Original research papers

COMPARATIVE ANALYSIS OF KINETICS PARAMETERS DURING DIFFERENT LANDING AFTER SPLIT FRONT LEAPS

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Abstract
Introduction. Dance and rhythmic gymnastics are high leap demanding sports. Leaps are fundamental human movements that require complex motor coordination of both the upper and lower body extremities. The aim of this study was to compare the kinetics parameters of two types of landing after performing front split leaps. ***Material and methods.*** Fifteen high-level acrobatic gymnasts with a mean age of 22 ± 2.76 years and mean training experience of 12.27 ± 2.34 years participated in the study. Examinations of kinetics parameters of the movements analysed were carried out using the Vicon system and Kistler plates. Gymnasts completed front split leaps with balanced landing (arabesque position) and moving landing (continued movement). ***Results.*** Values of vertical ground reaction force and values of muscle torque in the hip joint were statistically significant higher ($p < 0.001$) for balanced landing. The value of leg stiffness was also significantly ($p < 0.001$) higher for balanced landing (5.69 ± 2.45 kN/m) compared to moving landing (1.89 ± 0.43 kN/m). For balanced landing, the sequence of maximal peaks of torques from the highest to the lowest values were found in the hip (5.81 ± 1.06 Nm/kg), ankle (3.56 ± 0.71 Nm/kg), and knee (2.01 ± 0.75 Nm/kg) joints. For the split leap with moving landing, the most loaded joints, in descending order, were the ankle (3.50 ± 0.42 Nm/kg), hip (3.39 ± 0.78 Nm/kg), and knee (2.21 ± 0.57 Nm/kg) joints. ***Conclusions.*** The findings of the study can help to improve the methodology of training the technique and protect gymnasts and dancers against unnecessary injuries.

Key words: biomechanics, front leaps, kinetics parameters, landing, leg stiffness

Introduction

Biomechanics is a scientific field that concerns itself with the mechanical principles of human movement and provides information on muscular function and its characteristics. Gymnastics and dance require balance, strength, flexibility, agility, coordination, and endurance. One of the most common and fundamental gymnastics and dance movements is leaps. Leaps require complex motor coordination of both upper and lower body segments [1, 2]. Moreover, to make it all more interesting and complex, leap performance is in most cases followed by an additional manipulation of the apparatus (ball, rope, hoop, or ribbon), which may involve throwing or passing through it using different techniques. One of the basic and most common leaps is a split leap. The split leap is a movement in which an athlete leaps into the air and performs a split. The purpose of the exercise is to demonstrate the ability to leap in the air with height as well as show flexibility and strength, both of which are needed to attain a split position without external leg support. Also, in order to remain airborne during the split position, the athlete needs strength to propel the body upward with sufficient kinetic energy to compensate for the loss of vertical momentum that results from raising the legs into a split position while airborne. In dance, the perceived quality of the split leap or the split jump depends in a large part on the application of various dance techniques. In particular, emphasis is often placed on pointing the feet while airborne, especially during the split, so as to extend the leg lines. Also, proper technique typically requires straight legs and a full split position at the apex of the leap or jump. Thus, mastering dance and gymnastics technique requires repetitive physical loading that may exceed the limits of the athlete's anatomical and physiological capabilities and lead to injuries. Musculoskeletal injuries are considered to be very common among dancers. The incidence of injuries varies from 17% to 95 % [3]. Overuse injuries are predominant; these are, among others, tendinosis, stress fractures, and injuries that manifest at the lower limb, hip, and spine [4-6]. Further understanding of the biomechanics of a dance is essential to identify the specific musculoskeletal demands placed on the body and to uncover the pathomechanics that may lead to injury [6]. To reduce both injury incidence and prevalence, it is crucial to implement effective injury prevention strategies and rehabilitation, biomechanically safe and efficient technique training practices, and improved dance and gymnastics pedagogy. Research which has been carried out so far in dance biomechanics has focused on impact (e.g., jumps) and high pressure (e.g., pirouettes) movements as well as describing typical ballet movements [7, 8]. The aim of this study was to compare kinetics parameters between two types of landing after performing front split leaps.

