

Performance Evaluation of Penché Rotation in Rhythmic Gymnastics Using Statistical Parametric Mapping

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Abstract: In rhythmic gymnastics (RG), maintaining balances is essential for the successful execution of routines. In coaching practice, objective tools for assessing balance during routine execution are essential. Kinematic movement patterns have been analyzed using statistical parametric mapping (SPM), which evaluates movement and improves the understanding of tasks. This study examined three-dimensional (3D) lower extremity joint angles during static balance exercises and penché rotation in RG, then evaluated performance in penché rotation with SPM. The results showed a significant difference in the joint angles of the supporting leg during the initiation of rotation, while this difference tended to persist throughout the entire rotation for the lifted leg. This may indicate which specific joint motions do not align with threshold values in the movement patterns of the static balance test, which can be interpreted as a performance issue in dynamic rotation. This underscores SPM as a valuable tool for evaluating performance during rotation techniques in RG.

1 INTRODUCTION

Rhythmic gymnastics (RG) is a highly technical and artistic sport that requires athletes to integrate strength, flexibility, coordination, and precise execution of complex movements (Agopyan & Örs, 2019). Gymnasts incorporate the same jumps, balance elements, and rotations in their routines, emphasizing the significance of rotational elements during the 2013-2016 Olympic cycle (Gateva, n.d.). Among these, executing the high turn of the back leg is one of the most challenging elements, demanding exceptional balance, lower-body strength, and control. It is also called penché rotation (Agopyan & Örs, 2019). The successful execution of this movement significantly impacts scoring and overall

performance in competitive RG (Aleksandraviciene, Zaicenkoviene, Stasiule, & Stasiulis, 2015).

In RG, gymnasts perform balance exercises by standing on one leg while the free leg is raised in different positions, which is an extreme challenge in terms of postural balance. The primary factors affecting balance include genetic predisposition, vestibular system condition, age, support surface, center of gravity height, limb positioning, training, strength, coordination, flexibility, emotional state, and fatigue (Sobera & Rutkowska-Kucharska, 2019a). Balance exercise can generally be categorized into static (maintaining a stable position while stationary) and dynamic balance (maintaining stability during movement). Both balances are crucial for routine execution, as RG prioritizes accuracy and perfection (Shigaki et al., 2013). Several studies have

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examined the kinematics of various gymnastics movements, focusing on flexibility, muscle activation, and balance control (Donti, Bogdanis, Kritikou, Donti, & Theodorakou, 2016). Performance variability in balance tasks was twice as high in the younger gymnast compared to the older one (Rutkowska-Kucharska, Szpala, Jaroszczuk, & Sobera, 2018). Sobera et al. (2019a) noted that balance abilities vary significantly across different age groups, making it difficult to generalize results across all skill levels. However, balance stability in RG remains a complex task. In coaching practice, objective tools for assessing balance during routine execution are essential.

Differences in kinematic waveforms between tasks have been assessed using statistical parametric mapping (SPM), which evaluates movement and improves the understanding of strategies employed to achieve the various tasks (Martonick et al., 2022). This improved understanding can lead to enhanced performance, effective treatment approaches for sports injuries, precise strength and conditioning programs, and improved rehabilitation strategies (Yona, Kamel, Cohen-Eick, Ovadia, & Fischer, 2023). Several studies have applied SPM to the field of biomechanics. Morais et al. (2024) compared the swimming velocity among different levels of swimmers using SPM. Patoz et al. (2022) assessed the association of the factor and the step frequency on the running kinetics using SPM. To our knowledge, no studies have employed the SPM method to evaluate performance during execution in RG, which could demonstrate the differences in kinematic waveforms between static trials and dynamic rotations. The aim of the present study was to analyze the 3D joint angles of the lower extremities during a static balance test and penché rotation using a wearable IMU system. We then assessed the performance of the penché rotation technique in RG using SPM by comparing it with static balance exercises.

