

Tibialis posterior strength and lower extremity kinematics in Kathak dancers with pronated feet: A biomechanical analysis

Research Article

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Abstract

Study aim: The aim of this study is to find out the correlation between a pronated foot with tibialis posterior muscle strength and lower extremity kinematics during gait in Kathak dancers.

Materials and methods: An observational study in which 30 female Kathak dancers of age ranging from 18 to 25 years were included after assessing for foot type and tibialis posterior muscle strength was conducted, and lower extremity kinematics were analyzed. Foot posture index, tibialis posterior muscle strength: manual muscle testing (modified Medical Research Council grading), lower limb kinematics (GaitON Software) were the outcome measures used to assess.

Results: Statistical analysis was done using the Pearson correlation coefficient test, according to which there is no correlation between foot posture index and tibialis posterior muscle strength ($p > 0.05$). There is a significant positive correlation between foot posture index and frontal plane rear foot angle during midstance bilaterally.

Conclusion: The study concludes that tibialis posterior muscle strength has not been affected in Kathak dancers with a pronated foot. Lower limb kinematics in the frontal plane has been affected more than sagittal plane kinematics in Kathak dancers with a pronated foot.

Keywords: Kathak dancers · Pronated foot · Tibialis posterior muscle strength · Gait analysis

1. Introduction

Kathak is an ancient form of Indian classical dance and arose from Kathaks, or storytellers, of North India. Kathaks narrate their tales through facial and eye expressions, rhythmic hand gestures, and foot movements. The three main elements of Kathak are Nritya (pure dance), Nritya (expressive), and Natya (dramatic elements). Dancers use ankle bells called Ghungroos while performing the dance, which includes spinning movements of the foot (chakkars). It gives rhythm to their performance (Chatterjee et al., 2013). The existence of ankle bells

(Ghungroos), which weigh around 1.5 kg on each side, increases the foot's discomfort. Repeated use of these ankle bells results in tendon strain and other connective tissue damage during performance, leading to muscular imbalance (Chatterjee et al., 2013).

“Chari Bheda” is one of the indispensable portions of the Kathak, representing the formation of numerous types of foot movements presented while dancing. Footwork in Kathak dance involves repeated rapid foot stamping over the floor. They must perform various contorted bodily movements at a high rate, ranging from 1 to 108. This may expose the foot to a greater amount of stress, which

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leads to significant biomechanical changes (Chatterjee *et al.*, 2013).

Kathak dance is known for its intricate footwork and rhythmic precision; its biomechanical demands may contribute to both adaptive and maladaptive musculoskeletal outcomes. The recent work by Oliva *et al.* (2023) underscores the role of exercise in modulating movement pattern-related disorders, offering a valuable framework for interpreting the neuromuscular adaptations seen in dancers. Integrating this perspective from dance medicine can enhance our understanding of how repetitive, culturally embedded movement practices shape musculoskeletal health.

Footwork in Kathak dance reduces the summit point of the medial longitudinal arch of the foot. As a result, the foot develops deformations such as overpronation over time. Sabharwal *et al.* (2017) state that more than 90% of the Kathak dancers developed pronated feet. The typical starting position of Kathak dancers during performance includes excessively externally rotated feet. The forefeet are positioned outward of the foot axis, putting excessive pressure on the medial foot. This typically results in a hyperpronated foot. Dancers often adopt this inappropriate posture during periods of nonpractice as well. This makes the foot prone to deformation. Furthermore, the performance over hardened floors increases the effect of the ground reaction force on the foot during stamping (Simmel *et al.*, 2013).

Overstamping the foot causes excessive load on the intrinsic muscles and foot inverters, ultimately resulting in the flattening of the medial longitudinal arch, which eventually leads to foot pronation. The medial longitudinal arch flattening results in a displacement of the talus. This alters the axis of the Talocalcaneal joint to below 45° in the anteroposterior direction. This results in significant pronation of the foot, accompanied by considerable eversion and valgus deformity in the rear foot. This may also disrupt the other tarsal bones, thereby resulting in severe foot pronation (Simmel *et al.*, 2013).

