribute to improved flexibility, postural stability, and neuromuscular coordination, providing empirical justification for integrating such methods into youth figure skating development programs in combination with accessible motion capture systems for individualized performance monitoring.

1. Introduction

Figure skating is a competitive sport that intricately integrates artistic performance with technical execution, demanding exceptional body control, coordination, and spatial awareness from athletes. In the ladies' singles event, jumps represent a key scoring component. Among these, the toe loop jump—valued for its relatively high base score and its self-generated take-off without external assistance—is widely utilized in both solo jumps and high-difficulty combinations. It serves as an important indicator of a skater's technical ability and overall control.

The toe loop jump consists of four distinct phases: entry preparation, toe-pick take-off, aerial rotation, and landing glide. Of these, the take-off phase serves as the starting point of the kinetic chain and directly influences the aerial trajectory and landing stability. It is, therefore, the most critical stage in the jump sequence. Successful take-off execution largely depends on the coordination among lower limb joint force timing, angular changes, and trunk stability. Quantitatively analyzing the kinematic features of this phase is essential for understanding jump mechanics and guiding targeted training interventions.

Within current youth figure skating development systems, increasing emphasis is being placed on foundational physical training as a means of enhancing technical performance. Ballet-based training, in particular, is commonly incorporated into figure skating programs for its focus on core control, lower limb strength coordination, posture extension, and spatial expression. By emphasizing body-line symmetry, rhythmic movement, and precise control of the center of mass, ballet theoretically provides a strong foundation for body control and technical expression during jump execution[1]. However, despite its widespread adoption in practice, there remains a lack of systematic, quantitative

  DOI: 10.25236/gemmsd.2025.083

evidence regarding whether ballet-based training produces measurable kinematic improvements, particularly in the take-off phase.

Existing research on ballet's influence in figure skating has primarily examined performance quality, aesthetics, or subjective evaluation of aerial positions. Few studies have investigated objective biomechanical parameters, such as time-series changes in joint angles. Among amateur or novice athletes, technical execution is more likely to be constrained by physical capacity and control, making them susceptible to common errors such as delayed take-off, incorrect force application direction, and poor synchronization of lower limb flexion–extension. These limitations can impair jump quality but are also more readily improved through targeted foundational training. Consequently, investigating differences in key technical elements between skaters with and without ballet-based training holds substantial theoretical and practical significance[2].

Traditional 3D motion capture systems, while accurate, are often costly and logistically demanding, limiting their applicability in real training environments. In recent years, markerless motion capture systems such as OpenCap—powered by video reconstruction algorithms—have advanced rapidly, enabling efficient acquisition of multi-joint kinematic data. Such systems are especially suitable for controlled, repeatable movements in off-ice simulated training, allowing researchers to capture take-off joint motion in natural, non-intrusive conditions. This provides a reliable platform for quantitatively comparing athletes of different training backgrounds.

Given this context, the present study recruited amateur female skaters with and without ballet-based training backgrounds to investigate the take-off phase of an off-ice simulated toe loop jump. Using OpenCap, we captured angular changes in the left and right knees, left and right hips, and pelvic tilt. Standardized time-series analysis combined with Statistical Parametric Mapping (SPM1d) was used to compare joint control strategies, force-application timing, and postural stability between groups. The aim was to determine whether ballet-based training produces identifiable kinematic differences during the take-off phase[3].

The findings from this study are expected to enhance the understanding of figure skating jump mechanics—particularly the movement generation processes in the take-off phase—and provide quantitative evidence for evaluating the effectiveness of ballet-based training. This may also inform evidence-based approaches for optimizing technical skills among youth amateur skaters and promote the scientific integration of foundational training into specialized skill development[4][5].

