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Kinematic analysis of the gait in professional ballet dancers

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Background: A ballet dance routine places extreme functional demands on the musculoskeletal system and affects the motor behaviour of the dancers. An extreme ballet position places high stress on many segments of the dancer's body and can significantly influence the mobility of the lower limb joints. **Objective:** The aim of this study was to observe the differences in the gait pattern between ballet dancers and non-dancers. **Methods:** Thirteen professional ballet dancers (5 males, 8 females; age 24.1 ± 3.8 years; height 170.2 ± 8.5 cm; weight 58.3 ± 11.2 kg) participated in this research. We compared these subjects with twelve controls (3 males, 9 females; mean age 24.3 ± 2.75 years; height 173.3 ± 6.01 cm; weight 72.2 ± 12.73 kg). None of the participants had any history of serious musculoskeletal pathology or injury or surgery in the lower limbs. Control group had no ballet experience. Each participant performed five trials of the gait at self-selected walking speed. Kinematic data was obtained using the Vicon MX optoelectronic system. The observed data was processed in the Vicon Nexus and Vicon Polygon programmes and statistically evaluated in Statistica. Non-parametric test (Mann-Whitney U test, $p < .05$) was applied for comparing the dancers and the controls. **Results:** Significant differences ($p < .05$) were found in all lower limb joints. In the dancers, greater hip extension (−15.30 ± 3.31° vs. −12.95 ± 6.04°; $p = .008$) and hip abduction (−9.18 ± 5.89° vs. −6.08 ± 2.52°; $p < .001$) peaks together with increased pelvic tilt (3.33 ± 1.26° vs. 3.01 ± 1.46°; $p = .020$), pelvic obliquity (12.46 ± 3.05° vs. 10.34 ± 3.49°; $p < .001$) and pelvic rotation (14.29 ± 3.77° vs. 13.26 ± 4.91°; $p = .029$) were observed. Additionally, the dancers demonstrated greater knee flexion (65.67 ± 4.65° vs. 62.45 ± 5.24°; $p = .002$) and knee extension (3.80 ± 4.02° vs. −1.54 ± 5.65°; $p < .001$) peaks during the swing phase when compared to the controls. Decreased maximal ankle plantar flexion was observed during the loading response (−8.84 ± 3.74° vs. −10.50 ± 3.99°) and increased maximal ankle plantar flexion in terminal stance (−20.30 ± 4.93° vs. −17.00 ± 3.99°; $p = .025$) was observed for the dancers. **Conclusion:** The results confirm that long-term intensive ballet training affects the kinematic pattern of particular joints during gait performance. The findings suggest overloading in the lumbosacral region and dysfunction or weakness of several muscles in ballet dancers.

Keywords: ballet dancers, gait cycle, kinematics, angular range of motion, walking

Introduction

Ballet dancers are a unique combination of artists and high-performance athletes; as a result their bodies are subjected to considerable stress by precision movements requiring great strength, coordination and excessive range of motion in multiple segments of the body (Leanderson, Eriksson, Nilsson, & Wykman, 1996; Lepelley, Thullier, Koral, & Lestienne, 2006). The ability to dance on the tips of the toes requires progressive development of the kinematic chain from the toes to the back, any disruption of which may result in overuse injury anywhere in the chain (O'Kane & Kadel, 2008). The high incidence of the overloaded conditions is also related to increased range of motion in many joints to reach aesthetic movements.

The majority of lower limbs movements during ballet are performed with hip external rotation and increased movement of the pelvis (Kiefer et al., 2011; Wilson & Deckert, 2009). The ballet position en'pointe requires extreme plantar flexion and foot pronation (Ahonen, 2008; Lung, Chern, Hsieh, & Yang, 2008). It is a special situation that distinguishes dance from other sports (Miller, 2006). Additionally, dancers often achieve ballet positions with compensation at the pelvis, lumbar spine, knee, ankle and foot joints (Gilbert, Gross, & Klug, 1998). Accordingly, a ballet dance places extreme functional demands on the musculoskeletal system and affects the motor

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behaviour of the dancers. Acute injuries during ballet can occur in various regions of the body, but overuse injuries predominate in the lower limbs (Stretanski & Weber, 2002).

