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Article

Comprehensive assessment of lower limb alignment and forces during dance landings under fatigue

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Abstract: This study investigates the impact of fatigue on Lower Limb Alignment (LLA) and Ground Reaction Forces (GRF) during dance landings, intending to understand how fatigue-induced changes affect joint mechanics and stabilization in trained dancers. Thirty dancers (mean age: 23.4 years) with a minimum of three years of training in high-impact dance forms, such as ballet and contemporary dance, participated in the study. A within-subject experimental design assessed each participant's landing mechanics before and after a fatigue-inducing protocol. Kinematic data were captured using a 3D motion capture system, while kinetic data were recorded with force plates. Joint angles at the hip, knee, and ankle were measured during the landing's initial contact, peak force, and stabilization phases. Vertical and medial-lateral GRF and time to stabilization (TTS) were also analyzed pre- and post-fatigue. The fatigue protocol consisted of plyometric exercises and repetitive dance-specific movements designed to mimic the physical demands of a dance performance. Measurements were taken immediately after the fatigue protocol and at intervals of 15 min, 1 h, 24 h, and 48 h post-fatigue to assess both immediate and delayed effects of fatigue. Significant changes in joint angles were observed across all phases of the landing. Post-fatigue, hip and knee flexion increased significantly at initial contact (hip: +2.7°, knee: +3.6°, $p < 0.05$), reflecting compensatory adjustments for impact absorption. Ankle dorsiflexion also increased significantly during stabilization (+2.7°, $p = 0.028$). Vertical GRF increased across all phases post-fatigue (initial contact: +4.4 N/kg, $p = 0.009$), indicating a reduced ability to absorb impact forces efficiently. TTS was significantly prolonged at all post-fatigue intervals, particularly within the first 15 min post-exertion (+34 ms, $p = 0.008$), suggesting impaired neuromuscular control and balance.

Keywords: lower limb alignment; ground reaction forces; motion capture system; stabilization; neuromuscular control

1. Introduction

Dance is a physically demanding art form that requires strength and precision, especially in movements involving jumps and landings [1]. These high-impact movements place significant stress on the lower limbs, particularly the joints, muscles, and tendons, which must work in tandem to absorb forces and maintain balance [2,3]. As dancers are subjected to prolonged periods of physical exertion, they experience fatigue, which can impair their ability to land safely and efficiently [4,5]. Fatigue-induced changes in landing mechanics can compromise performance and increase the risk of musculoskeletal injuries, such as strains, sprains, or stress fractures, particularly in the lower limbs [6,7]. Thus, understanding how fatigue impacts the biomechanics of dance landings is critical for injury prevention and performance optimization [8].

Fatigue affects neuromuscular coordination and control, altering movement patterns and making it more difficult for the body to maintain proper alignment during physical activities [9]. Studies on athletes in other sports have shown that fatigue can result in increased joint flexion, altered Ground Reaction Forces (GRF), and delayed stabilization following impact [10,11]. These changes can reduce the efficiency of force absorption, placing additional strain on the musculoskeletal system [12]. In dance, where precise control and alignment are paramount, fatigue severely threatens performance quality and dancer safety [13].

While the impact of fatigue on athletic performance has been well-documented in sports such as running, basketball, and gymnastics, research focusing specifically on the effects of fatigue in dance, particularly in landing mechanics, is limited [14–16]. Most studies in dance biomechanics focus on injury risk factors, such as landing stiffness or foot placement, without adequately addressing how fatigue alters joint kinematics and kinetics [17,18]. Given the high demands placed on dancers during rehearsals and performances, understanding fatigue-induced changes in landing mechanics is critical to inform injury prevention strategies, training programs, and recovery protocols [19,20].

Dance landings, in particular, involve complex, dynamic movements that require precise neuromuscular control to avoid injury [21]. The hip, knee, and ankle joints must coordinate to absorb vertical forces upon impact, maintain balance, and stabilize the body [22]. Under fatigued conditions, these mechanisms can become compromised. Joint angles at the hip, knee, and ankle are likely to shift, and dancers may exhibit less control over GRF, leading to prolonged Time To Stabilization (TTS) and increasing the risk of lateral instability [23,24]. This has implications for dancers in professional settings, where fatigue accumulates throughout a performance or multiple rehearsals, potentially exacerbating the risk of acute and chronic injuries.

This study addresses the gap in the literature by examining how fatigue affects lower limb alignment (LLA) and the forces that are felt during dance landings. Specifically, it aims to explore the changes in joint angles, vertical and medial-lateral GRF, and TTS under fatigued conditions. The study focuses on the pre- and post-fatigue phases, using a within-subject design to assess fatigue's immediate and delayed effects on landing mechanics. Thirty trained dancers with varying levels of professional experience were recruited for the study, and motion capture technology alongside force plates was used to capture detailed kinematic and kinetic data. This study offers valuable insights for dance professionals, physical therapists, and biomechanists by providing a biomechanical profile of the fatigue-induced alterations in dance landing mechanics.

The rest of the paper is organized as follows: Section 2 outlines the methodology, including the experimental design, participants, fatigue protocol, and measurement apparatus. Section 3 presents the results, focusing on changes in joint mechanics and GRF before and after fatigue. Section 4 discusses the findings and their implications for performance and injury risk. Section 5 concludes with a summary of key insights, practical applications, and recommendations for future research.

2. Methodology

2.1. Study design

This study employed a within-subject experimental design to assess the impact of fatigue on LLA and GRF during dance landings. The participants, all trained dancers with varying levels of professional and semi-professional experience, were evaluated before and after undergoing a fatigue-inducing exercise protocol. The study aimed to simulate dancers' physical conditions during performances, mainly focusing on the biomechanical alterations that occur under fatigue. A total of 30 dancers, aged between 18 and 30, participated in the study. All participants had at least three years of training in dance forms that involved repetitive jumping and landing tasks, such as ballet, jazz, and contemporary dance. Dancers with musculoskeletal injuries within the past six months or any medical conditions that could potentially alter their movement patterns were excluded from the study. Each participant provided informed consent before data collection, and the institutional review board approved the study protocol.