2. Methods

This study employed a cross-sectional comparative design to examine the influence of ballet-based training on the lower limb kinematic characteristics of amateur female figure skaters during the take-off phase of an off-ice simulated toe loop jump. Given the potential for ballet training to induce long-term adaptations in movement control and postural stability, participants were divided into two groups based on training history: those with long-term ballet-based training and those without systematic ballet experience. All participants performed standardized off-ice simulated toe loop take-offs under identical testing conditions. The analysis focused on the take-off phase, capturing time-series joint kinematic data to identify potential differences in movement control strategies between groups.

2.1 Participants

Twelve amateur female figure skaters (aged 11–15 years) with the technical ability to perform a toe loop jump were recruited. All had a minimum of two years of skating experience and could consistently execute a single-revolution toe loop. Participants were grouped according to ballet training history:

Experimental group ($n = 6$): had completed at least 12 months of ballet-based training (≥ 2 sessions per week), covering basic ballet technique, floor exercises, and body control classes.

Control group ($n = 6$): had never received ballet training or had only attended less than three months of sporadic classes.

All participants were members of the same municipal-level skating club, trained under the same coaching staff, and had not sustained major injuries within the preceding two months. Written informed consent was obtained from each participant's legal guardian, and the study protocol was approved by the institutional ethics committee.

2.2 Movement Task and Testing Procedure

An off-ice simulation protocol was used to isolate the take-off phase and avoid confounding effects from aerial rotation and landing. The target movement was a simulated toe loop take-off: participants stood on a flat surface in a standard toe loop stance and performed the full force-generation and push-off sequence, replicating on-ice take-off mechanics as closely as possible. Arm swings were permitted, but no aerial rotation or landing was included.

Testing took place in a standardized training venue with a non-slip mat surface. Each participant performed five simulated take-offs, from which the first three technically stable and complete trials were selected for analysis. Prior to testing, all participants completed a 10-minute standardized warm-up, including dynamic stretching and jump simulation drills, to ensure movement consistency and optimal muscle readiness, as shown in Figure 1:

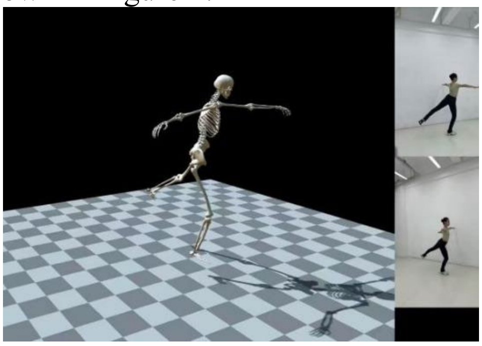

Fig. 1 OpenCap markerless motion capture system

2.3 Data Acquisition and Processing

A markerless 3D motion capture system (OpenCap) was used, employing two iPhone 16 Pro cameras recording at 60 Hz from synchronized angles. Camera positioning followed OpenCap's dual-camera calibration protocol, including chessboard calibration and placement of a field ruler prior to recording. Participants wore tight-fitting athletic clothing to prevent occlusion of anatomical landmarks.

The OpenCap platform automatically reconstructed a standardized human skeletal model and generated angular change data for selected joints. The take-off phase was defined from the onset of preparatory flexion in the take-off leg to the moment when the toe-pick leg completely left the ground. All kinematic data were expressed as frame-by-frame joint angles, normalized to 100 data points representing 0%–100% of the take-off cycle.

Five key variables were extracted:

-Left knee flexion angle

-Right knee flexion angle

-Left hip flexion angle

-Right hip flexion angle

-Pelvic tilt angle

These indicators collectively describe the angular movement patterns of lower limb extension and pelvic control, providing insights into force-generation strategies, joint coordination, and postural stability during take-off, as shown in Figure 2:

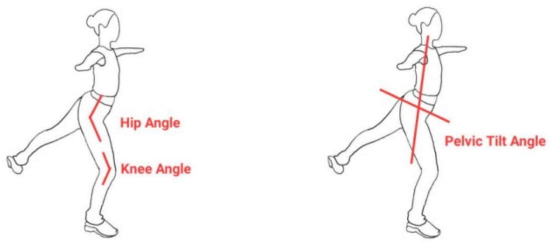

Fig. 2 Biomechanical indicators

2.4 Data Analysis

To preserve the dynamic characteristics of the movement, Statistical Parametric Mapping (SPM1d) was applied to the standardized time-series data. SPM1d enables point-by-point statistical testing across the entire time domain, offering greater sensitivity than traditional peak-value analysis for detecting subtle differences during cyclic or short-duration high-intensity movements in kinematic studies.