In individuals with pronated feet, characterized by a flattened arch and excessive inward rolling of the foot, the tibialis posterior tendon often becomes overworked. This increased demand can lead to tendon fatigue and dysfunction and, over time, contribute to the development of adult-acquired flatfoot deformity (Koura *et al.*, 2017). The FPI-6 was developed as a diagnostic tool in various ways. It can be used to determine biomechanical risk factors for certain issues, investigate the relationship between foot type and certain risk factors, identify foot type and patient classification for therapeutic purposes, and assess differences in the foot structure (Aquino *et al.*, 2018).

An assessment of muscle strength is typically performed as part of a patient's objective assessment. It is used to evaluate weakness and can be effective in differentiating true weakness from imbalance or poor endurance. It may be referred to as motor testing, muscle strength grading, or manual muscle testing (Naqvi *et al.*, 2019). GaitON is a two-dimensional software suitable for analysis due to its lower cost compared to three-dimensional motion capture systems, which require minimal equipment, consisting of only a high-speed camera and software. Optimal for clinics, small research laboratories, and field evaluations where financial constraints and spatial limitations exist. It facilitates a more accessible approach to the participants. It offers valuable insights when utilized appropriately (Michellini *et al.*, 2020).

The GaitON system features numerous adjustable settings, making it an ideal tool for both clinical and research applications. It provides extensive evaluation modules, encompassing both static and dynamic assessments, including gait analysis. The adaptable video input accommodates analysis with multiple camera types, ranging from mobile devices to advanced digital cameras, guaranteeing versatility for various research configurations. It also encompasses efficient data processing modules that substantially decrease analysis time and produce structured reports with normative values for straightforward interpretation. Additionally, it supplies all computed data and reference values in Excel format, facilitating data organization and subsequent analysis. It also offers a comprehensive examination of gait metrics, facilitating a profound understanding of gait mechanics (Alam *et al.*, 2024).

Therefore, the aim of the study is to investigate the correlation between foot pronation and tibialis posterior muscle strength in Kathak dancers and to explore the relationship between foot pronation and lower extremity kinematics during gait in Kathak dancers. It is essential to educate Kathak dancers regarding possible biomechanical changes in the lower extremities resulting from extended dance practice, as well as to underscore the significance of early evaluation and intervention to avert musculoskeletal issues associated with pronated foot posture in Kathak dancers.

2. Materials and methods

2.1 Methodology

The research was executed as an observational study by employing a correlational methodology in accordance

with the STROBE Guidelines. The research population did not receive any intervention; instead, the focus was on observing the influence of factors and their causal relationships among Kathak dancers. The research consisted of a single group without a control group. The research took place over 3 months at the Abhijaat Kathak School in Kotturpuram, Chennai.

2.2 Sampling method

A convenient sampling method was employed to select the study participants. The sample size consisted of 30 Kathak dancers who met the inclusion criteria. The sample size is determined by the Fisher z-transformation formula: $n = 3 + (Z_{1-\alpha/2} + Z_{1-\beta})^2 / [\text{atanh}(r)]^2$. The calculated sample size for a Fisher z-transformation, assuming a moderate effect size ($r = 0.50$), $\alpha = 0.05$, and 80% power, the sample was calculated as $n \approx 29$. Therefore, we adopted a sample size of 30 participants.

2.3 Participant selection

The study settings were in and around Chennai. There were several academies, but the Kathak dancers were very few and obtained permission from a single Kathak dancing school. Initially, 50 female Kathak dancers from the Abhijaat Kathak School were approached. A detailed explanation of the study objectives and procedures was provided, and informed consent was obtained from those who were willing to participate.

Kathak dancers aged 18–25 years, both male and female, with a minimum of 2 years of experience. Foot posture index (FPI) scores ranging from +6 to +9 were included for the study. The history of recent injuries or surgeries of the lower limb, neurological deficits, congenital deformities of the lower limb, and participation in other sports activities were excluded. Demographic data of the participants are presented in Table 1.