2 MATERIALS AND METHODS

2.1 Participants

In this study, six female gymnasts participated (age 13 ± 1 years; height, 157.5 ± 4.5 cm; body mass, 41.5 ± 2.5 kg), who have been trained for the Asian championship 2024. All participants had no musculoskeletal injuries within the past year. This study was approved by the Institutional Review Board of the Mongolian University of Science and Technology and the Research Ethical Committee of

the Mongolian National University of Education. Before collecting data, informed consent was obtained from all participants and their coaches.

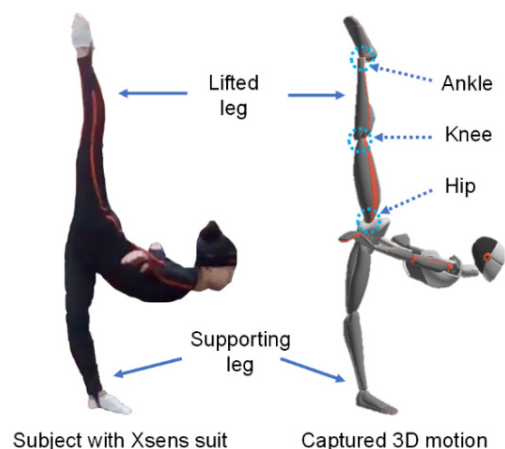


Figure 1: Participants wear Xsens MVN suits, and perform a static balance test.

2.2 Experimental Setup

The Xsens wearable motion capture system (MVN Analyze, Movella, Netherlands) was used to capture full-body joint kinematics during static balance and dynamic rotation in RG. The recording sampling rate was 120 Hz. It has been shown that this system is one of the most commonly used IMU-based wearable motion capture systems for assessing performance and techniques in sports activities (Camomilla, Bergamini, Fantozzi, & Vannozzi, 2018; Khuyagbaatar et al., 2024). The system includes 17 IMU sensors, a body pack, and a wireless router. The body pack connects several strings of sensors and collects their data through a wireless link to the router, which is connected to a computer running Xsens MVN Analyze software (Schepers, Giuberti, & Bellusci, 2018). The 17 IMU sensors placed on the head, sternum, pelvis, left/right shoulder, upper arm and forearm, hand, upper and lower leg, and foot under the suit (Dambadarjaa et al., 2024). In the MVN Analyze software, participant height and foot length were entered to create a 23-link rigid body biomechanical model, which automatically calculated 3D joint angles during movements (Khuyagbaatar et al., 2025). Before the experiment, all gymnasts were asked to perform N-pose and T-pose calibration, which estimates the orientation of the sensors with respect to the corresponding segments as well as the proportions of the person being tracked (Schepers et al., 2018). Then, participants were asked to perform three times of static balance tests and penché rotation technique.

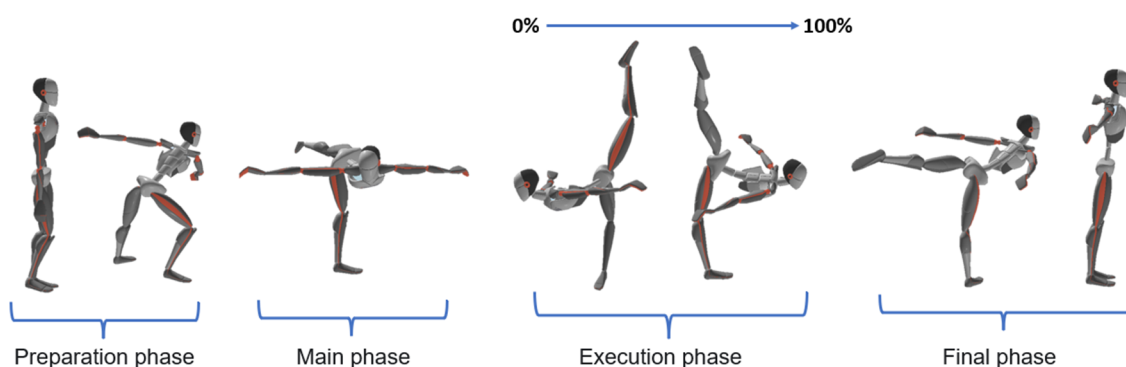


Figure 2: Execution of the penché rotation technique. Indicates the four main phases: preparation phase, main phase, execution phase and final phase.