All analyses were performed in MATLAB using the spm1d toolbox. For each variable, independent-samples t-tests were conducted to compare the two groups' joint angles throughout the take-off cycle. The significance level was set at $\alpha = 0.05$, with thresholds corrected using Random Field Theory. Significant time intervals were identified as supra-threshold clusters in the SPM plots. Mean ± standard deviation curves were plotted for each group, with significant intervals highlighted to indicate the timing and phase of observed differences.

3. Results

A comparative analysis was conducted between the ballet-trained and non-trained groups on the lower limb kinematic characteristics of an off-ice single-revolution toe loop take-off. The main findings are presented below.

3.1 Left and Right Knee Joint Angles

Changes in the left knee flexion angle are illustrated in Figure 3, with the corresponding SPM statistical results shown in Figure 4. In the ballet-trained group, the left knee flexion angle reached its maximum at approximately 70% of the normalized take-off cycle, with a peak angle of about 70°. In contrast, the non-trained group reached its peak at approximately 40% of the cycle, with a maximum angle of around 23°.

Changes in the right knee flexion angle are presented in Figure 5 with SPM results in Figure 4 & Figure 6. Significant group differences were observed between approximately 30% and 40% of the take-off cycle, with the ballet-trained group demonstrating greater angles than the non-trained group. No significant differences were identified in the remaining portions of the cycle.

