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Comparison of gait kinematics between professional ballet dancers and non-dancers

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Abstract

OBJECTIVES: The aims of the study were to assess the kinematics of the lower limbs and pelvis during normal walking in professional ballet dancers and to investigate relationships between movements of segments of the lower limbs and pelvis.
METHODS: Thirty one professional ballet dancers and twenty eight controls completed five walking trials at their preferred speed. Kinematic data in the basic anatomical planes for ankle, knee, and hip joints as well as for the pelvis were collected with an optoelectronic motion system.
RESULTS: The female ballet dancers had in comparison with the controls significantly larger ($p < 0.01$) knee flexion in the swing phase and hip abduction in the preswing phase. Compared to the control group, the male ballet dancers had significantly larger dorsiflexion in the final stance and the total pelvic tilt range of motion. The number of significant correlations between kinematic parameters was higher in the female ballet dancers.
CONCLUSIONS: It can be concluded that specific movement techniques and compensatory strategies used in ballet dance can alter relationships between movements of segments of the lower limbs during normal walking. The relationships between movements in the joints of the lower limbs and pelvis are stronger in women.

INTRODUCTION

Classical ballet dance is an activity which places very high demands on the musculoskeletal system (Procházková *et al.* 2014). Proper execution of ballet techniques requires extraordinary range of motion (ROM) in the joints of the lower limbs, which increases the risk of injury not only during dancing but also during activities of daily living (Lung *et al.* 2008). Extreme ROM contributes to changes in posture during both static and dynamic activities (Gupta *et al.* 2004).

Experience in clinical practice suggests that most ballet dancers exhibit movement with hypermobility in certain joints. Neuromuscular activity has a key role in joint protection by ensuring proper joint centration (Stastny *et al.* 2014). Iunes *et al.* (2016) found that female ballet dancers had in stance larger hip external rotation and increased lumbar lordosis than non-dancers. Ballet tech-

ORIGINAL ARTICLE

nique en-pointe requires excessive plantarflexion, which leads to instability in the ankle joint (Lung *et al.* 2008). Consequently, overloaded structures of the foot may function worse during walking at absorbing impacts originating from foot contact, and therefore the ground reaction forces must be absorbed at the higher positioned body structures which can result in their damage (Hillstrom *et al.* 2013). In ballet, the incidence of chronic injuries caused by overloading is higher than the incidence of acute traumatic injuries (Garrick & Requa 1993; O'Malley *et al.* 1996).

Classic ballet technique also requires hip external rotation which enables lifting the lower limb higher (d'Hemecourt & Luke 2012). Joint hypermobility caused by training can manifest only in certain parts of the body; however, the hypermobile parts are often compensated by parts with reduced range of motion (Tichý 2000). When hip external rotation is limited, the required rotation can be achieved using compensatory mechanisms, such as tibial external rotation with flexed knee and pelvic anteversion Frequent utilization of compensatory mechanisms associated with chaining of dysfunctions (in the proximal-distal or distal-proximal directions) affects function of any other joint included in the kinematic chain, therefore increasing the risk of its injury even during basic locomotor activities (d'Hemecourt & Luke 2012).

From the biomechanical point of view, the human body during walking is a structure consisting of segments interconnected by joints into different types of kinematic chains. Head position in space, which is very important for keeping upright posture, is maintained by cooperation of the musculoskeletal and vestibular systems (Fanta *et al.* 2013). Muscle activity of the lower limb during gait differs between the stance phase where the foot is "fixed" on the ground (closed kinematic chain) and the swing phase where the foot is part of an open kinematic chain (Steindler 1977). Movement of the lower limbs during walking is characterized by cyclic alternations between the two forms of the kinematic chain. The ratio between durations of closed and open kinematic chain during normal walking ranges between 65:35 (Véle 1997) and 60:40 (Rose & Gamble 2006).

Due to inertia, during the gait swing phase, speed of movement of a distal segment is affected by movement of a proximal segment (McMullen & Uhl 2000). During the gait stance phase stability of proximal segments depends on stability of distal segments. Instability in the foot can therefore negatively influence the trunk stabilization which increases metabolic cost of movement as well as risk of falls (Graham *et al.* 2011).

Long-term intensive ballet training, increased demands on extraordinary ROM in the joints of the lower limbs, and overuse of compensatory strategies could lead to pathological alterations in the musculoskeletal system. The aim of our study was to assess the kinematics of the lower limbs and the pelvis during normal walking in professional ballet dancers. Moreover, we wanted to investigate relationships between movements of individual segments of the lower limbs and the pelvis during normal walking.