Details of static balance and rotation technique can be found in section 2.3.

2.3 Static Balance and Penché Rotation

Gymnasts first performed a static balance test while wearing an Xsens MVN suit with IMU sensors under the supervision of an experienced coach. The static balance test is defined as standing on one leg with a flat foot while holding the other leg back (Figure 1).

This exercise requires much more activation of all muscles since it requires one leg stance with the free leg positioned vertically in a split, and the trunk must be bent forward as close to the horizontal direction as possible (Sobera & Rutkowska-Kucharska, 2019b). Then, they performed a 360-degree penché rotation technique, which requires the trunk to bend forward and the leg to be positioned almost at a 180-degree angle backward (Batista, Garganta, & Ávila-Carvalho, 2023). It has been noted that the most frequently executed rotation in competition because gymnasts can achieve a high number of turns, probably because it is performed with a flat foot (Agopyan & Örs, 2019) (Figure 2). This technique has four main phases: preparation phase, main phase, execution phase, and final phase (Lisitskaya, 1982).

2.4 Statistical Analysis

Before conducting statistical analysis, all kinematic data were time-normalized to a full task cycle consisting of 100 data points (Papi, Bull, & McGregor, 2020). In the static balance test, the start (0%) and end points (100%) are defined between the holding position depicted in Figure 1. For penché rotation, the start (0%) and end points (100%) correspond to the beginning and end of the execution phase, as illustrated in Figure 2. SPM was used to statistically compare lower extremity joint angles

between the static balance test and the execution phase of the penché rotation by implementing open-source spm1d MATLAB code (www.spm1d.org).

3 RESULTS

During the rotation, gymnasts exhibited increased plantarflexion of the ankle ($p=0.001$, 0-27%) and hyperextension of the knee ($p=0.024$, 0-21%) and hip ($p=0.046$, 0-10%) in the supporting leg, while demonstrating a more flexed knee ($p<0.001$, 0-100%) in the lifted leg throughout the entire execution phase compared to the static balance test (Figure 3). In the frontal plane of motion, greater ankle adduction ($p=0.038$, 0-6%) was observed in the supporting leg during the initial stage of execution. For the lifted leg, there was increased ankle abduction ($p < 0.001$, 0-74%), knee adduction ($p = 0.010$, 9-42%), and hip adduction ($p < 0.001$, 0-100%) (Figure 4). In the transverse plane of motion, greater ankle ($p<0.001$, 0-82%) and knee internal rotation ($p=0.005$, 0-16%) and hip external rotation ($p<0.001$, 0-100%) were demonstrated. For the lifted leg, there was only knee external rotation, which increased significantly ($p < 0.001$, 0-100%) throughout the entire execution phase (Figure 5).

4 DISCUSSIONS

This study applied SPM analysis to assess the performance in penché rotation in RG by comparing lower extremity kinematics in three anatomical planes against a static balance test. The SPM analysis allows for the analysis of movement complexity as a entirety (Papi et al., 2020). Results showed a difference in joint kinematics for supporting and