Table 1. Demographic data of the tested participants

Variable	Values
Total sample size	30 females
Mean age (years)	22.43 ± 1.81
Mean height (cm)	159 ± 5.34 cm
Mean weight (kg)	63 ± 8.56 kg
Number of years of Kathak experience (years)	2.95 ± 0.95

Source: Authors' own work

2.4 Data collection procedure

In accordance with the Principles of the Declaration of Helsinki, ethical approval was obtained from the Institutional Ethical Committee (IEC) (Reference Number: 2863/IEC/2021), and the recruitment process commenced. Of the 50 approached dancers, 42 met the inclusion criteria and underwent a foot posture assessment using the FPI. On the basis of FPI results, 30 dancers who scored between +6 and +9 were selected as participants. Due to the unavailability of male dancers at the time of data collection, only female participants were included in the study.

The participants were made to stand with bilateral limb support. They were instructed to undertake several trials before assuming a relaxed standing posture on a bench elevated 50 cm above the floor for visual and manual examination. Each participant underwent evaluation of rear foot parameters, including palpation of the talar head, assessment of curves above and below the malleoli, inversion and eversion of the calcaneus, as well as forefoot parameters such as bulging in the area of the Talo navicular joint (TNJ), congruence of the medial longitudinal arch, and abduction/adduction of the forefoot relative to the rearfoot. A score ranging from +1 to +5 signifies a normal foot, a score from +6 to +9 denotes a pronated foot, and a score exceeding +10 indicates a highly pronated foot. A score ranging from −1 to −4 signifies a supinated foot, while a score from −5 to −12 denotes a highly supinated foot.

2.5 Manual muscle testing

Tibialis posterior muscle strength was measured using manual muscle testing and graded with the modified Medical Research Council (MRC) grading system.

2.6 For grades 5 (normal) to 2 (poor)

The participant was in a short sitting position with the ankle slightly plantar flexed. The therapist was seated on a low bench beside the tested foot. One hand stabilized the ankle just above the malleoli. The other hand was contoured around the dorsum and medial aspect of the foot at the level of the metatarsal heads, and gives resistance toward eversion and dorsiflexion. The participant was made to move the foot into inversion by demonstrating it.

2.7 Grade 1 (trace) and grade 0 (zero)

The participant was in the short sitting position, and the therapist was seated on a low bench, palpating the tendon

of the tibialis posterior between the medial malleolus and the navicular bone. The participant was made to invert the foot by instructing them to turn the foot down and in. Tibialis posterior muscle strength was graded using the modified MRC grading system.

2.8 Gait analysis

The Nikon D3300 camera, which captures video at 60 fps, 1,080 p in MPEG-4 format, was used to capture the gait of the participants, and analysis was conducted using GaitON Software. GaitON is a two-dimensional motion analysis software that features an in-built reference protocol for gait. These reference values are based on the model of J. Perry (RLA Medical Center, California) (Auptimo, n.d). Participants were instructed to avoid loose clothing and wear skinny pants and t-shirts, and to tuck them in. Colored tapes were used as markers and placed in following landmarks; bilateral posterior superior iliac spine, greater trochanter, lateral femoral condyle, lateral malleoli, midpoint of calf, midpoint of Achilles tendon, and insertion point of Achilles tendon at calcaneum and in the lateral aspect of the foot one marker in front of the calcaneum and other over the base of the fifth phalanx (Hans, 2022). The gait acquisition protocol was conducted on a 10-m walkway. Each participant completed three gait trials, and the average of these trials was used for analysis. Gait speed was controlled rather than self-selected to maintain consistency across participants. The camera was positioned approximately 2–3 m from the subject to ensure full-body visibility and minimize visual distortion; standard calibration procedures of the GaitON software were followed. Limb dominance was not considered. The gait pattern of the participants was captured with a camera in the sagittal and frontal planes. Lower extremity

Table 2. Correlation between foot posture index and tibialis posterior muscle strength ($n = 30$)

R value		95% CI		P-value	
Right	Left	Right	Left	Right	Left
-0.162	0.007	0.493 to 0.211	-0.354, 0.366	0.393	0.970

Source: Authors' own work

kinematics of gait phases, stance, and swing phase parameters of gait (hip, knee, and ankle joint) angles were recorded. They were analyzed using the GaitON software, the reports were generated, and the results were interpreted accordingly.