METHODS

Participants

Thirty one professional ballet dancers employed at the Mahen Theatre in Brno, Czech Republic participated in our study: 17 women (mean ± SD: age = 24.9 ± 4.7 years, body height = 163.8 ± 4.1 cm, body mass = 49.6 ± 4.8 kg) and 14 men (mean ± SD: age = 24.9 ± 6.0 years, body height = 176.4 ± 5.1 cm, body mass = 68.9 ± 6.2 kg). They had average ballet dance experience of 19 years (range 9–28). All dancers practiced 5 or 6 days a week, on average 7.3 hours a day (range 6–10).

The control group comprised 28 participants: 18 women (age 23.0 ± 2.0 years, body height 165.2 ± 6.2 cm, body mass 58.9 ± 6.5 kg) and 10 men (age 25.1 ± 2.2 years, body height 179.5 ± 5.0 cm, body mass 77.9 ± 8.2 kg). Members of the control group were not participating in any elite-level sporting or other physical activities and they were free of any structural or functional impairment that could affect their gait.

All the participants provided their written consent and the study was approved by the institutional ethics committee.

Data acquisition

Walking trials were conducted on a 9-meter-long walkway, which had in its center embedded two force plates (Kistler 9286AA, Kistler Instrumente AG, Winterthur, Switzerland) used for recording kinetic data (sampling frequency 200 Hz). Kinematic data were collected with optoelectronic motion system Vicon MX (Vicon Motion Systems, Oxford Metrics Group, London, United Kingdom) using 7 infrared cameras (T10, sampling frequency 120 Hz, resolution 1000x1000 pixels). All the participants underwent anthropometrical measurements where their body mass, body height, functional length of the lower limbs, and ankle and knee widths were obtained. These data were then used to calculate the joint centers. Prior to recording the walking trials, sixteen reflective markers were attached on the lower limbs and the pelvis according to the Vicon Plug-in Gait model.

Each participant underwent several trials for familiarization and five trials recorded for analysis. They walked barefoot at their self-selected preferred speed on the walkway. Recorded kinematic data were filtered in Vicon Nexus 1.6 (Woltring filter with a cutoff frequency of 10 Hz) and based on the kinetic data were divided into the stance and swing phases. The resulting data were analyzed in Vicon Polygon 3.5.

Data were then averaged from the five recorded trials, normalized to 100% of gait cycle and peak values for kinematic variables of interest as well as full ROMs were determined in the three anatomical planes for further use in statistical analysis.

Statistical analysis

Statistica 10.0 (StatSoft, Inc., Tulsa, OK, USA) was used for all statistical analyses. Shapiro-Wilk test was performed to assess normality of data distribution. Two sample t-test was used to detect differences between the ballet dancers and the control group for variables that conformed to the normal distribution while Mann-Whitney U test was used for those that did not. Associations between variables were determined with Spearman rank correlation coefficients. Statistical significance for all the tests was assumed for $p < 0.05$.

RESULTS

Age and anthropometric measures

No statistical differences were found between the ballet dancers and the control group in age or body height. The control group had significantly larger body mass both in women (p = 0.001) and men (p < 0.001).

Comparison of gait kinematics between the ballet dancers and the control group

Table 1 presents results for all observed groups.

Women

Ballet dancers had significantly greater (p = 0.037) knee flexion peak in the swing phase. They also displayed greater hip abduction during the initial swing (p = 0.013) as well as greater hip ROM in the transverse plane (p = 0.011).

Men

The ballet dancers achieved significantly larger dorsiflexion peak in the terminal stance (p = 0.006) and displayed smaller knee flexion peak in the stance phase (p = 0.004). Their total pelvis tilt ROM was significantly larger (p = 0.005) than in the control group.

Relationships between the segments of the lower limbs and the pelvis

Women

Knee flexion peak in the swing phase in the ballet dancers significantly correlated with: dorsiflexion peak in the terminal stance (r = 0.54, p = 0.025), plantarflexion peak in the preswing (r = -0.57, p = 0.017), and hip extension peak in the stance phase (r = -0.48, p = 0.049). In the control group it significantly correlated (r = -0.48, p = 0.044) with hip internal rotation peak in the stance phase.