Excessive loading of the foot (e.g. particularly in relation to prolonged foot pronation in the ballet positions) has traditionally been identified as a risk factor for many overuse injuries (Buldt et al., 2013; Chuter & Janse de Jonge, 2012; Levinger et al., 2010). Abnormal foot motion affects the proximal structure due to a dynamic coupling mechanism between the lower limbs segments. As a result, greater stress might be applied through the foot to the proximal segments during the particular phase of the gait (Levinger et al., 2010; Powell, Long, Milner, & Zhang, 2011). This altered motion places stress on the related musculoskeletal structures, which are predisposed to overuse injury via microtrauma incurred over repetitive gait cycle (Barwick, Smith, & Chuter, 2012). This pathomechanics should be associated with the development of lower back pain, altered function of the hip and pelvis or the patellofemoral syndrome (Chuter & Janse de Jonge, 2012). Many of these injuries have previously been attributed to excessive foot pronation. Recently, emphasis has turned to the key role of lumbopelvic instability in altered foot motion and lower limb pathomechanics (Barwick, Smith, & Chuter, 2012; Chuter & Janse de Jonge, 2012).

The ballet dance induces an altered postural alignment of the body, which may result in changes in the musculoskeletal system and manifest in the performance of the gait cycle. Differences in movement patterns are not isolated to specific athletic manoeuvres, but rather manifest themselves in activities like walking (Bovi, Rabuffetti, Mazzoleni, & Ferrarin, 2011). Human gait requires complex coordination of the multiple segments of the body, particularly the lower limbs (Franz, Paylo, Dicharry, Riley, & Kerrigan, 2009; Liederbach, 2010; You et al., 2009). Many previous studies have shown that athletes exhibit different gait kinematic patterns that have greater propensity for lower limbs injuries (Barton, Levinger, Crossley, Webster, & Menz, 2012; Franz, Paylo, Dicharry, Riley, & Kerrigan, 2009; Powell et al., 2011). The study by Lung, Chern, Hsieh, & Yang (2008) describes the differences in the gait pattern between dancers and non-dancers; however, these authors evaluated only the ground reaction forces, foot pressure pattern and the centre of pressure. This is the first study to observe the kinematic variables in the walking pattern of dancers (Lung et al., 2008).

The obtained kinematic analysis of the gait cycle can clarify the relationship between the particular segments of dancer's body and should elucidate the undesirable impact of ballet training on the musculoskeletal system. However, the current study provides useful information on describing the walking pattern of dancers, which may help in understanding the causes of musculoskeletal disorders of this specific group of the population.

Objective

The aim of this study was to observe the differences in movement of lower limbs and pelvis during the gait between dancers and healthy non-dancing controls.

Material and methods

Subjects

Thirteen professional dancers (5 males, 8 females; age 24.1 ± 3.8 years; height 170.2 ± 8.5 cm; weight 58.3 ± 11.2 kg) from the ballet company of Moravian Theatre in Olomouc participated in this research. The criterion for inclusion to the experimental group was the professional level in ballet dance. Subjects that performed dance training five to six times a week over 3 to 8 hours per day, minimum, were selected. The selected subjects had an average dancing experience of 16.1 ± 4.8 years. We compared this experimental group with twelve controls (3 males, 9 females; mean age 24.3 ± 2.75 years; height 173.3 ± 6.01 cm; weight 72.2 ± 12.73 kg) for kinematic analysis during gait. The exclusion criteria for all subjects were any serious musculoskeletal pathology, severe pain or history of injuries or surgery to the lower limbs which may affect the results of this study. All subjects did not perform sport activities at professional level. Additionally, control group had no ballet experience.