3. Data analysis

The data of foot posture index, tibialis posterior muscle strength, and lower extremity kinematics of Kathak dancers were tabulated, and the Pearson correlation coefficient was calculated. One-sample *t*-test was employed to determine the difference between normative values and the mean values of Kathak dancers. The data analysis was done by using IBM SPSS version 25.

4. Results

Table 2 shows the mean value of FPI score (7.80 and 7.40 for left and right foot, respectively) and tibialis posterior muscle strength (3.83 and 3.79 for left and right foot, respectively). *R* value for correlation between FPI score and tibialis posterior muscle strength in Kathak dancers with pronated foot occurred nonsignificant as $p > 0.05$.

Table 3. Mean values and correlation between foot posture index and variables related to lower extremity kinematics during gait sagittal plane (ankle) ($n = 30$)

Variables	Mean value		R value		95% CI		P-value	
	Right	Left	Right	Left	Right	Left	Right	Left
FPI score	7.80	7.40						
Initial contact ankle	102.9	102.02	0.460	0.289	0.120, 0.704	-0.080, 0.588	0.010	0.122
Loading response ankle	102.23	101.10	0.154	0.123	-0.218, 0.487	-0.248, 0.463	0.415	0.517
Mid stance ankle	87.36	88.05	-0.012	0.161	-0.371, 0.350	-0.212, 0.493	0.950	0.394
Terminal stance ankle	90.72	87.92	0.026	0.198	-0.337, 0.383	-0.175, 0.521	0.892	0.295
Pre-swing ankle	107.34	104.66	0.128	0.281	-0.244, 0.467	-0.088, 0.582	0.499	0.133
Initial swing ankle	87.90	87.14	-0.087	-0.021	-0.434, 0.282	-0.378, 0.342	0.648	0.911
Mid swing ankle	90.21	92.50	-0.377	0.110	-0.649, -0.019	-0.261, 0.452	0.040	0.562

Source: Authors' own work

Table 4. Correlation between foot posture index and lower extremity kinematics during gait sagittal plane (knee) ($n = 30$)

Variables	Mean value		R value		95% CI for R		P-value	
	Right	Left	Right	Left	Right	Left	Right	Left
FPI score	7.80	7.40						
Initial contact knee	177.46	176.07	0.644	0.386	0.369, 0.815	0.030, 0.655	<0.001	0.035
Loading response knee	173.80	166.26	0.550	0.180	0.237, 0.760	-0.193, 0.507	0.002	0.340
Mid stance knee	174.23	172.93	0.607	0.412	0.316, 0.794	0.061, 0.672	<0.001	0.024
Terminal stance knee	167.26	166.19	0.509	0.138	0.182, 0.735	-0.234, 0.475	0.004	0.466
Pre swing knee	147.25	146.67	0.309	0.134	-0.058, 0.602	-0.238, 0.472	0.097	0.481
Initial swing knee	123.00	122.16	0.094	-0.057	-0.276, 0.439	-0.409, 0.310	0.621	0.763
Mid swing knee	157.88	155.56	0.063	0.036	-0.304, 0.414	-0.329, 0.391	0.740	0.851

Source: Authors' own work

Table 5. Correlation between foot posture index and lower extremity kinematics during gait sagittal plane (hip) ($n = 30$)

	Mean value		R value		95% CI for R		P-value	
	Right	Left	Right	Left	Right	Left	Right	Left
FPI score	7.80	7.40						
Initial contact	19.64	20.31	-0.597	-0.313	-0.788, -0.302	-0.605, 0.053	<0.001	0.092
Loading response	12.93	14.22	-0.549	-0.365	-0.759, -0.235	-0.641, -0.005	0.002	0.047
Mid stance	-1.30	-0.31	-0.685	-0.471	-0.838, -0.431	-0.711, -0.133	<0.001	0.009
Terminal stance	-11.93	-11.07	-0.519	-0.278	-0.741, -0.195	-0.580, 0.091	0.003	0.137
Pre swing	-8.55	-7.75	-0.497	-0.299	-0.727, -0.167	-0.595, 0.069	0.005	0.109
Initial swing	20.93	21.07	-0.357	0.016	-0.636, 0.004	0.346, 0.374	0.057	0.933
Mid swing	22.28	22.36	-0.135	-0.009	-0.472, 0.237	-0.368, 0.352	0.476	0.963