Before the experiment, participants underwent a standardized 15-minute warm-up session consisting of dynamic stretches and low-impact movements to prepare for the physical demands of the test. After the warm-up, baseline data were collected during controlled jump landings typical of their dance routines. These landings were performed on a force plate, while motion capture technology was used to record the joint angles and alignment of the lower limbs, specifically focusing on the hip, knee, and ankle joints. To induce fatigue, participants engaged in a structured fatigue protocol involving a combination of high-intensity plyometric exercises and repetitive dance movements such as jetés and sautés. The fatigue protocol was designed to mimic the physical demands of a prolonged dance performance. Fatigue was monitored using subjective (perceived exertion) and objective (heart rate) measures. Post-fatigue data collection was conducted once participants reached a predefined level of physical exhaustion, as confirmed by their heart rate and self-reported fatigue levels. In the post-fatigue phase, participants performed the same jump-landing tasks as in the baseline phase. The motion capture system and force plates recorded data for comparison. These data allowed for an in-depth analysis of changes in LLA and the forces exerted during landings under fatigued conditions. Special attention was paid to joint angles at the hip, knee, and ankle and the vertical and horizontal GRF generated during landings.

2.2. Participants

This study involved 30 dancers recruited from local dance academies and professional companies. The participants were selected based on their extensive dance experience and proficiency in performance styles that demand frequent jumping and landing movements. All participants met strict inclusion criteria to ensure the relevance and quality of the data. The participants ranged in age from 18 to 29 years (mean age: 23.4 years). A balanced gender distribution was maintained, with 15 male and 15 female dancers participating in the study. All dancers had excellent physical health, with no reported musculoskeletal injuries in the past six months and no history of lower limb injuries or surgeries in the past year. The participants were advanced-level dancers with at least three years of training in dance styles requiring high-impact landings, such as ballet, contemporary, and jazz. On average, participants had 6.7 years of formal dance training (range: 3–12 years), and many were actively involved in professional or semi-professional dance productions during the study.

1) Professional Level: 12 participants had full-time careers in dance and regularly performed in professional companies or theatre productions. These dancers were highly conditioned to handle rigorous performance schedules' physical and mental demands.
2) Advanced Amateurs: 18 participants were pre-professional or involved in intensive dance programs at universities and conservatories. Though not yet entirely professional, these dancers had extensive training regimens and were regularly involved in high-level performances.

(see **Table 1**) All participants underwent a pre-screening process, which included a physical assessment by a certified sports therapist to ensure they were free from conditions that could affect the study's outcome. This screening ensured that participants were physically capable of completing the fatigue protocol without risking injury. The physical characteristics of the participants were recorded as part of the study. The average height was 167.8 cm, ranging from 155.2 cm to 181.9 cm. The average body weight was 60.4 kg, with the lightest participant weighing 49.3 kg and the heaviest 73.5 kg. The participants had an average Body Mass Index (BMI) of 21.4 kg/m^2, with BMI values ranging from 19.3 to 23.6 kg/m^2, which falls within the healthy range for their age group. These details were important for ensuring that any variations in landing mechanics were not related to differences in body size but rather to the effects of fatigue on biomechanical performance.

Table 1. Physical characteristics.

Characteristic	Average	Range
Height (cm)	167.8	155.2–181.9
Weight (kg)	60.4	49.3–73.5
Body Mass Index (BMI) (kg/m^2)	21.4	19.3–23.6

The physical characteristics were taken into account when analyzing biomechanical data to ensure any variances in landing mechanics were not attributed to differences in body mass or height but rather to fatigue-induced changes. Participants were required to demonstrate proficiency in at least one dance style with high-intensity landings.

The breakdown of dance styles was as follows:

1) Ballet: 60% (18 participants) had primary training in ballet, a style known for demanding vertical jumps and precise landings.
2) Contemporary Dance: 40% (12 participants) were primarily trained in contemporary dance, which incorporates a variety of dynamic movement patterns, including both vertical and lateral jumps.

3) Jazz Dance: 30% (9 participants) also had jazz dance experience, adding to the diversity of the landing techniques evaluated in the study.

All participants engaged in regular training sessions, averaging 14.5 h of dance practice per week (range: 10 to 20 h). Their routines included strength and conditioning programs specifically designed for dancers, focusing on lower limb stability, core strength, and flexibility. This rigorous training regimen ensured that participants were accustomed to the high physical demands required by the study and that the data accurately reflected the effects of fatigue on well-trained dancers.

2.3. Fatigue protocol

The fatigue protocol (**Figure 1 a–c**) was designed to simulate the physical demands dancers experience during prolonged performances, where sustained high-intensity movements lead to significant fatigue. The protocol structure ensured that participants reached a predetermined level of fatigue, with measurements taken at specific intervals to assess the impact on LLA and GRF.

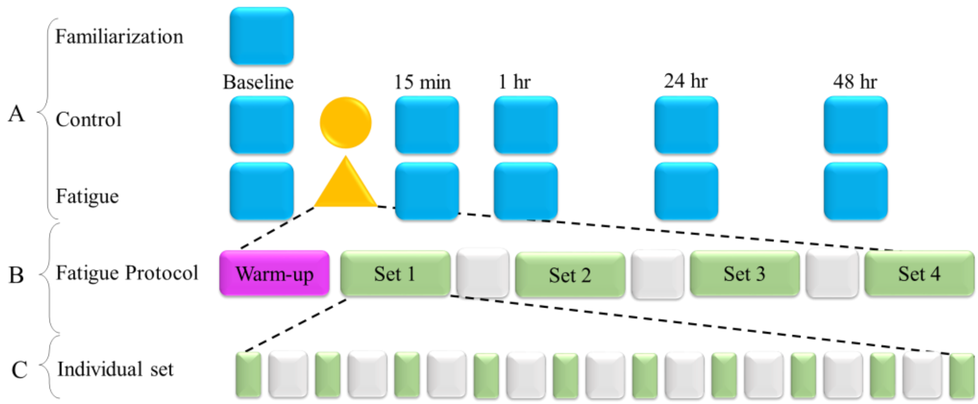

Figure 1. Design of the study.