Methods

Participants were required to attend a single testing session at the gait laboratory. Kinematic data was obtained using seven infra-red cameras of the Vicon MX (Oxford Metrics Group, London, UK) optoelectronic system. This three-dimensional motion analysis system was used to capture motion at the pelvis, hip, knee and ankle with sampling frequency of 120 Hz. Sixteen reflective markers were attached to the skin on specific anatomical landmarks in accordance with the standard kinematic model, PlugInGait. Prior to the gait measurement, static calibration of the subjects in resting stand of 30 s was conducted. During the resting stance, the subjects stood bare foot and maintained a horizontal gaze, the arms and hands hung vertically. Subsequently, each participant was instructed to perform five trials of the gait at self-selected walking speed without shoes.

Data analysis

Three successful trials of the gait were processed in Vicon Nexus 1.0 and Vicon Polygon (Oxford Metrics Group, London, UK). We evaluated one gait cycle from each analyzed trials to exclude acceleration and deceleration phase of the gait. We calculated the average walking speed of dancers (1.33 ± 0.13 m·s^{-1}) and controls (1.25 ± 0.23 m·s^{-1}). Then the data was exported to Microsoft Excel for analysis. There were calculated average values of three trials of each subject for statistical analysis. Kinematic variables included characteristic peak values (defined as the maximal or minimal joint angle during selected gait phase) and the range of motion (defined as the difference between the maximal and minimal joint angle values).

Maximal angular motion of the lower limbs and pelvis in all three planes during the gait cycle was calculated for the following angles – the ankle peaks in the sagittal plane during loading response, midstance and terminal stance (plantar/dorsal flexion); the knee peaks in the sagittal plane (flexion/extension) during the stance and swing phases; hip peaks in the sagittal (flexion/extension) and frontal planes (adduction/abduction); the range of pelvic movement in the sagittal (pelvis tilt), frontal (pelvis obliquity) and transverse planes (pelvis rotation). Average curves, normalized to 100% of the gait cycle, were created for kinematics of the pelvis and the lower limbs.

Statistical analysis

Data was statistically evaluated in Statistica (Version 10.0; StatSoft, Inc., Tulsa, OK, USA). Non-parametric test (Mann-Whitney *U* test, $p < .05$) was performed to compare the differences between the dancers and controls for gait kinematics as well as the walking speed and the body height of the subjects. *P* values less than .05 were considered as significant. The mean and standard deviation were calculated for all variables. Both lower limbs of the same subject were finally evaluated as one leg; dominance of the lower limbs was not considered.

Results

Significant differences ($p < .05$) were not found in the walking speed ($p = .35$) and the height ($p = .15$) of the participants. Thus these variables had no effect on the observed data.

The mean values and the standard deviations of the measured variables in ballet dancers when compared to controls are shown in Table 1.

The results of Mann-Whitney *U* test showed that significant differences ($p < .05$) between the groups were found in all joints of the lower limbs. Selected kinematic variables in the observed groups are shown in Figures 1–5.

Significant differences ($p < .05$) were found in increased hip extension ($p = .008$) and hip abduction ($p < .001$) together with the increased pelvic tilt

Table 1
Maximal values (M ± SD) of selected angular variables

Variable	Ballet dancers	Controls
Ankle plantar flexion during loading response	**−8.84 ± 3.74**	−10.50 ± 3.99
Ankle dorsal flexion	12.17 ± 2.67	11.48 ± 4.01
Ankle plantar flexion during terminal stance	**−20.30 ± 4.93**	**−17.50 ± 4.60**
Knee flexion during stance	17.13 ± 9.50	17.05 ± 5.89
Knee extension during stance	3.46 ± 3.73	4.02 ± 5.62
Knee flexion during swing	**65.67 ± 4.65**	**62.45 ± 5.24**
Knee extension during swing	**3.80 ± 4.02**	**−1.54 ± 5.65**
Hip extension	**−15.30 ± 3.31**	**−12.95 ± 6.04**
Hip flexion	30.71 ± 3.91	29.83 ± 4.80
Hip abduction	**−9.18 ± 5.89**	**−6.08 ± 2.52**
Hip adduction	7.80 ± 3.91	5.61 ± 3.40
Pelvic tilt (sagittal plane)	**3.33 ± 1.26**	**3.01 ± 1.46**
Pelvic obliquity (coronal plane)	**12.46 ± 3.05**	**10.34 ± 3.49**
Pelvic rotation (transverse plane)	**14.29 ± 3.77**	**13.26 ± 4.91**

Note. Variables printed in bold have statistically significant ($p < .05$) differences between ballet dancers and controls.