Hip abduction peak in the initial swing in the ballet dancers highly correlated with knee ROM in the frontal plane (r = 0.80, p < 0.001) as well as with pelvic obliquity ROM (r = 0.73, p < 0.001) while in the control group it significantly correlated with ankle dorsiflexion peak (r = -0.53) as well as with knee extension peak in the terminal stance (r = 0.51, p = 0.032).

Total hip ROM in transverse plane in the ballet dancers significantly correlated with: plantarflexion peak at the end of the stance phase (r = -0.72, p = 0.001), hip extension peak in the stance phase (r = 0.57, p = 0.017), hip internal rotation peak in the stance phase (r = 0.57, p = 0.017), and total pelvis ROM in the transverse plane (r = 0.54, p = 0.024). The same parameter for the control group significantly correlated only with hip flexion peak in the swing phase (r = 0.50, p = 0.034).

Men

The number of statistically significant relationships was much lower in men than in women. In the ballet dancers significant correlations were found only between knee flexion peak in the stance phase and knee extension peak in the terminal stance (r = 0.57, p = 0.044) and between hip abduction peak in the initial swing and total hip ROM in the sagittal plane (r = 0.62, p = 0.025) In the control group significant correlations were detected between dorsiflexion peak in the terminal stance and hip flexion peak in the swing phase (r = -0.69, p = 0.029) as well as between knee flexion peak during stance phase and hip abduction peak in the initial swing (r = 0.62, p = 0.025).

DISCUSSION AND CONCLUSIONS

Women

Two most important components of physical fitness for classical ballet are flexibility and muscular strength (Bennell *et al.* 1999). Extraordinary flexibility is necessary for proper execution of individual ballet techniques (Rubini *et al.* 2011).

In female ballet dancers increased knee flexion in the gait swing phase is one of the traits typical for ballet walk, identifiable even with observational analysis. Anderson *et al.* (2004) reported that the main factors contributing to this trait were increased flexion moment in the hip joint during preswing as well as increased concentric activity of the rectus femoris muscle and the ankle plantar flexors. Increased muscular strength of the hip flexors, the iliopsoas muscle in particular, is considered to result from practicing front développé (Clippinger 2007).

These findings were corroborated also by significant correlation between knee flexion in the swing phase and reduced ankle dorsiflexion in the terminal stance we found in the female ballet dancers. Steinberg *et al.* (2006) reported that ballet dancers have lower dorsiflexion ROM. This is probably caused by large amount of time spent dancing on the tips of the toes (in en pointé) which has high force demands on plantarflexors. Hamilton *et al.* (1992) found that balled dancers had significantly stronger both plantarflexors and dorsiflexors when compared to non-dancers.