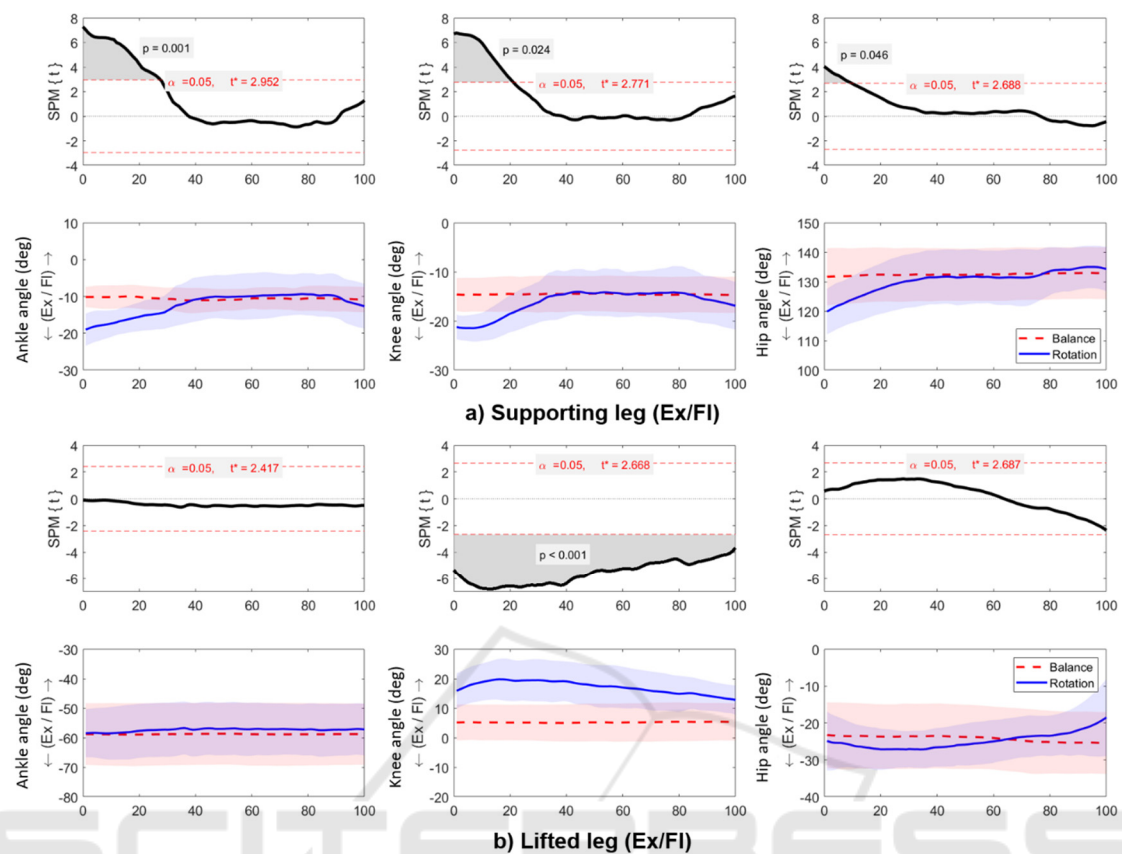


Figure 3: Kinematic waveforms for ankle, knee, hip in sagittal plane. A solid blue line indicates rotation technique, and a dashed red line indicates balance test. Shaded gray areas indicate where the threshold was exceeded.

lifted legs during static balance and dynamic rotation techniques. This could indicate which specific joint motions do not align with threshold values in the movement patterns of the static balance test, which can then be interpreted as a performance issue in dynamic rotation. Assessing the overall movement patterns revealed that performing the rotation technique caused the supporting leg's ankle and knee joints to be more extended and internally rotated at the start of the movement. While flexion and external rotation of the knee, as well as adduction of the hip, differed significantly from the static pose, these changes could negatively impact the performance level. For the lifted leg, the knee joints were flexed and externally rotated throughout the execution. Additionally, ankle abduction and hip adduction were observed during the entire rotation, which may help stabilize the rotation but could lead to poor performance. Generally, the SPM indicated that a significant difference in the kinematics of the supporting leg was observed during the initiation of rotation, while this difference tended to persist throughout the entire rotation for the lifted leg.

The 3D joint kinematics in RG were measured using the Xsens MVN system, which is the most commonly used commercial wearable system with an error below 10 degrees, and is recommended for feedback training during gymnastic movements (Barreto et al., 2021). During the penché rotation, which requires bending the torso forward and opening the leg 180° backward (Agopyan, 2014). In kinematic measurement with the Xsens system, the opening of the leg angle can be represented by the supporting leg's flexion and the lifted leg's extension. Our results indicated that the supporting leg's flexion ranged from 122° to 141°, while the lifted leg's extension varied from 14° to 32° during the static balance test, leading to a maximum leg angle opening of about 170°. During rotation, the supporting leg's flexion ranged from 112° to 127°, and the lifted leg's extension varied from 18° to 32° at the start of execution, which was about 160° of opening of the leg. As a result, the flexion-extension range of motion of the lifted leg is similar between static and rotational movements except for the knee joint angle, while the joint angles of the supporting leg differ during the

initiation of execution. This was also confirmed by SPM analysis. Thus, athletes should be aware of the extension that occurs in the supporting leg during the initiation of the rotation.