The process began with a familiarization session, as shown in **Figure 1a**, where participants were introduced to the testing environment and equipment. Baseline data were collected during this phase before the fatigue protocol was implemented. The testing schedule included multiple assessments, not only immediately post-fatigue but also at 15 min, 1 h, 24 h, and 48 h after fatigue, allowing for an analysis of both immediate and residual effects of fatigue on biomechanics.

Figure 1b illustrates that the fatigue protocol consisted of a warm-up phase followed by four high-intensity exercises. The warm-up, lasting approximately 15 min, included dynamic stretching and low-intensity movements to prepare the participants' muscles for the following demanding exercises. After the warm-up, participants completed four exercises designed to induce fatigue. Each set involved repetitive dance-specific movements (such as jumps and landings) and plyometric exercises (e.g., tuck jumps and lateral bounds). The intensity of the exercises progressively increased with each set, ensuring that participants reached a state of physical exhaustion by the end of the protocol. The exercises targeted the lower limbs, focusing on the muscles responsible for stability and impact absorption during landings.

The protocol monitored participants' fatigue levels using subjective and objective measures. Participants reported their Perceived Exertion Levels (RPE), and heart rates were continuously recorded using wearable monitors. **Figure 1c** shows that the protocol involved collecting data after each set, ensuring that fatigue levels were consistently monitored. Once participants reported an RPE of 8 or higher and their heart rates reached approximately 85% of their maximum, they were considered sufficiently fatigued. The post-fatigue data collection occurred immediately after the fatigue protocol, capturing how the state of exhaustion influenced landing mechanics. Follow-up tests were conducted at intervals of 15 min, 1 h, 24 h, and 48 h to assess the prolonged effects of fatigue on LLA and forces during landings. These time points, shown in **Figure 1a**, allowed the researchers to determine fatigue's immediate and delayed impact on biomechanical performance.

After the fatigue protocol, participants were allowed a brief recovery period of approximately one minute before performing the post-fatigue jump landing tasks. These tasks were identical to those in the baseline phase and were performed on the same force plate and motion capture system. This design directly compared lower limb kinematics and kinetics before and after fatigue, providing a comprehensive understanding of how fatigue alters landing mechanics.

2.4. Apparatus and variables measured

The experimental setup for this study utilized advanced biomechanical analysis tools to capture kinematic and kinetic data during dance landings. The apparatus allowed for precise tracking of LLA, joint angles, and the forces exerted during landings, providing a detailed view of how fatigue influenced the mechanics of these movements. Data collection occurred in two phases—before and after the fatigue protocol—enabling a comprehensive comparison of pre-fatigue and post-fatigue conditions.

i) Apparatus

1) Motion Capture System: The primary apparatus used to capture kinematic data was a 3D motion capture system. This system consisted of a set of high-speed cameras (sampling rate: 200 Hz) strategically positioned around the experimental area to capture the participants' movements from multiple angles. Reflective markers were placed on key anatomical landmarks of the participants, including the pelvis, hip, knee, ankle, and foot. These markers allowed the system to track the positions and angles of the lower limb joints with high precision throughout the jump landing tasks.

The motion capture system was calibrated before each session to ensure accuracy. The cameras recorded participants' movements in real-time, and the data were later processed using biomechanical software to reconstruct the lower limb joint angles and alignment during each landing phase.

2) Force Plates: Ground reaction force (GRF) data were recorded using an in-ground force plate system, sampling at 1000 Hz. The force plates were integrated into the floor of the testing area and positioned to capture the foot placement during landings. These plates measured the vertical, medial-lateral, and anterior-posterior forces exerted during each landing, providing comprehensive information on how

the lower limbs absorbed and redistributed the impact forces. The force plate data allowed for an analysis of the magnitude and direction of forces during different landing phases, particularly under fatigued conditions.

3) Heart Rate Monitors: During the fatigue protocol, participants wore heart rate monitors to track their cardiovascular response to physical exertion. The heart rate data were used to determine when participants reached the required level of fatigue, ensuring consistency in the physiological response across participants.

4) Ratings of Perceived Exertion (RPE) Scale: In addition to objective measures, subjective fatigue levels were recorded using the RPE scale. Participants rated their exertion levels on a scale from 1 to 10 during and after the fatigue protocol, with 10 representing maximum fatigue. These subjective ratings were used alongside the heart rate data to confirm when participants had reached the desired fatigue state.

ii) Variables Measured

1) Joint Angles and LLA: Kinematic data from the motion capture system were used to calculate joint angles at the hip, knee, and ankle during the jump landing tasks.

The following variables were measured for each participant:

(1) Hip Flexion/Extension Angle: The angle of the hip joint during the landing indicates how much the hip flexes to absorb the impact.
(2) Knee Flexion/Extension Angle: The knee's response to landing forces is essential for assessing the risk of joint stress or injury.
(3) Ankle Dorsiflexion/Plantarflexion Angle: The angle of the ankle, as the foot contacts the ground, affects how forces are transmitted through the lower limbs.

Joint angles were analyzed at three key moments during the landing: initial contact, peak force, and stabilization. Any deviations in alignment, such as excessive knee valgus or hip rotation, were noted as potential indicators of increased injury risk, particularly under fatigued conditions.

2) GRF: The force plates measured the GRF generated during landings, which were divided into the following components:

(1) Vertical GRF: The primary force exerted upward during the landing, representing the impact forces that the lower limbs must absorb.
(2) Medial-Lateral GRF: Forces acting side-to-side, which can indicate instability or improper alignment during landing.
(3) Anterior-Posterior GRF: Forces in the forward-backward direction reflect the dynamic balance of the landing and the control over body movement.