Tab. 1. Peak angular values and ROMs in the ballet dancers and the control group

	Women		Men	
	Dancers	**Controls**	**Dancers**	**Controls**
Ankle				
SP plantarflexion peak 1	-6.9 ± 2.50	-7.9 ± 3.06	-6.7 ± 1.9	-6.0 ± 2.29
SP dorsiflexion peak	13.7 ± 2.23	14.0 ± 2.65	**13.9 ± 2.55***	10.6 ± 2.59
SP plantarflexion peak 2	-21.7 ± 5.37	-21.8 ± 3.7	-19.2 ± 4.91	-17.3 ± 2.54
SP ROM	35.4 ± 4.68	35.8 ± 4.71	33.1 ± 5.92	27.9 ± 3.54
TP external rotation peak	-24.2 ± 6.02	-21.9 ± 4.14	-17.1 ± 3.92	-12.8 ± 6.24
TP internal rotation peak	7.0 ± 6.74	8.4 ± 4.84	5.9 ± 4.53	10.0 ± 7.68
TP ROM	31.2 ± 7.40	30.3 ± 6.29	23.0 ± 3.92	22.8 ± 6.64
Knee				
SP flexion peak 1	15.9 ± 5.08	18.7 ± 3.27	**14.0 ± 5.9***	21.3 ± 4.88
SP extension peak	1.3 ± 2.02	1.7 ± 2.00	2.2 ± 1.69	1.9 ± 1.42
SP flexion peak 2	**63.7 ± 3.52***	61.3 ± 3.16	63.7 ± 3.8	63.7 ± 9.35
SP ROM	62.4 ± 3.72	59.6 ± 4.74	61.5 ± 4.63	61.8 ± 8.93
FP abduction peak	4.2 ± 4.24	3.6 ± 4.87	14.4 ± 7.72	8.9 ± 6.97
FP adduction peak	-8.8 ± 5.52	-11.5 ± 7.38	-3.6 ± 4.24	-4.9 ± 3.56
FP ROM	13 ± 3.60	15.1 ± 5.08	18 ± 5.93	13.7 ± 4.17
TP external rotation peak	-12.4 ± 7.28	-12.2 ± 5.26	-11.6 ± 7.11	-11.1 ± 5.95
TP internal rotation peak	10.0 ± 7.87	6.6 ± 8.2.00	11.7 ± 8.04	10.7 ± 8.65
TP ROM	**22.4 ± 7.8***	18.8 ± 5.75	23.3 ± 5.88	21.8 ± 7.07
Hip				
SP flexion peak	30.6 ± 3.78	29.3 ± 3.30	28.4 ± 3.41	28.0 ± 1.74
SP extension peak	-17.1 ± 3.67	-16.0 ± 2.65	-16.2 ± 2.58	-16.2 ± 3.64
SP ROM	47.7 ± 3.86	45.3 ± 4.23	44.6 ± 2.6	44.2 ± 3.82
FP abduction peak	**-7.7 ± 2.01***	-6.1 ± 1.85	-6.7 ± 1.84	-6.2 ± 1.72
FP adduction peak	9.6 ± 3.19	9.1 ± 2.24	7.5 ± 1.82	6.3 ± 3.02
FP ROM	17.3 ± 3.5	15.2 ± 2.26	14.2 ± 2.49	12.5 ± 3.24
TP external rotation peak	-0.9 ± 4.98	-2.6 ± 4.16	-1.2 ± 5.19	-2.8 ± 3.67
TP internal rotation peak	5.0 ± 5.11	6.3 ± 3.97	6.1 ± 4.49	6.0 ± 3.70
TP ROM	5.9 ± 4.87	8.9 ± 2.72	7.3 ± 4.55	8.8 ± 3.47
Pelvis				
Tilt anterior peak	1.0 ± 4.98	2.6 ± 4.16	1.2 ± 5.19	2.8 ± 3.67
Tilt posterior peak	5.0 ± 5.11	6.3 ± 3.97	6.1 ± 4.49	6.0 ± 3.70
SP ROM	4.0 ± 4.59	3.7 ± 0.75	**4.9 ± 1.15***	3.2 ± 0.82
Obliquity down peak	-6.4 ± 2.62	-5.4 ± 1.58	-4.5 ± 2.05	-5.0 ± 2.5
Obliquity up peak	5.8 ± 4.1	4.8 ± 0.75	3.8 ± 0.92	3.7 ± 1.24
FP ROM	12.2 ± 3.64	10.2 ± 1.92	8.3 ± 2.60	8.7 ± 3.20
External rotation peak	-5.8 ± 1.94	-6.6 ± 2.44	-5.7 ± 1.61	-6.9 ± 2.22
Internal rotation peak	6.2 ± 3.85	6.3 ± 2.63	5.8 ± 2.34	6.9 ± 1.89
TP ROM	12 ± 5.45	12.9 ± 5.01	11.5 ± 3.83	13.8 ± 3.95

SP = sagittal plane; FP = frontal plane; TP = transverse plane; ROM = range of motion.
All values are in degrees and presented as mean ± standard deviation. * indicates statistical significant difference with the control group.

Most of the ballet techniques requiring hip abduction are based on the basic position of the lower limbs called turnout, in which the iliopsoas muscle is being co-activated and acting as a hip abductor. Increased hip abduction in the initial swing exhibited by the female ballet dancers may be caused either by increased activity of the iliopsoas muscle or by increased ligament laxity in the pelvic area.

Long-term repetition of some ballet techniques causes shortening of the hip abductors (Winslow & Yoder 1995). Their proper function has a significant effect on neuromuscular control of the knee during dynamic activities (Kipp *et al.* 2011). It can be assumed that shortening of the hip abductors may be in some ballet techniques compensated by co-contraction of the hamstrings and the quadriceps femoris muscle, which is acting as the synergist of the iliopsoas muscle and the knee stabilizers.

In the female ballet dancers, correlation between peak hip abduction in the initial swing and total knee ROM in the frontal plane and pelvic obliquity can be caused by movement compensation in the neighboring joints compensating for excessive hip abduction (Clippinger 2007) or by increased pelvis ROM in the frontal plane resulting from practicing side-développé technique.