A study has several limitations. While whole-body kinematics are important for balance, only lower extremity joint kinematics were compared between the static balance test and the rotation technique. The sample size and lack of diversity may have affected the results. Future studies will involve high-level professional gymnasts with a larger sample size, which may help to provide more insights into the relationship between the balance test and rotation techniques.

then assessed the performance of the penché rotation techniques using SPM analysis, comparing it to static balance exercises. The SPM analysis revealed a significant difference in the kinematics of the supporting leg during the initiation of rotation (0-30%), while this difference tended to persist throughout the entire rotation for the lifted leg. This could indicate which specific joint motions do not align with threshold values in the movement patterns of the static balance test, which can then be interpreted as a performance issue in dynamic rotation. This highlights the SPM as a valuable tool for evaluating performance during rotation techniques in RG.

5 CONCLUSIONS

We analyzed the 3D joint angles of the lower extremities during the static balance test and penché rotation technique using a wearable IMU system. We

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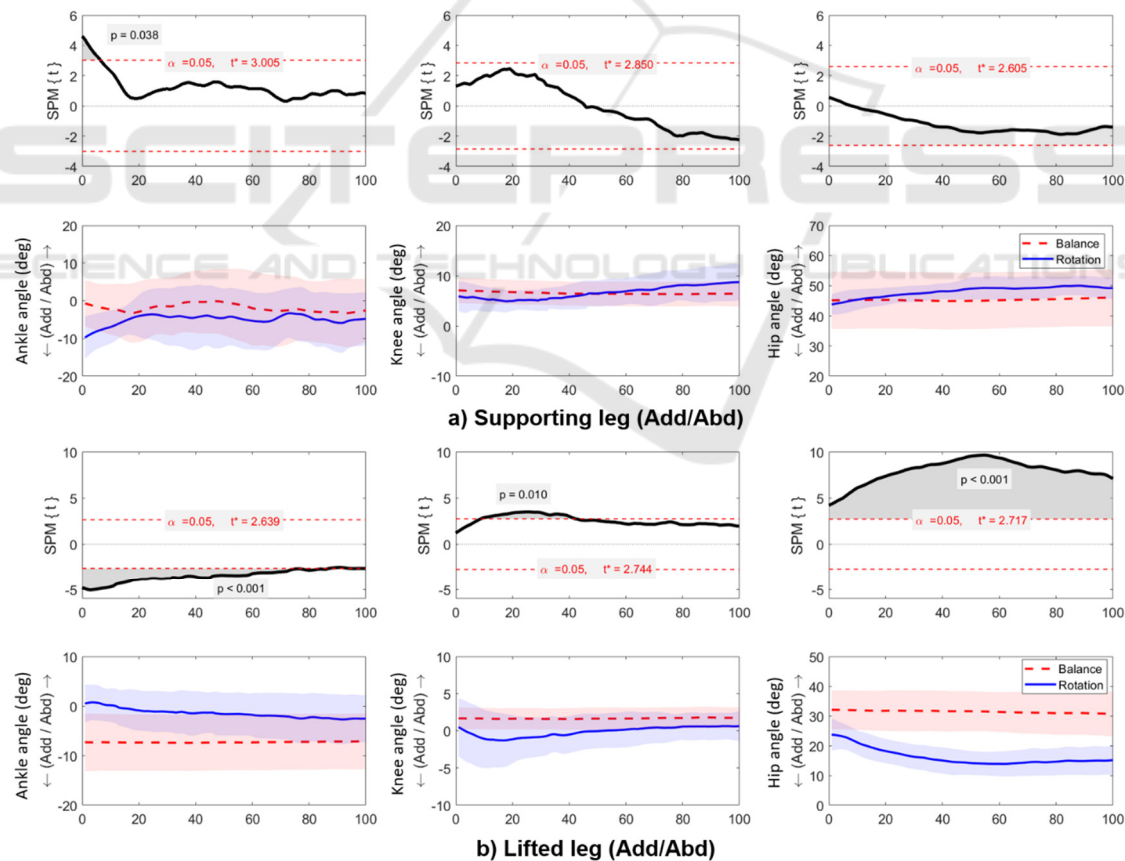