These forces were recorded at initial ground contact, peak force absorption, and stabilization. An increase in vertical GRF under fatigued conditions could indicate that the muscles responsible for absorbing impact were less effective, potentially increasing the risk of injury.

3) TTS: Another key variable measured was TTS, the time participants regained total balance after landing. This variable was calculated based on the force plate data when the medial-lateral and anterior-posterior GRFs returned to baseline levels. Longer TTS values under fatigued conditions were interpreted as evidence of reduced neuromuscular control and balance.

4) Jump Height and Impact Velocity: In addition to joint angles and forces, jump height and impact velocity were calculated from the kinematic data. These

variables were used to assess whether fatigue affected the initial jump performance and the speed at which participants impacted the ground during landing. Fatigue is expected to reduce jump height and impact velocity, altering the landing mechanics.

All variables were analyzed using statistical software to compare pre-fatigue and post-fatigue conditions. Paired t-tests or repeated measures ANOVA were applied to determine if significant changes occurred in joint angles, GRF, and TTS. The findings provided a detailed biomechanical profile of how fatigue affects LLA, balance, and the ability to absorb impact during dance landings.

3. Results

3.1. Changes in joint angles (hip, knee, and ankle)

The changes in joint angles at the hip, knee, and ankle under pre-fatigue and post-fatigue conditions, as shown in **Table 2** and **Figure 2**, reveal significant alterations in landing mechanics due to fatigue. At the hip, joint angles increased across all phases of the landing. At initial contact, the hip flexion increased from 22.4° pre-fatigue to 25.1° post-fatigue (mean difference: +2.7°, p = 0.031), suggesting greater flexion as the body prepares to absorb impact. During the peak force phase, hip flexion rose from 45.7° pre-fatigue to 48.5° post-fatigue (mean difference: +2.8°, p = 0.024). Similarly, at stabilization, the angle increased from 18.6° to 21.4° (mean difference: +2.8°, p = 0.019), indicating more prolonged flexion as the body regains balance. Similar trends were observed at the knee. The knee flexion at initial contact increased from 15.3° pre-fatigue to 18.9° post-fatigue (mean difference: +3.6°, p = 0.008), reflecting a compensatory mechanism for impact absorption. During peak force, knee flexion increased from 82.1° pre-fatigue to 85.7° post-fatigue (mean difference: +3.6°, p = 0.011), while at stabilization, knee flexion rose from 12.5° to 15.8° (mean difference: +3.3°, p = 0.013), indicating a slower return to full extension. At the ankle, there was a significant increase in dorsiflexion. At initial contact, the angle increased from 5.7° pre-fatigue to 8.4° post-fatigue (mean difference: +2.7°, p = 0.042), and at peak force, it rose from 18.4° to 20.9° (mean difference: +2.5°, p = 0.037). Finally, during stabilization, the dorsiflexion angle increased from 10.1° pre-fatigue to 12.8° post-fatigue (mean difference: +2.7°, p = 0.028).

Table 2. Joint angle changes pre-fatigue and post-fatigue conditions.

Joint	Phase	Pre-Fatigue Angle (°)	Post-Fatigue Angle (°)	Mean Difference (°)	*p*-value
Hip	Initial Contact	22.4 ± 2.3	25.1 ± 2.7	+2.7	0.031
	Peak Force	45.7 ± 3.8	48.5 ± 4.1	+2.8	0.024
	Stabilization	18.6 ± 1.9	21.4 ± 2.1	+2.8	0.019
Knee	Initial Contact	15.3 ± 1.6	18.9 ± 2.0	+3.6	0.008
	Peak Force	82.1 ± 4.9	85.7 ± 5.2	+3.6	0.011
	Stabilization	12.5 ± 1.2	15.8 ± 1.5	+3.3	0.013
Ankle	Initial Contact	5.7 ± 1.1	8.4 ± 1.3	+2.7	0.042
	Peak Force	18.4 ± 2.4	20.9 ± 2.7	+2.5	0.037
	Stabilization	10.1 ± 1.6	12.8 ± 1.9	+2.7	0.028

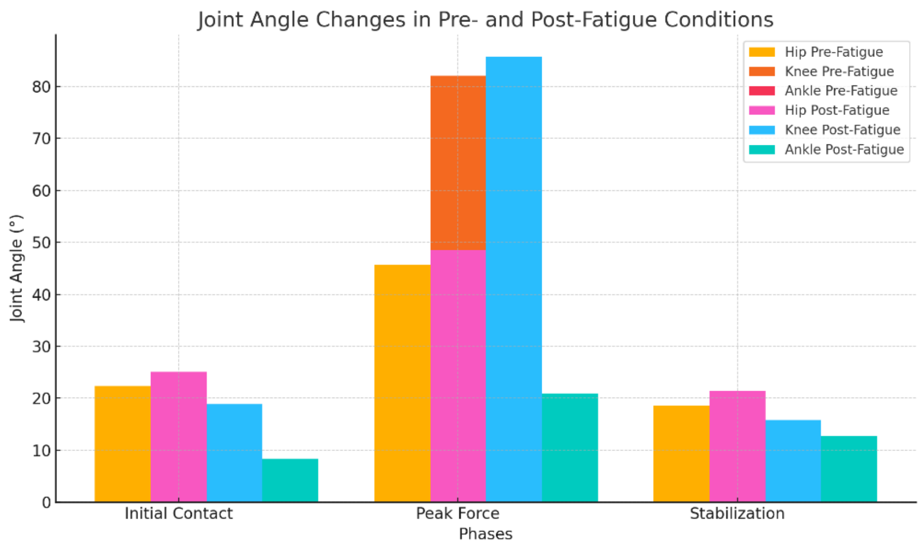

Figure 2. Joint Angle changes in pre-fatigue and post-fatigue conditions.