Material and methods

Fifteen high-level acrobatic gymnasts aged 22 ± 2.76 years with a mean training experience of 12.27 ± 2.34 years, a body weight of 57.5 ± 7 kg, and a height of 168.6 ± 6.39 cm participated in the study. The gymnasts had been practising dance for an average of 2 years. The subjects gave written consent to participate in the experimental procedures, which were approved by the Research Ethics Committee of the Józef Piłsudski University of Physical Education in Warsaw. The experiment was carried out in an indoor hall adapted to conducting biomechanical tests. Prior to the experiment, anthropometric measurements were taken in each of the subjects. Afterwards, thirty-four spherical markers were placed at anatomical landmarks according to the biomechanical model followed in the PlugInGait standards available in the motion capture system (Vicon Motion Systems Ltd, UK). Two force plates (Kistler Holding AG, CH) embedded into the floor were used to measure ground reaction force data at a sampling rate of 1000 Hz. A motion capture system consisting of nine infra-red cameras was employed to collect kinematics data at a sampling rate of 100 Hz. The force plates were synchronised with the motion capture system. Before the trials were conducted, both systems were calibrated according to the manufacturers' recommendations. Each gymnast performed three trials of the two different front split leaps. Each of the jumps began with a chassé step. The jumps differed in terms of the landing phase. In the first type of leap, a balanced landing was performed (Fig. 1A), which means that the landing was stopped on one lower limb in the modified arabesque position. In the second type, a moving landing was made (Fig. 1B), without any break: one lower limb landed on one platform, the other limb landed on the next platform, and then the subjects continued to make a few more steps.

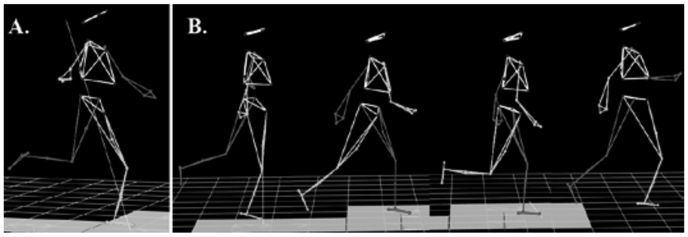

Figure 1. Phases of landing after front split leaps: A. balanced landing (modified arabesque position) and B. moving landing (continued movement)

The analysis took into account maximal values of the vertical ground reaction force and maximal values of torques in the sagittal plane for the lead leg joints during balanced landing (BL) and moving landing (ML) recorded for the best trial. Moreover, leg stiffness (K) was calculated by taking the ratio of the peak vertical ground reaction force (GRF_{max}) to the vertical displacement of the knee joint ($\Delta L = L_{max} - L_{min}$) during contact with the platform: $K = \frac{GRF_{max}}{\Delta L}$.

We took into account the vertical displacement of the knee joint instead of the centre of mass (CoM) because during the split leap, each of the gymnasts changed the position of the arms, which resulted in a large variation of the CoM position. The contact phase was defined from the first contact of the toe with the ground until the moment when the angle at the knee joint reached a minimum. Statistical analysis was conducted using Statistica software (StatSoft, USA). The differences were considered significant at 0.05 for all analyses. The normality of the distributions of all parameters was verified using the Shapiro-Wilk test. Student's parametric t-test for dependent samples was used.

Results

Joint loading and leg stiffness were analysed in terms of the relationship between the balanced and moving landing and a comparison of all joints in one limb for two types of landing separately.

Relationship between balanced and moving landing

A statistically significant difference (p = 0.0001) was found between the vertical values of ground reaction force for balanced and moving landing (Fig. 2). Peak vertical ground reaction force generated during the balanced landing was approximately 29.5% greater than that of the moving landing. Such a result affected the values of muscle torques and leg stiffness parameters.

There were no statistically significant differences between the values of muscle torques for the ankle and knee joints when comparing the two types of landings. However, the values of muscle torque in the hip joint were significantly higher (p = 0.0005) during the balanced landing (Fig. 2). The value of leg stiffness was significantly (p = 0.0001) higher for balanced landing (5.69 ± 2.45 kN/m) compared to moving landing (1.89 ± 0.43 kN/m) as well. The change of the vertical height of the knee was significantly (p = 0.0003) lower for the balanced landing (0.08 ± 0.03 m) compared to the moving landing (0.18 ± 0.03 m).