Increased total hip ROM in the transverse plane in female ballet dancers is thought to be a result of adaptive physiological changes induced by ballet practice (Gupta *et al.* 2004). The authors stated that increased hip external rotation indicates shortening of the external hip rotators and the posterior part of the joint capsule, accompanied by increased flexibility of the internal hip rotators and the anterior part of the joint capsule. As a result of these changes the hip external rotators are capable of producing greater muscular strength during hip internal rotation.

Adequate extent of hip external rotation is important for ballet dancers as it allows attaining the turnout position properly (Sherman *et al.* 2014; Hamilton *et al.* 2006). When the extent is inadequate, the turnout is assumed using compensatory strategies, such as pronation of the feet and pelvic anteversion. Hamilton *et al.* (2006) reported that ballet dancers frequently utilize compensatory strategies to attain the turnout position, which increases their predisposition to injury. This finding is supported by the relationships we found between total hip ROM in the transverse plane and between: ankle plantarflexion in preswing, hip internal rotation peak as well as knee extension peak in the stance phase, and total hip ROM in the transverse plane. Attaining turnout by hyperpronation of the subtalar joint causes delay of external rotation of the tibia and femur as well as pelvic anteversion and increased lumbar lordosis (Valmassy 1996).

In the female ballet dancers smaller plantarflexion in the initial swing and smaller hip extension manifested in increased knee flexion in the swing phase. Increased hip abduction during the initial swing associated with reduced pelvic obliquity manifested in greater knee ROM in the frontal plane. Smaller ankle plantarflexion in the terminal stance was compensated by increased hip and pelvis rotation.

<u>Men</u>

The number of observed significant correlations in the men was lower than in the women. The male ballet dancers had significantly greater ankle dorsiflexion in the terminal stance than the control group. Sufficient range of ankle dorsiflexion is important for properly attaining plié as well as for shock absorption during jump landings (by eccentric contraction of the ankle dorsal flexors) (Ahonen 2008). Albisetti *et al.* (2010) observed that due to inadequate ankle dorsiflexion male ballet dancers were at risk of developing a hypermobile medial longitudinal arch of the foot. This may lead to forefoot varus and stress fractures of the bases of the metatarsals. Their finding was not corroborated by our study, where it was found that the male ballet dancers exhibited greater ankle dorsiflexion than the control group.

Ballet dancers exhibit reduced knee flexion during walking, that may be caused by activation of the gluteus maximus muscle during the gait stance phase. According to Perry & Burnfield (2010), the gluteus maximus muscle there acts as a stabilizer, preventing excessive flexion through the iliotibial tract.

Pelvic tilt during gait cycle oscillates between the neutral position of the pelvis and anteversion, with a ROM of 4° (Perry & Burnfield 2010). According to Lung *et al.* (2008), larger pelvic tilt during gait cycle in male ballet dancers is caused by ballet walk. Ballet walk in comparison with normal walking requires larger forward shift of the center of gravity, which is also associated with pelvic anteversion accompanied with an increased lumbar lordosis. The relationship we found between total hip ROM in the sagittal plane and peak hip abduction in the initial swing suggests that pelvic tilt in may be a form of "compensation" since it appears that the hip abductors in male ballet dancers are rather dysfunctional (Clippinger 2007; Gupta *et al.* 2004). This is not a physiological compensation but rather an indicator of the lumbar spine overloading.

<u>Study limitations</u>

Different body mass between the ballet dancers and the control group both in men and women can be considered a limit of this study. Professional ballet dance places specific demands on body composition and it is difficult to find a random population sample with comparable anthropometric parameters. However, our study investigated kinematic parameters which are considered to be less affected by body mass than kinetic parameters. Another limit of the study was that we did not evaluate ankle parameters in the frontal plane due to the ambiguous character of the motion as well as possible error of measurement.

General conclusions

When assessing the differences between the ballet dancers and controls, it is insufficient to evaluate only the differences between individual kinematic parameters. It is also necessary to consider the differences in relationships between the parameters of the joints in the kinematic chain of the lower limb and the pelvis. Only then is it possible to obtain the full information about possible differences in gait kinematics between the ballet dancers and controls and see them in a broader context.

The number of significant relationships between angular parameters of the joints of the lower limbs is higher for women. These relationships in female ballet dancers are influenced by repeated execution of the ballet techniques and by the subsequent adaptive physiological changes.

It can be concluded that specific movement techniques and use of compensatory strategies in ballet dance can alter relationships between movements of some segments of the lower limbs during walking. The relationships between joint parameters in the kinematic chain of the lower limb and the pelvis in the ballet dancers found in the present study can help physical therapists treat health issues of ballet dancers.

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