3.2. Vertical GRF

In **Table 3** and **Figure 3**, which compare GRF during key landing phases, significant increases in vertical GRF were observed across all phases post-fatigue. At Initial Contact, GRF increased from 18.3 N/kg pre-fatigue to 22.7 N/kg post-fatigue (mean difference: +4.4 N/kg, p = 0.009), indicating a higher impact force when participants hit the ground under fatigued conditions. During the Peak Force phase, GRF rose from 32.8 N/kg pre-fatigue to 37.6 N/kg post-fatigue (mean difference: +4.8 N/kg, p = 0.005), suggesting that the body absorbs significantly higher forces at the point of maximum impact when fatigued. Even during Stabilization, the GRF increased from 12.5 N/kg to 14.9 N/kg post-fatigue (mean difference: +2.4 N/kg, p = 0.034), reflecting a slower return to baseline stability and a greater demand on the musculoskeletal system during the balance recovery phase. **Table 4** and **Figure 4** examine how GRF changes over time post-fatigue. At 15 min post-fatigue, GRF increased to 36.1 N/kg compared to 32.4 N/kg pre-fatigue (mean difference: +3.7 N/kg, p = 0.012), showing a substantial immediate impact of fatigue on force absorption. After 1 h, GRF remained elevated at 34.8 N/kg (mean difference: +2.9 N/kg, p = 0.018), though some recovery was evident. By 24 h post-fatigue, GRF had decreased to 33.5 N/kg (mean difference: +1.4 N/kg, p = 0.045), showing further recovery but still reflecting residual fatigue effects. After 48 h, GRF returned to near baseline levels at 32.8 N/kg (mean difference: +0.3 N/kg, p = 0.240), indicating that most participants had fully recovered by this time.

Table 3. GRF for phases of the landing.

Phase	Pre-Fatigue GRF (N/kg)	Post-Fatigue GRF (N/kg)	Mean Difference (N/kg)	*p*-value
Initial Contact	18.3 ± 2.1	22.7 ± 2.4	+4.4	0.009
Peak Force	32.8 ± 3.5	37.6 ± 3.9	+4.8	0.005
Stabilization	12.5 ± 1.7	14.9 ± 1.9	+2.4	0.034

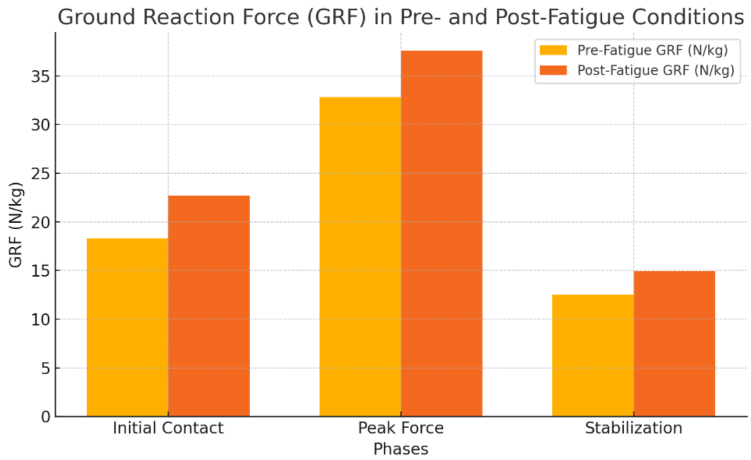

Figure 3. GRF for phases of the landing.

Table 4. GRF at time intervals.

Time Interval	Pre-Fatigue GRF (N/kg)	Post-Fatigue GRF (N/kg)	Mean Difference (N/kg)	*p*-value
Baseline	32.8 ± 3.5	N/A	N/A	N/A
15 min	32.4 ± 3.4	36.1 ± 3.6	+3.7	0.012
1 h	31.9 ± 3.2	34.8 ± 3.5	+2.9	0.018
24 h	32.1 ± 3.3	33.5 ± 3.1	+1.4	0.045
48 h	32.5 ± 3.1	32.8 ± 3.2	+0.3	0.240

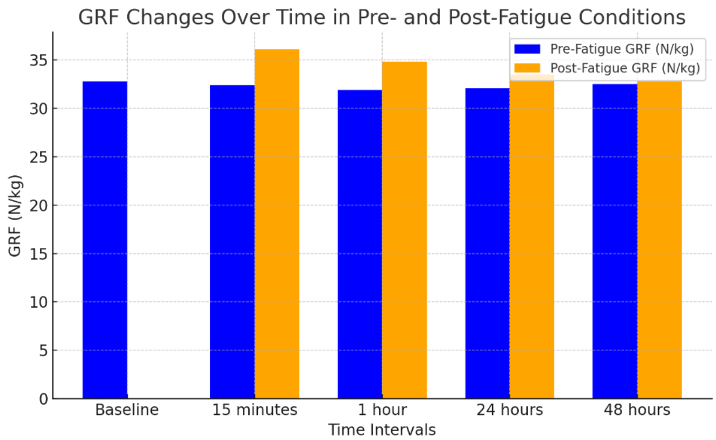

Figure 4. GRF at time intervals.

3.3. TTS

In **Table 5** and **Figure 5**, TTS was measured at several post-fatigue intervals to evaluate how quickly participants recovered their ability to stabilize after landing. At 15 min post-fatigue, TTS increased significantly from 181 ms pre-fatigue to 215 ms (mean difference: +34 ms, p = 0.008), indicating an immediate effect of fatigue on balance recovery. During this interval, participants required more time to regain stability, reflecting impaired neuromuscular control. After 1 h, TTS improved slightly to 207 ms (mean difference: +24 ms, p = 0.015), but participants still took longer than in pre-fatigue conditions. By 24 h, TTS had further decreased to 194 ms (mean difference: +12 ms, p = 0.041), showing continued recovery but not reaching pre-fatigue levels. Finally, by 48 h, TTS had returned to 181 ms, close to baseline values, with no significant difference from pre-fatigue (mean difference: +1 ms, p = 0.278), indicating full recovery.