Source: Authors' own work

Table 3 shows the mean value of the FPI score and variables related to sagittal plane kinematics of the ankle joint during each event of the gait cycle. There is no significant correlation between FPI and sagittal plane Ankle joint kinematics during all the events of the gait cycle on both feet, as $p > 0.05$, except for initial contact and mid swing of the right side

Table 4 shows the mean value of the FPI score and variables describing a sagittal plane kinematics of the knee joint during each event of the gait cycle. There is a significant positive correlation between FPI score and knee joint kinematics during initial contact, loading response, mid-stance, and terminal stance on the right side and initial contact and mid-stance of the left side, as $p < 0.05$. There is no significant correlation between FPI and all other events of the gait cycle on both sides, as $p > 0.05$.

Table 5 shows the mean value of FPI score and sagittal plane kinematics variables of hip joint during each events

of gait cycle. R value for correlation between FPI score and variable-related hip joint kinematics during initial contact, loading response, mid-stance, terminal stance, pre swing, initial swing, and mid swing are presented.

There is a significant negative correlation between FPI score and hip joint kinematics during loading response and mid-stance of both side and initial contact, terminal stance and pre swing of right side as $p < 0.05$. There is no significant correlation between FPI and hip joint kinematics during initial swing and mid swing on both sides as $p > 0.05$. There is no significant correlation between FPI and hip joint kinematics during initial contact, terminal stance, pre swing of left side as $p > 0.05$.

Table 6 shows the mean value of the FPI score and variables related to frontal plane kinematics of the rear foot, knee, and pelvis during mid-stance of gait.

There is a significant positive correlation between FPI score and rear foot angle during mid-stance on both feet.

There is no significant correlation between FPI score and knee adduction/abduction during mid-stance on both feet. There is no significant correlation between FPI score and pelvic drop during mid-stance on both feet.

Table 7 shows a comparison between the mean of lower extremity kinematics of Kathak dancers and normative values using one-sample *t*-tests. Ankle joint kinematics of Kathak dancers has a significant difference when compared with normative values in initial contact, loading response, terminal stance, initial swing, mid swing on both side and also in mid-stance of left side as $p < 0.05$. There is no significant difference between ankle joint kinematics of Kathak dancers and normative values in pre swing phase of both side and mid-stance of the right side as $p > 0.05$. Knee joint kinematics of Kathak dancers has a significant difference when compared with normative values in initial contact, pre swing and mid swing on both sides and also in loading response and mid-stance of the right side as $p < 0.05$.

There is no significant difference between knee joint kinematics of Kathak dancers and normative values in terminal stance, initial swing phase of both side and in loading response, and mid-stance of left side as $p > 0.05$. Hip joint kinematics of Kathak dancers has a significant difference when compared with normative values in all events of gait cycle as $p < 0.05$.

There is a significant difference between mid-stance rear foot angle of Kathak dancers and normative values on both sides as $p < 0.05$. There is no significant difference between mid-stance pelvic drop of Kathak dancers and normative values on both sides as $p > 0.05$. There is a significant difference between mid-stance knee adduction of Kathak dancers and normative values on both side as $p < 0.05$.

This table demonstrates how Kathak dancers differ from the established normative gait kinematics across ankle, knee, and hip movements. Significant positive or negative mean differences (Δ), supported by confidence intervals and moderate-to-large effect sizes, indicate distinct biomechanical adaptations linked to dance training.

In contrast, angles with small or clinically negligible effect sizes – despite statistical significance – represent minor deviations unlikely to reflect functional limitation.