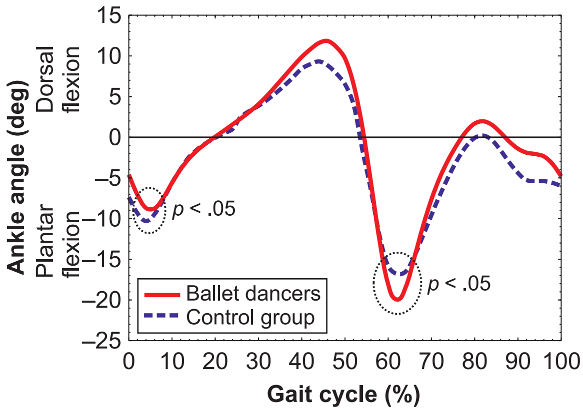

Figure 1. Ankle movement in the sagittal plane during gait in dancers and the control group

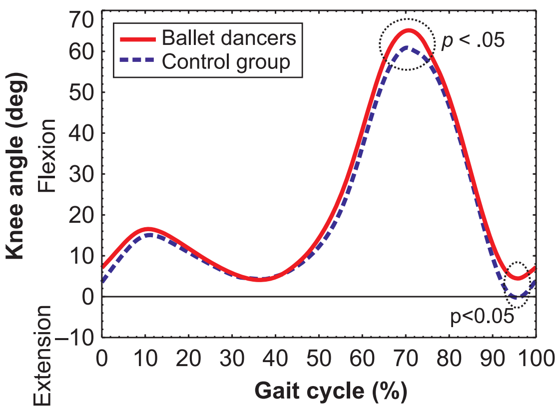

Figure 2. Knee movement in the sagittal plane during gait in dancers and the control group

($p = .020$), pelvic obliquity ($p < .001$) and pelvic rotation ($p = .029$) for the dancers. They also demonstrated greater knee flexion ($p = .002$) and knee extension ($p < .001$) peaks during swing when compared to the controls. Additionally, the dancers demonstrated decreased maximal ankle plantar flexion during loading response ($p = .032$) and increased maximal ankle plantar flexion in the terminal stance ($p = .025$).

Discussion

The current study compares the kinematics of the lower limbs and the pelvis in ballet dancers and the controls during the gait cycle and provides an insight into their compensation mechanisms. Previous studies (Ahonen, 2008; Chatfield, Krasnow, Herman, & Blessing, 2007; Kiefer et al., 2011; Koutedakis, Owolabi, & Apostolos, 2008; Russell, Shave, Kruse, Koutedakis, & Wyon, 2011; Wilson & Deckert, 2009) investigated kinematic

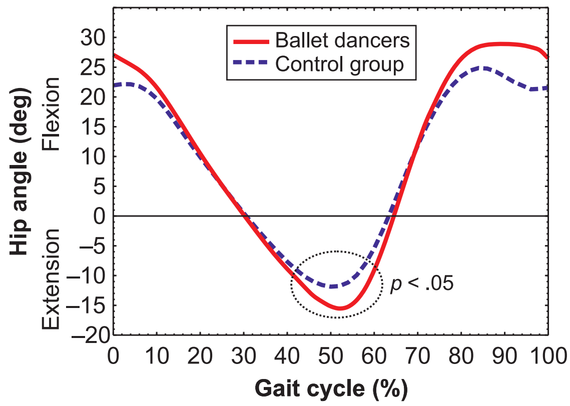

Figure 3. Hip movement in the sagittal plane during gait in dancers and the control group