Table 5. TTS at time intervals.

Time Interval	Pre-Fatigue TTS (ms)	Post-fatigue TTS (ms)	Mean Difference (ms)	*p*-value
Baseline	180 ± 12	N/A	N/A	N/A
15 min	181 ± 14	215 ± 18	+34	0.008
1 h	183 ± 13	207 ± 15	+24	0.015
24 h	182 ± 12	194 ± 13	+12	0.041
48 h	180 ± 11	181 ± 10	+1	0.278

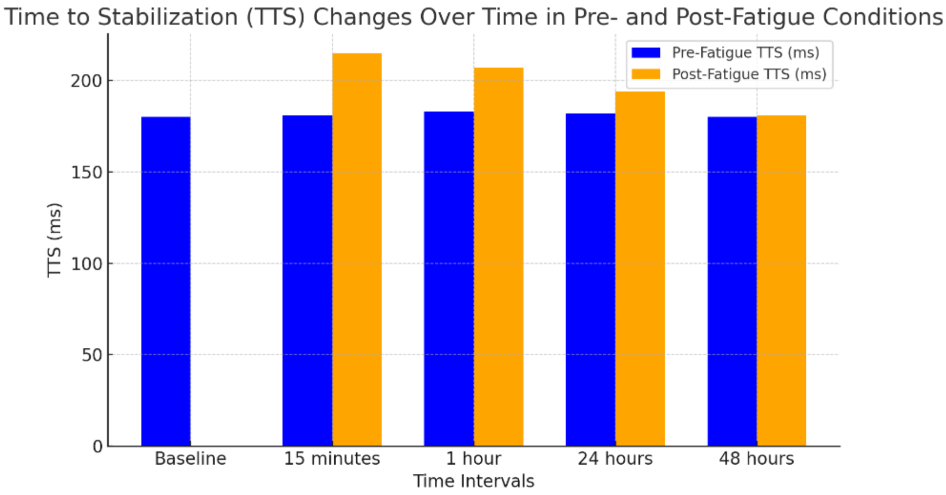

Figure 5. TTS at time intervals.

Table 6 and **Figure 6** provide a breakdown of TTS during different landing phases. During the initial landing phase, TTS increased from 210 ms pre-fatigue to 245 ms post-fatigue (mean difference: +35 ms, p = 0.007), indicating a slower response in regaining balance immediately after contact. At peak force, TTS increased from 325 ms to 357 ms (mean difference: +32 ms, p = 0.013), reflecting continued difficulty stabilizing during the most forceful part of the landing. During the final stabilization phase, TTS increased even more significantly, from 425 ms pre-fatigue to 475 ms post-fatigue (mean difference: +50 ms, p = 0.004), highlighting the prolonged effect of fatigue on regaining complete postural control after landing.

Table 6. TTS at phase.

Phase	Pre-Fatigue TTS (ms)	Post-fatigue TTS (ms)	Mean Difference (ms)	*p*-value
Initial Landing	210 ± 15	245 ± 18	+35	0.007
Peak Force	325 ± 22	357 ± 26	+32	0.013
Stabilization	425 ± 30	475 ± 35	+50	0.004

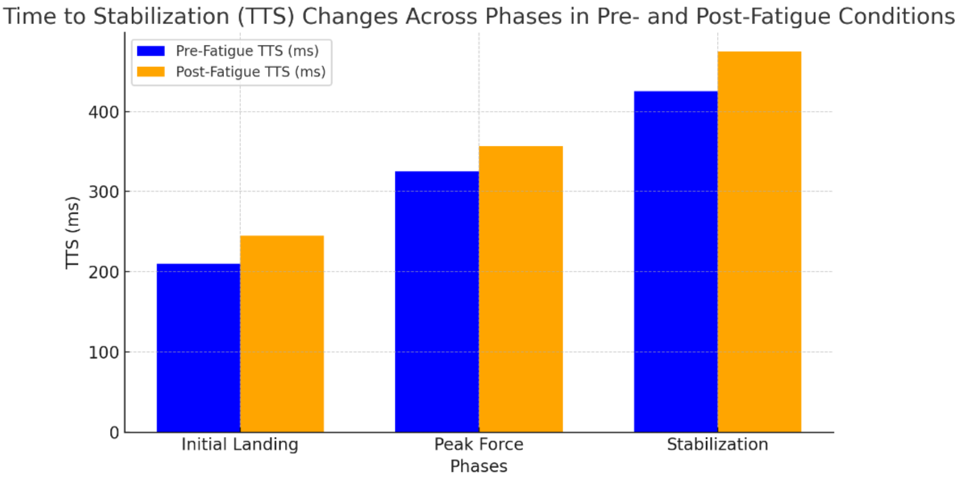

Figure 6. TTS at phase.

3.4. Jump height and impact velocity

The analysis of Jump Height and Impact Velocity pre- and post-fatigue, as shown in **Table 7** and **Figure 7**, highlights the significant impact of fatigue on participants' jumping performance and landing mechanics. For Jump Height, pre-fatigue values averaged 43.7 cm, while post-fatigue values dropped to 38.9 cm (mean difference: −4.8 cm, $p = 0.002$). This decrease in jump height indicates that fatigue significantly reduced the participants' ability to generate the explosive power necessary for achieving maximum vertical displacement during the jump. The diminished jump height can be attributed to muscular fatigue, particularly in the quadriceps and calf muscles, critical for force production during the takeoff phase. Regarding Impact Velocity, pre-fatigue values averaged 3.25 m/s, which increased to 3.58 m/s post-fatigue (mean difference: +0.33 m/s, $p = 0.009$). The increase in impact velocity indicates that participants descended faster when landing in a fatigued state. This higher descent rate suggests a reduction in the control over eccentric muscle contractions during the landing phase, leading to a quicker and less controlled contact with the ground. This can elevate the risk of injury due to the increased forces acting on the lower limbs upon impact.