5. Discussion

The objective of this study is to investigate the relationship between foot pronation and tibialis posterior muscle strength, as well as the impact of pronated foot posture on lower limb kinematics during gait in Kathak dancers. Our findings indicate no significant correlation between FPI scores and tibialis posterior muscle strength among the participants. This suggests that while pronation and hyperpronation are prevalent in Kathak dancers, these postural deviations do not necessarily compromise the strength of the tibialis posterior muscle.

Even though statistically not significant, clinically, there is a mild to moderate reduction in the strength of the tibialis posterior muscle, which, in turn, over a long period of time, may lead to functional collapse of the arch, musculoskeletal pain, and balance issues, and eventually lead to pronation since long-term observation may necessitate the problems.

The absence of a significant relationship between FPI scores and tibialis posterior strength aligns with the findings of Neville *et al.* (2010), who reported that flatfoot deformity can occur without corresponding deficits in tibialis posterior muscle strength. Conversely, our results contrast with those of Alam *et al.* (2019), who demonstrated that tibialis posterior strengthening exercises improved navicular drop, muscle activity, and dynamic balance in individuals with flat feet. This discrepancy may be attributed to differences in study populations, methodologies, or the specific demands placed on the foot musculature in Kathak dancers. Migliorini *et al.*, (2023) findings support the argument that tibialis posterior strength and FPI scores are clinically meaningful in assessing injury risk and performance capacity. This also aligns with the broader goal of dance medicine:

Table 6. Correlation between foot posture index and lower extremity kinematics during gait frontal plane ($n = 30$)

Variables	Mean value		<i>R</i> value		95% CI		Significance	
	Right	Left	Right	Left	Right	Left	Right	Left
FPI score	7.80	7.40						
Mid stance rear foot angle	17.37	14.76	0.946	0.961	0.889, 0.974	0.919, 0.981	<0.001	<0.001
Mid stance knee adduction/abduction	1.61	1.17	-0.127	-0.199	-0.466, 0.244	-0.522, 0.174	0.503	0.533
Mid stance pelvic drop	3.60	2.20	-0.010	-0.079	-0.369, 0.352	-0.427, 0.290	0.958	0.679

Source: Authors' own work

Table 7. Comparison between mean values of lower limb kinematics of kathak dancers with normative values