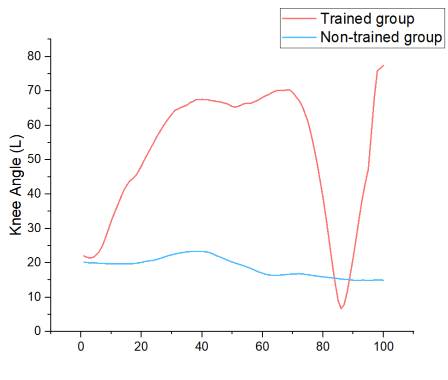

Fig. 3 Left Knee Joint Angle

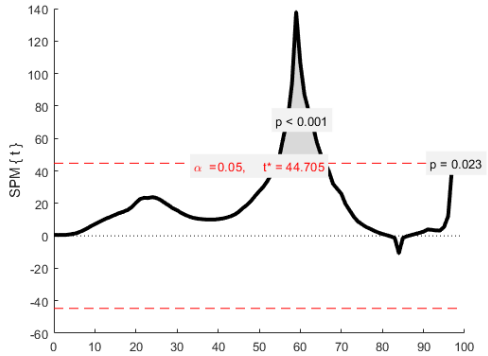

Fig. 4 Left Knee Joint Angle SPM test results

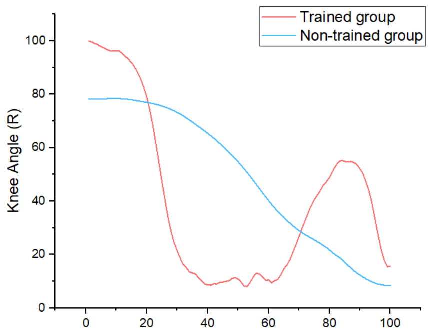

Fig. 5 Right Knee Joint Angle

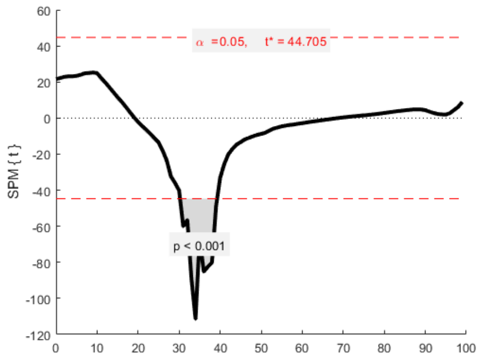

Fig. 6 Right Knee Joint Angle SPM test results

3.2 Left and Right Hip Joint Angles

Changes in the left hip flexion angle are shown in Figure 7, with SPM results in Figure 8. Significant differences between groups occurred between approximately 50% and 60% of the cycle, with the ballet-trained group reaching a maximum angle of approximately 90° at around 58% of the cycle, followed by a gradual decrease after 60%. The non-trained group showed no substantial fluctuations in left hip flexion across the cycle.

Changes in the right hip flexion angle are shown in Figure 9, with SPM results in Figure 10. No significant group differences were detected during the take-off phase. However, the ballet-trained group displayed a pattern of initial decrease followed by an increase, whereas the non-trained group exhibited a steady, gradual decline throughout the cycle.

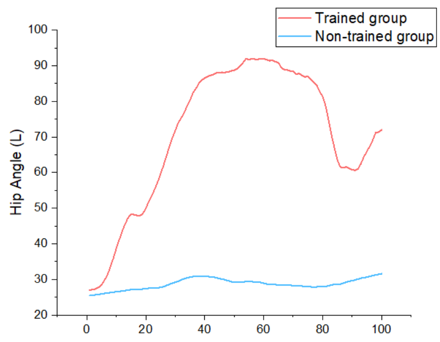

Fig. 7 Left Hip Joint Angle

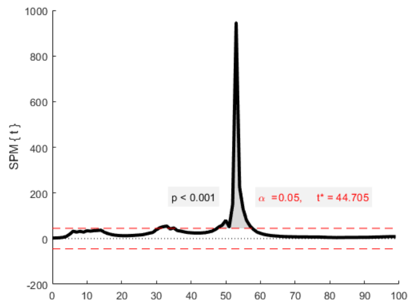

Fig. 8 Left Hip Joint Angle SPM test results

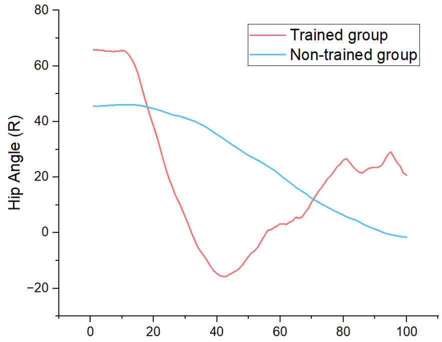

Fig. 9 Right Hip Joint Angle

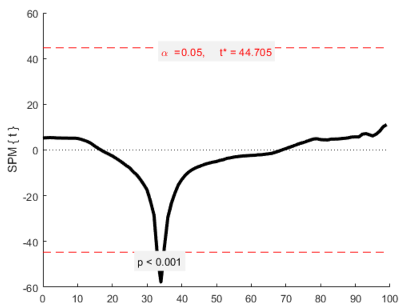

Fig. 10 Right Hip Joint Angle SPM test results

3.3 Pelvic Tilt Angle

Changes in pelvic tilt angle are depicted in Figure 11, with SPM results in Figure 12. Significant group differences were identified between approximately 40% and 50% of the take-off cycle. In the ballet-trained group, pelvic tilt decreased steadily from −17.5° to −52.5° during the first 45% of the cycle, followed by an increase to −12.5° between 45% and 100%. In contrast, the non-trained group's pelvic tilt decreased from −18.5° to −27.5° in the first 45% of the cycle, then continued to decline gradually thereafter.