Table 7. Jump height and impact velocity for pre and post fatigue.

Variable	Pre-Fatigue	Post-Fatigue	Mean Difference	*p*-value
Jump Height (cm)	43.7 ± 4.2	38.9 ± 3.8	−4.8	0.002
Impact Velocity (m/s)	3.25 ± 0.28	3.58 ± 0.33	+0.33	0.009

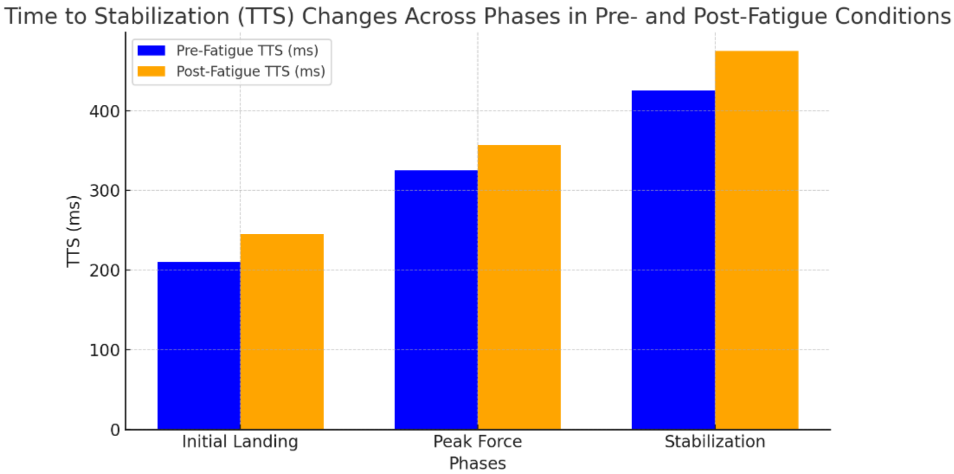

Figure 7. Jump height and impact velocity for pre and post fatigue.

3.5. Medial-lateral GRF (stability and balance)

The analysis of Medial-Lateral GRF, as presented in **Table 8** and **Figure 8**, focuses on participants' side-to-side (medial-lateral) stability during the landing phase, measured pre- and post-fatigue. The Medial-Lateral GRF provides crucial information on how fatigue affects the ability to maintain lateral stability and balance throughout the landing movement. At Initial Contact, pre-fatigue GRF averaged 2.8 N/kg, while post-fatigue values increased to 3.6 N/kg (mean difference: +0.8 N/kg, $p = 0.011$). This indicates that participants experienced greater lateral forces when fatigued, reflecting a reduced ability to control side-to-side stability immediately upon ground contact. The increased medial-lateral forces at this early landing phase could lead to instability, increasing the risk of lateral injuries, such as ankle sprains. During the Peak Force phase, where the body is subjected to maximum GRF, pre-fatigue GRF was 5.2 N/kg, rising to 6.1 N/kg post-fatigue (mean difference: +0.9 N/kg, $p = 0.004$). This further increase in lateral forces during the peak impact suggests that fatigue compromises vertical force absorption and weakens the ability to maintain lateral control under the highest load conditions. At the Stabilization phase, pre-fatigue GRF averaged 1.8 N/kg, increasing to 2.4 N/kg post-fatigue (mean difference: +0.6 N/kg, $p = 0.021$). Even in the later stages of landing, participants demonstrated reduced lateral stability, with greater side-to-side forces evident during the period of balance recovery. This suggests that fatigue prolongs the time it takes to regain complete stability after landing, possibly contributing to increased instability and injury risk.

Table 8. Medial-lateral GRF measured against movements.

Movement Phase	Pre-Fatigue GRF (N/kg)	Post-Fatigue GRF (N/kg)	Mean Difference (N/kg)	*p*-value
Initial Contact	2.8 ± 0.4	3.6 ± 0.5	+0.8	0.011
Peak Force	5.2 ± 0.6	6.1 ± 0.7	+0.9	0.004
Stabilization	1.8 ± 0.3	2.4 ± 0.4	+0.6	0.021

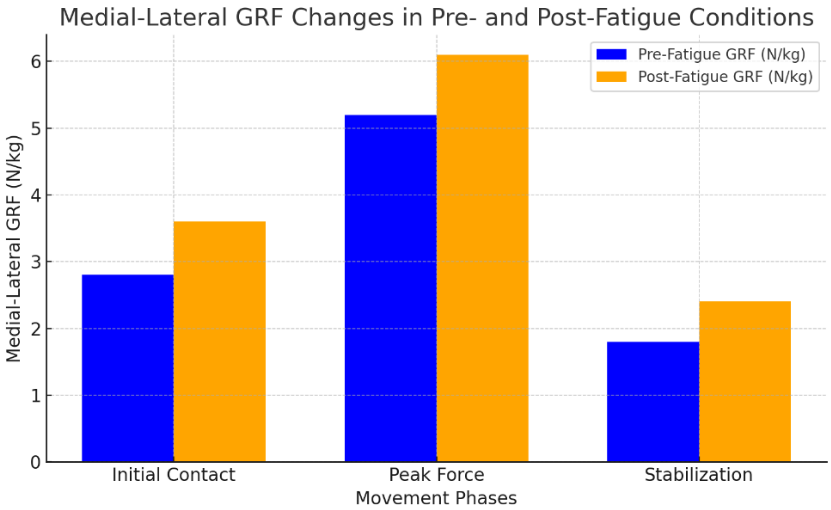

Figure 8. Medial-lateral GRF measured against movements.