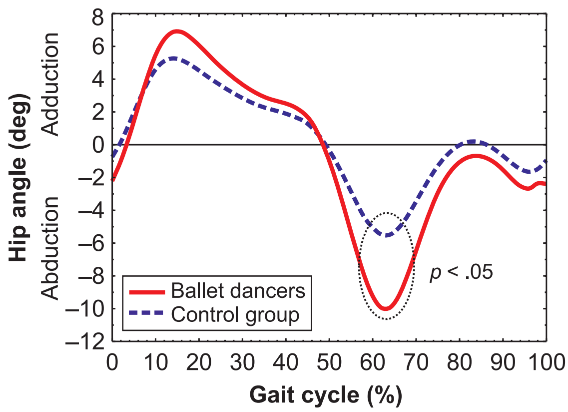

Figure 4. Hip movement in the frontal plane during gait in dancers and the control group

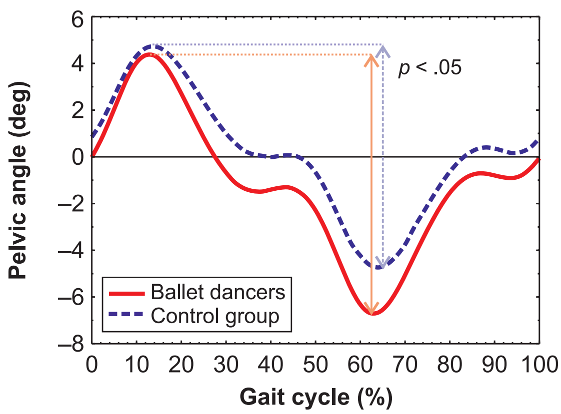

Figure 5. Pelvic movement in the frontal plane during gait in dancers and the control group

motion during various ballet positions or movements, but these studies did not provide information on how ballet influences common daily movements like walking. The compensatory changes in the gait pattern may contribute to overloading or to the development of severe injuries to the musculoskeletal system.

Our results demonstrate significantly increased maximal extension and abduction of the hip together with increased pelvic tilt, obliquity and rotation for the dancers. In ballet dance, extreme ankle position in plantar flexion and foot pronation are required (Clippinger, 2007; Lung et al., 2008). Increased foot pronation may reduce pelvic stability during the gait cycle (Barwick et al., 2012; Clippinger, 2007; Chuter & Janse de Jonge, 2012). Duval, Lam, and Sanderson (2010) reported that foot pronation induced an anterior tilt of the pelvis and increased the degree of lumbar lordosis. The greater motion of the pelvis in sagittal and frontal planes may also substitute decreased vertical deviation due to collapse of the medial arch of the foot (Childress & Gard, 2006), which is common in dancers due to frequent repetition of dancer's position turnout (Clippinger, 2007).

Pelvic tilt and rotation are also involved in controlling the deviation of the centre of mass (COM) during the gait cycle (Childress & Gard, 2006). The increased pelvic tilt may be explained by ballet movement using toe-heel walking in every-day training, which requires greater displacement of the COM during walking (Lung et al., 2008). Due to dancers have the tendency for anterior pelvic tilt, putting the lumbar spine into extension. This increased anterior pelvic tilt places the surrounding structures at higher risk of injury (Smith, 2009).

Mediolateral pelvic stability cannot be maintained without the addition of active control at the stance-leg hip abductors (Pandy, Lin, & Kim, 2010). In dancers, the muscle strength and flexibility is typically unbalanced around the pelvis, with the most commonly lacking hip abduction (Wilson, Lim, & Kwon, 2004). Dysfunction of the hip abductors (especially the gluteus medius) has led to similar biomechanical changes as those attributed to foot pronation. Ahonen (2008) describes that the changes in the frontal hip movements can relate to foot alignment in excessive pronation during gait. These kinematic changes lead to frontal plane pelvic drop with internal and adducted knee position during single leg weight bearing. This pathomechanical model predisposes numerous lower limbs injuries at the knee and more distally, e.g. ankle hypermobility, ankle injury, the iliotibial band friction syndrome, anterior cruciate ligament injury, patellofemoral pain syndrome and low back pain (Barwick et al., 2012; Chuter & Janse de Jonge, 2012).

Dance training reduces the number of constraints on ankle-hip coordination in order to enhance adaptability and flexibility of the movement pattern (Kiefer et al., 2011). Additionally, the coordination between the pelvis and the hips seems to be a key element to facilitate the maximum range of motion of the lower limbs in ballet (Chuter & Janse de Jonge, 2012).