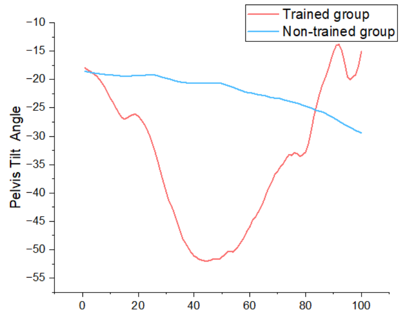

Fig. 11 Pelvic Tilt Angle

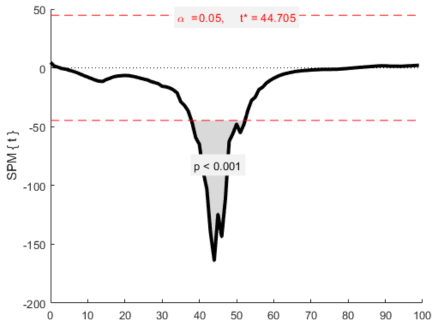

Fig. 12 Pelvic Tilt Angle SPM test results

4. Discussion

The comparative analysis between ballet-trained and non-trained figure skaters during the off-ice execution of a 360° toe loop take-off revealed that the primary differences occurred in the angular changes of the left knee, left hip, and pelvic tilt. These findings highlight the biomechanical influence of ballet-based training on lower limb movement patterns and postural control during take-off.

4.1 Lower Limb Extension Movements

In a toe loop jump, the left leg functions as the gliding leg that extends during take-off, while the right leg serves as the toe-pick leg, initiating the upward propulsion. After entering the take-off from a glide, the left leg should actively flex at the knee to lower the center of mass, preserving glide speed and generating potential energy for extension. The right leg extends fully behind the body to maintain balance and ensure complete hip and knee extension before engaging the toe-pick[6][7]. The magnitude and timing of the left leg's extension are critical determinants of both jump height and take-off velocity.

The present results indicate that ballet-trained skaters executed more complete and coordinated lower limb extensions. Figures 5 and 6 show that the ballet-trained group exhibited larger changes in left knee and left hip flexion angles compared with the non-trained group. The variability in these angles suggests active modulation of joint motion, whereas the non-trained group displayed flatter, less dynamic curves—indicating reliance on forced muscular contraction to jump upward rather than using joint flexion to store and release elastic energy. This lack of effective joint loading in the non-trained group likely limited their ability to lower the center of mass, reduced glide speed, and constrained the muscle lengthening–shortening cycle, ultimately impairing take-off height, rotation, and overall jump execution quality[2].

The data for both knees and hips further suggest that systematic ballet training enhances the ability to actively flex the joints, effectively lower the center of mass, and preserve glide speed before take-off. This finding supports the notion that foundational ballet technique, floor exercises, and body control training produce lasting improvements in lower limb extension mechanics, benefiting both the take-off and preparatory phases[3].

4.2 Pelvic Tilt Control

In a toe loop jump, increased anterior pelvic tilt allows the skater to fold at the hips while maintaining upper body stability, thereby lowering the center of mass and optimizing take-off conditions. This action enhances stability during the loading phase and facilitates an efficient transfer of force during the subsequent rapid extension[8].

Our results show that the ballet-trained group achieved a much greater range of pelvic tilt—decreasing from −17.5° to −52.5° before returning to −12.5°—compared with the modest range of the non-trained group (−18.5° to −27.5°). This pronounced change suggests that ballet-trained skaters possess superior muscular control and are better able to actively deepen hip and knee flexion, fold the pelvis, and stabilize the body prior to take-off. The sharp decrease followed by a rapid increase in pelvic tilt in the ballet-trained group reflects a deliberate preparatory movement pattern designed to store and release energy efficiently[4].

Conversely, the non-trained group's smaller and more gradual change in pelvic tilt implies limited capacity to coordinate upper and lower body segments effectively. This restriction likely contributed to stiffer, less continuous take-off movements, reducing jump height and speed[5][9].