3.6. Delayed effects of fatigue

The analysis of the Delayed Effects of Fatigue on Lower Limb Mechanics, as shown in **Table 9** and **Figure 9**, reveals how key biomechanical variables, such as hip flexion, knee flexion, vertical GRF, and TTS, change over time following the onset of fatigue. Measurements were taken at intervals of 15 min, 1 h, 24 h, and 48 h post-fatigue, allowing for a comprehensive evaluation of the recovery process. Hip Flexion (°) increased immediately post-fatigue, rising from 45.7° pre-fatigue to 49.9° at 15 min (mean difference: +4.2°, p = 0.014). This increase indicates that participants adopted a more flexed hip position during landing to compensate for reduced muscle efficiency. Over time, hip flexion gradually decreased to 48.7° at 1 h, 47.0° at 24 h, and 46.1° at 48 h, approaching pre-fatigue levels. By 48 h, the participants had recovered mainly their ability to maintain more efficient hip mechanics. Knee Flexion (°) followed a similar trend, increasing from 82.1° pre-fatigue to 86.9° at 15 min (mean difference: +4.8°, p = 0.010), indicating greater knee flexion under fatigued conditions to absorb impact forces. This flexion gradually decreased over the recovery period to 85.3° at 1 h, 83.6° at 24 h, and 82.7° at 48 h, with full recovery observed by 48 h. Vertical GRF also increased significantly post-fatigue, rising from 32.8 N/kg pre-fatigue to 37.5 N/kg at 15 min (mean difference: +4.7 N/kg, p = 0.011). This higher GRF reflects the body's reduced ability to absorb impact forces under fatigue efficiently. Over the recovery period, GRF values decreased to 35.9 N/kg at 1 h, 33.8 N/kg at 24 h, and 32.9 N/kg at 48 h, gradually returning to pre-fatigue levels. Finally, TTS increased from 210 ms pre-fatigue to 255 ms at 15 min (mean difference: +45 ms, p = 0.007), indicating that participants took longer to regain balance post-fatigue. This delay in stabilization reflects impaired neuromuscular control immediately following the fatigue protocol. Over time, TTS improved to 238 ms at 1 h, 222 ms at 24 h, and 211 ms at 48 h, suggesting that participants recovered their ability to stabilize within two days.

Table 9. Delayed effects of fatigue on lower limb mechanics.

Variable	Pre-Fatigue	15 min	1 h	24 h	48 h	*p*-value (pre vs. post)
Hip Flexion (°)	45.7 ± 3.8	49.9 ± 4.1	48.7 ± 4.0	47.0 ± 3.9	46.1 ± 3.6	0.014
Knee Flexion (°)	82.1 ± 4.9	86.9 ± 5.1	85.3 ± 5.0	83.6 ± 4.8	82.7 ± 4.6	0.010
Vertical GRF (N/kg)	32.8 ± 3.5	37.5 ± 3.8	35.9 ± 3.7	33.8 ± 3.6	32.9 ± 3.5	0.011
TTS (ms)	210 ± 15	255 ± 19	238 ± 17	222 ± 16	211 ± 14	0.007

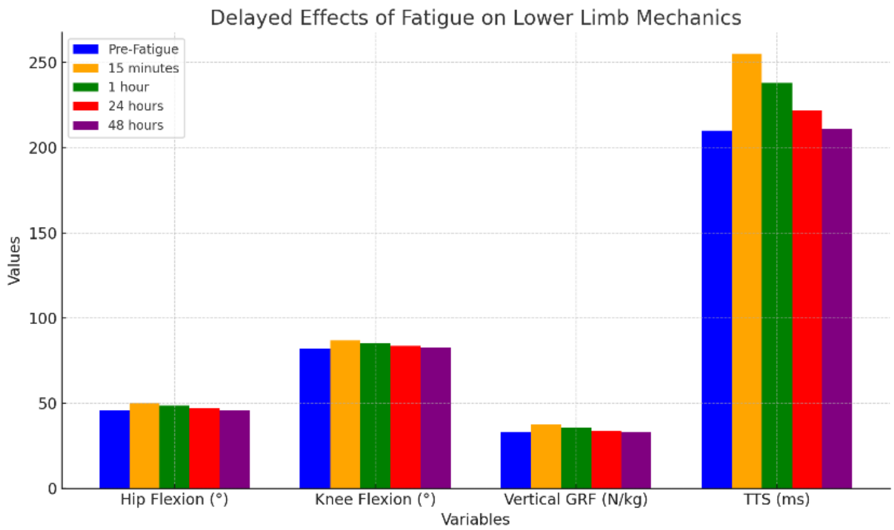

Figure 9. Delayed effects of fatigue.

4. Conclusion and future work

This study comprehensively assesses how fatigue affects LLA and GRF during dance landings, highlighting the significant biomechanical changes that occur under fatigued conditions. The results demonstrate that fatigue increases joint flexion at the hip, knee, and ankle during all landing phases, which can alter the body's ability to absorb impact forces efficiently. In particular, the significant increases in vertical and medial-lateral GRF post-fatigue suggest that dancers experience more incredible difficulty in maintaining stability and balance, particularly in the immediate aftermath of exertion. TTS was also significantly prolonged, indicating reduced neuromuscular control due to fatigue. This impairment in postural control and balance, combined with the increased forces acting on the lower limbs, may elevate the risk of injury, especially in professional or semi-professional settings where dancers are exposed to prolonged periods of physical exertion.

Additionally, the study showed that while some recovery occurs within 24 h, full biomechanical recovery takes up to 48 h, suggesting that adequate recovery time is essential for minimizing injury risks and optimizing performance. These findings underscore the importance of fatigue management in dance training and performance. To mitigate the negative effects of fatigue, dance professionals and trainers should incorporate structured recovery periods, strength and conditioning programs focused on improving neuromuscular control, and landing mechanics into dancers' routines.

By addressing the impact of fatigue on landing mechanics, these strategies can enhance dancers' performance, reduce the risk of overuse injuries, and promote long-term musculoskeletal health.

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