We observed increased ankle plantar flexion in the toe-off phase. In another study, the flat-arched group demonstrated significantly greater forefoot plantar flexion during late stance (Levinger et al., 2010). The big toe and the first ray are very stressed in ballet dancers because they bear most of the weight in ballet shoes. Dysfunction of the first metatarsophalangeal joint may result in an inefficient propulsive phase. The final transfer of the force should occur through the hallux, which has been stabilized throughout the propulsive period of the gait by the flexor hallucis longus. In addition, repetitive plantar flexion and dorsiflexion of the foot in ballet movements lead to overloading of the flexor hallucis longus (Wilson, Lim, & Kwon, 2004). This fact suggests that dancers may compensate this insufficient take-off phase and reduced strength of the hallux by greater plantar flexion. Reduced push-off force of the stance leg may cause the risk of slipping (Parijat & Lockhart, 2008).

Our data shows significantly decreased ankle plantar flexion during loading response. We suppose this altered ankle motion may be caused by the flat-arched foot, which occurs in dancers due to excessive positions of the foot during ballet movements (Clippinger, 2007). Altered foot alignment may result in a failure to absorb forces applied to the limb during the gait cycle (Powell et al., 2011). The decreased plantar flexion during loading response may be compensated by reduced knee extension and increased pelvic rotation (Michaud, 1997).

We observed increased knee flexion in the toe-off phase. Several studies (Leanderson, Eriksson, Nilsson, & Wykman, 1996; Lung et al., 2008; Russell, 2010) observed that decreased extension at the knee in the swing phase may be explained by chronic ankle instability, which includes knee extensor weakness (McKean et al., 2007). Lung et al. (2008) have suggested that altered ankle motion increases the likelihood of ankle sprain. This impairment is the most frequently reported injury among dancers and often leads to chronic ankle instability (Lung et al., 2008). In addition, Clippinger (2007) found that the weakness of the quadriceps femoris occurs in dancers more frequently than in other athletes. The decreased quadriceps muscle strength may lead to more knee flexion in initial swing (Anderson, Goldberg, Pandy, & Delp, 2004). These findings are likely to result in increased stress being applied at the ankle joint structures during the gait cycle.

Describing the differences in the dancer's gait in relation to healthy subjects is the first step in trying to define how ballet activities affect common daily movements. However to establish the results, a larger sample of ballet dancers is needed and the amount of men should be increased. Rather few men (5 out of 13) compared to women participated in this study. This may cause gender effects on the results. Further research is required to compare groups of women and men separately. Although the differences in walking speed and the height of the participants were not statistically significant, movement of the lower limbs and pelvis may be affected by self-selected walking speed of the subjects.

In biomechanical gait analysis in dancers, it is important to investigate the comprehensive relationship between foot alignment and other proximal structures. Functional tasks like locomotion can clarify the relationship between particular segments of the dancer's body. Musculoskeletal disorders often arise from problems in the neighbouring joints, resulting in many compensatory mechanisms. It is important to understand these compensations and the functional relationship between the particular segments of the dancer's body to identify the main reason for the problems of the musculoskeletal system (Liederbach, 2010).

Conclusion

The results confirm that long-term intensive training of the ballet routine affects the kinematics of particular joints during gait performance. Statistically significant differences between the group of dancers and healthy subjects were found in kinematic variables of all joints of the lower limbs and pelvis.

Dancers demonstrated increased maximal extension and abduction of the hip together with increased pelvic tilt, obliquity and rotation. The increased motion of the pelvis would cause overloading especially in the lumbosacral region. Altered foot alignment results in failure to absorb the force applied to the limbs during the gait cycle.

These findings support that ballet dancers have a tendency to transfer the adjustment of the ballet positions into common daily and stereotype movements, e.g. walking. These changes in kinematics result in increased stress being applied not only to the ankle joints, but also influence the other structures of the lower limbs and the pelvis, and may increase the risk of overuse injury. Further research combining kinematic evaluation and electromyography is required to explain the impact of these differences and the clinical implications for the lower limbs and the pelvis.

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