Comparison of all joints in one limb for two types of landing separately

For the balanced landing, the highest to lowest loading of the joints was found for the hip (5.81 ± 1.06 Nm/kg), ankle (3.56 ± 0.71 Nm/kg), and knee (2.01 ± 0.75 Nm/kg) joints. All combinations of values were statistically significant ($p \leq 0.05$). In contrast, for the jump with the moving landing, the most loaded joint was the ankle joint (3.50 ± 0.42 Nm/kg), followed by the hip joint (3.39 ± 0.78 Nm/kg), and finally the knee joint (2.21 ± 0.57 Nm/kg).

Discussion

The main purpose of this study was to compare kinetics parameters between two types of landing after performing split leaps. It is essential to understand how the body lands after successive jumps like split leaps to prevent and avoid injuries to the lower extremity [1]. The simplest assessment of musculoskeletal system loads can be made using ground reaction forces and by comparing the values of joint torques to those in gait or obtained in other sports [9, 10].

As shown in Figure 2, after foot strike, the hip flexors dominated, producing a very high torque of about 5.81 ± 1.06 Nm/kg for the balanced landing and 3.39 ± 0.78 Nm/kg for the moving landing. For the knee and ankle joints, the flexor and dorsiflexor muscles also produced very high torque in both types of landing. When we compare these values to the ones that were obtained during gait [11], we discover that the values of torques in the hip joint during the landing in the arabesque position and during the moving landing are 11.62 and 6.78 times higher, respectively, than during gait (0.5 Nm/kg). In the knee joint, the values of the muscle torque in gait reached the value of up to 0.5 Nm/kg and were on average 4.22 times smaller compared to the

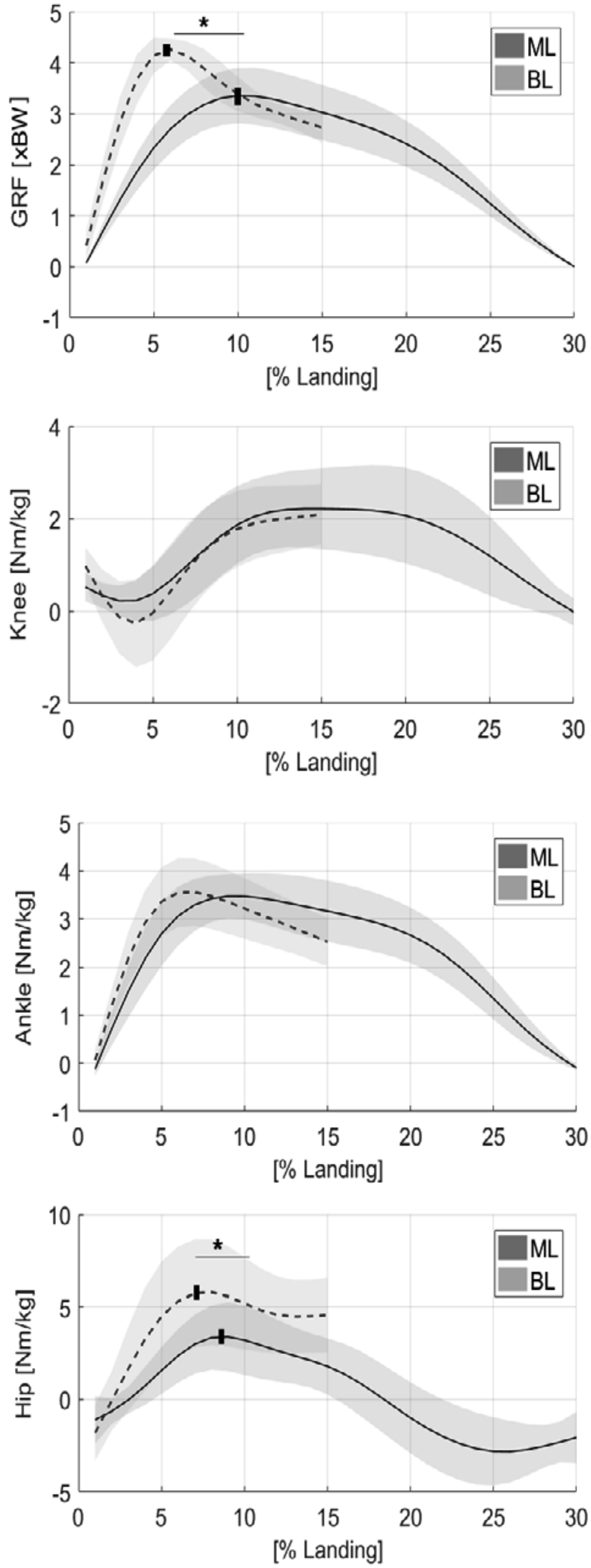

Figure 2. Kinetics parameters (vertical component of the ground reaction force and joint torques) during two types of landing: BL – balanced landing and ML – moving landing; xBW – times body weight; * – statistically significant differences (p ≤ 0.05)