5. Conclusions

5.1 Key Findings

(1) Enhancement of lower limb flexibility and loading capacity

Ballet-based training effectively improves the flexibility of the knee and hip joints. Skaters who have undergone systematic ballet training are able to deepen joint flexion during the take-off phase of the toe loop jump, actively storing energy for extension and thereby achieving greater take-off height and velocity.

(2) Improved postural stability through muscular control

By strengthening whole-body muscular control, ballet-based training enables skaters to maintain upper body stability while fully flexing the knees and hips and folding the pelvis. This lowers the center of mass effectively, preserving the integrity and continuity of the kinetic chain during take-off.

(3) Optimization of take-off timing and coordination

Ballet-based training enhances an athlete's ability to dynamically adjust posture and joint positions before and after take-off. At the instant of leaving the ground, trained skaters can achieve deeper lower limb extension and pelvic flexion, improving center-of-mass stability and take-off efficiency.

5.2 Training Recommendations

(1) Basic Movement Optimization

Ballet-based single-leg squat combinations: Actively flex the knee joint to strengthen extension power and joint stability.

Ballet-based control combinations: Actively extend the lower limbs while maintaining upper body stability to improve synchronization between knee, hip, and pelvic movements.

(2) Core Take-off Integration

Resistance band-assisted off-ice take-off drills: Deepen left knee flexion while actively pulling with the right knee to establish a complete lower limb kinetic chain for take-off.

Targeted obstacle take-offs: Control trunk forward lean, determine the optimal toe-pick location, and refine posture adjustments at the instant of take-off.

(3) Technical Transfer

Multi-environment adaptability training: Integrate off-ice, harness-assisted, and on-ice practice to ensure effective technical transfer and minimize environmental effects on movement patterns.

References

[1] Flanagan L, Quin E, Smith N A. Increased leap performance with no change to knee-drop landing kinetics, following a verbal cueing intervention[J]. Journal of Dance Medicine & Science: Official

Publication of the International Association for Dance Medicine & Science, 2025, (preprint): 1-9. DOI:10.1177/1089313X251318544.

[2] Vinken P. Kinematic motion characteristics and observer's expertise in perceived aesthetics of dance jumps[J]. Research in Dance Education, 2022, 25: 32-48. DOI:10.1080/14647893. 2022.2033714.

[3] Meriç B, Akdeniz H, Ağca Ö, Aydin M. The impact of core training in figure skating on the lower extremity kinematics of loop and toe loop jumps[J]. Niğde Üniversitesi Beden Eğitimi ve Spor Bilimleri Dergisi, 2017, 11(2): 188-194.

[4] Rebelo A, Pereira J, Martinho D, Valente-Dos-Santos J. Effects of a velocity-based complex training program in young female artistic roller skating athletes[J]. Journal of Human Kinetics, 2023, 86: 217-234. DOI:10.5114/jhk/159654.

[5] Hirosawa S. Kinematic considerations for achieving the quadruple axel jump: comparison with triple axel jumps among world-class figure skaters using tracking data[J]. Sports Biomechanics, 2025: 1-12. DOI:10.1080/14763141.2025.2464787.

[6] Chen L. Application of ballet basic training in figure skating training[J]. China Winter Sports, 2010. https://consensus.app/papers/application-of-ballet-basic-training-in-figure-skating-ling/247267c8444f5e5693ab0b57a999f4c7.

[7] Chen L. Ballet didactics in the dance training of figure skating[J]. China Winter Sports, 2011. https://consensus.app/papers/ballet-didactics-in-the-dance-training-of-figure-skating-ling/0652eddee30259f990141bfee441d787.

[8] Tang Y. Training of the figure skaters' dance skills[J]. China Winter Sports, 2011. https://consensus.app/papers/training-of-the-figure-skaters-dance-skills-yi-dan/505a0feed5765ffebeec2bcb258e600c.

[9] Teplá L, Procházková M, Svoboda Z, Janura M. Kinematic analysis of the gait in professional ballet dancers[J]. Acta Gymnica, 2014, 44(2): 85-91. DOI:10.5507/AG.2014.009.