Figure 4: Kinematic waveforms for ankle, knee, hip in frontal plane. A solid blue line indicates rotation technique, and a dashed red line indicates balance test. Shaded gray areas indicate where the threshold was exceeded.

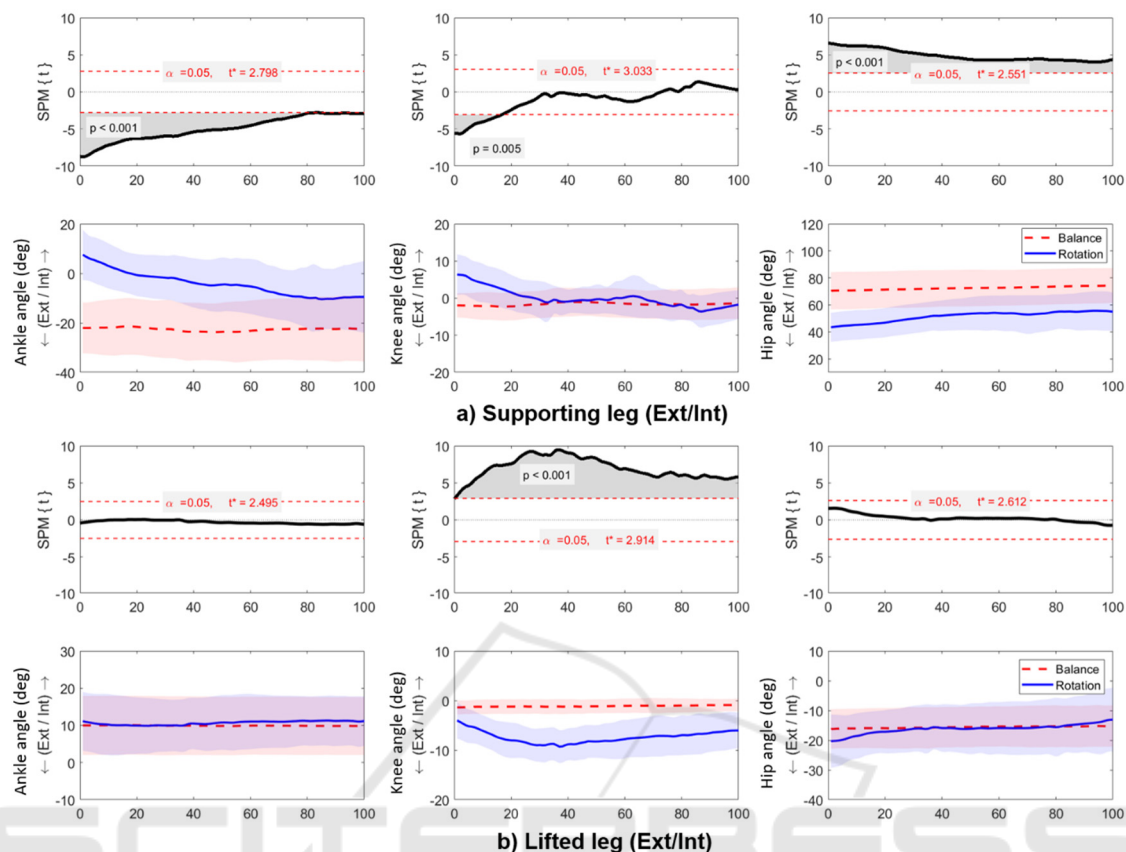


Figure 5: Kinematic waveforms for ankle, knee, hip in transverse plane. A solid blue line indicates rotation technique, and a dashed red line indicates balance test. Shaded gray areas indicate where the threshold was exceeded.

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