landings analysed. At the same time, the maximum value recorded in the ankle joint during gait was 1.5 Nm/kg [11], which is on average 2.35 times less than in the movement patterns analysed. This analysis shows that the hip and knee joints are the most vulnerable to injuries during the two types of landing after front split leaps. This information can be useful in preventing of chronic injuries and injuries in beginning and advanced dancers or gymnasts.

In terms of the vertical component of the ground reaction forces, as expected, the 4.2 ± 0.8 times and 3.2 ± 0.4 times body weight peak vertical ground reaction force during balanced and moving landing in this study was markedly greater than the 1.5 times body weight peak force during walking and the 2.5 times body weight peak force during running [12, 13]. A key component in vertical ground reaction force attenuation is leg stiffness, comprised of tissue compressibility and individual joint angular stiffnesses. Leg stiffness is a variable that has been used mainly in analyses of human locomotion. Elasticity is a property of macroscopic bodies which consists in the ability to recover the previous shape and volume after mechanical forces that cause deformation are removed. The ability to absorb and recover elastic energy in the human body is observed in tendino-muscular groups. One example of tissue that behaves like a spring that absorbs and releases the elastic energy during locomotion or jumping is the Achilles tendon. It is estimated that the Achilles tendon is able to accumulate 35% of the mechanical energy necessary for performing the running gait [14]. The quantitative measure of body elastic properties is stiffness, which is a measure of resistance to strain. According to the division of Latash and Zatsiorsky [15], stiffness calculated in this paper should be termed quasi-stiffness, because the measurements were performed not at equilibrium but during transient states. Moreover, the knee joint appears to be the chief modulator of leg stiffness, as the lever arm lengths of the femur and tibia place the knee in the best position of all lower extremity joints to help attenuate the vertical ground reaction forces [16, 17].

Because leg stiffness represents a quantitative measure of the elastic properties of the lower limbs, it can be assumed that a higher value for leg stiffness should positively affect the height of a vertical jump and the overall take-off efficiency [18]. Ranges of leg stiffness are 2-8 kN/m [18, 19], 5-95 kN/m [17], and 8-75 kN/m [20, 21] during countermovement jump (CMJ), drop jump (DJ), and hopping, respectively. In our study, the value of leg stiffness was 3 times higher for balanced landing (5.69 ± 2.45 kN/m) compared to moving landing (1.89 ± 0.43 kN/m). Higher values for balanced landing in the static position of the arabesque were associated mainly with smaller vertical displacement of the knee joint during shock absorption and greater values of vertical ground reaction force. Arampatzis et al. [22] as well as Kuitunen et al. [17] found that the greater the physical demand of an activity, regardless of whether it is running or leaping, the greater the amount of stiffness the leg tends to exhibit. Therefore, our result for balanced landing is in line with their research. In the case of the moving landing, this type of landing can be similar to DJ, that is a jump performed immediately after landing from a specific height. Laffaye and Choukou [23] stated that the minimum value for leg stiffness is the most beneficial for a drop jump. Therefore, we can assume that for dancers, it is better when they do not perform evolutions which end in a static position.

Moreover, in dance, which is a live performance art, not only visual but also auditory aesthetics must be considered in the desired impact of a choreography. Peak vertical ground reaction force and stiffness can be consciously modified with a dancer's focus on demonstrating a hard (increased stiffness) or soft (decreased stiffness) landing, where the hard landing results in a greater force, and the soft landing results in a lower force [24]. Therefore, it is possible that dancers may be subconsciously trained to modulate the auditory impact of the landing phase through the achievement of a soft (less stiff) landing. Furthermore, it is likely that increased stiffness during the landing phase would result in even greater vertical ground reaction forces than those measured in this study. Such ground reaction forces may be beyond the dancer's capacity to endure on a repetitive basis.

Conclusions

The results obtained in the research may be used to improve the teaching of dancing movements. Training sessions carried out in a biomechanical laboratory with the active participation of dancing teachers could form a basis for a prevention model of injuries and physical overloads occurring within this occupational group.

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