Lower limb kinematics	Mean		Normative value	Δ (Mean–norm)		95% CI (Δ)		Hedges' g (effect size)		P value (two-tailed significance)	
	Right	Left		Right	Left	Right	Left	Right	Left	Right	Left
Initial contact ankle	102.9	102.02	92.5	10.41	9.53	7.61 to 13.20	7.26 to 11.80	1.35	1.53	<0.001	<0.001
Loading response ankle	102.23	101.10	93	9.24	8.10	7.35 to 11.13	6.28 to 9.93	1.57	1.60	<0.001	<0.001
Mid stance ankle	87.36	88.05	82	5.36	6.05	–0.36 to 11.08	4.37 to 7.73	0.34	1.31	0.065	<0.001
Terminal stance ankle	90.72	87.92	80	10.72	7.92	6.96 to 14.49	4.07 to 11.77	1.02	0.77	<0.001	<0.001
Pre swing ankle	107.34	104.66	104	3.34	0.66	–0.51 to 7.19	–3.76 to 5.08	0.33	0.10	0.086	0.762
Initial swing ankle	87.90	87.14	99	–11.10	–11.86	–13.91 to –8.29	–14.73 to –9.00	–1.72	–1.84	<0.001	<0.001
Mid swing ankle	90.21	92.50	85	5.22	7.51	3.25 to 7.19	3.17 to 11.85	1.13	0.85	<0.001	0.001
Initial contact knee	177.46	176.07	173	4.46	4.73	2.16 to 6.76	2.75 to 6.71	0.85	1.01	<0.001	0.001
Loading response knee	173.80	166.26	160	4.27	9.99	1.93 to 6.60	6.36 to 13.63	0.87	1.09	<0.001	0.241
Mid stance knee	174.23	172.93	172.5	1.66	3.93	0.48 to 2.84	1.99 to 5.87	0.56	0.79	0.014	0.596
Terminal stance knee	167.26	166.19	167	8.63	9.57	5.75 to 11.51	6.23 to 12.90	1.65	1.75	0.778	0.386
Pre swing knee	147.25	146.67	141.5	4.18	5.22	1.16 to 7.20	2.05 to 8.38	0.51	0.60	0.000	0.002
Initial swing knee	123.00	122.16	121	16.53	16.77	12.42 to 20.65	12.30 to 21.23	2.50	2.28	0.094	0.290
Mid swing knee	157.88	155.56	151.5	1.53	3.53	–0.42 to 3.48	1.14 to 5.92	0.35	0.71	0.001	0.007
Initial contact hip	19.64	20.31	23.5	2.57	2.90	0.51 to 4.63	0.63 to 5.17	0.56	0.59	0.001	0.001
Loading response hip	12.93	14.22	22.5	2.67	2.27	0.04 to 5.30	–0.40 to 4.93	0.43	0.36	<0.001	<0.001
Mid stance hip	–1.30	–0.31	–3	4.41	3.49	1.57 to 7.26	0.53 to 6.45	0.74	0.54	0.007	<0.001
Terminal stance hip	–11.93	–11.07	–19	11.58	11.81	7.78 to 15.39	8.05 to 15.58	1.33	1.42	<0.001	<0.001
Pre swing hip	–8.55	–7.75	–11	9.47	9.69	6.46 to 12.48	6.49 to 12.88	1.32	1.27	0.007	0.002
Initial swing hip	20.93	21.07	13	7.88	8.01	4.84 to 10.91	4.28 to 11.74	1.26	1.18	<0.001	<0.001
Mid swing hip	22.28	22.36	26	7.13	7.10	4.80 to 9.45	4.34 to 9.86	1.50	1.39	0.001	<0.001
Mid stance rear foot angle	17.37	14.76	4	13.37	10.77	10.96 to 15.79	8.33 to 13.20	2.01	1.61	<0.001	<0.001
Mid stance pelvic drop	3.60	2.20	2.5	2.27	–0.20	–0.15 to 4.69	–1.96 to 1.57	0.34	–0.10	0.062	0.586
Mid stance knee add/abd	1.61	1.17	0	1.50	1.17	0.79 to 2.21	0.22 to 2.12	0.89	0.45	<0.001	0.017

Source: Authors' own work

optimizing movement efficiency while minimizing biomechanical strain.

The unique demands of Kathak dance, characterized by continuous contact of the medial foot with the floor and the use of heavy ankle bells (ghungroos), may contribute to the functional flatfoot over time (Sabharwal *et al.*, 2017). This repetitive stress could lead to elongation of the tibialis posterior tendon and a subsequent decrease in the height of the medial longitudinal arch, resulting in pronation and hyperpronation during weight-bearing activities. However, the maintained strength of the tibialis posterior muscle suggests a complex interplay between structural adaptations and muscular function in this population.

D'Elia's (2023) work on physical education and movement adaptation emphasizes that specialized training environments foster unique motor patterns and muscular adaptations. Repetitive, skill-specific movement – such as the rhythmic stamping and postural control in Kathak – can lead to targeted strengthening of muscles like the tibialis posterior. Motor learning and proprioceptive feedback in structured training settings may override structural deviations, allowing for functional resilience.

In terms of lower limb kinematics, our study found that increased foot pronation is associated with greater plantar flexion at the ankle during initial contact, increased knee extension during loading response and mid-stance, and reduced hip flexion and extension during various phases of gait. These findings are consistent with those of Marouvo *et al.* (2021), who reported reduced ankle dorsiflexion and hip flexion/extension in individuals with flatfoot. However, our observations regarding knee kinematics differ from Marouvo *et al.*'s (2021) findings of reduced peak knee extension in flatfooted subjects. These variations may reflect compensatory mechanisms employed by Kathak dancers to absorb stress forces not mitigated at the foot level.

Furthermore, our analysis revealed a positive correlation between foot pronation and rear foot eversion angles during mid-stance, with significantly increased rear foot eversion observed bilaterally. This supports the findings of Buldt *et al.* (2015), who reported a connection between increased pronated foot posture and elevated rear foot peak eversion during the stance phase of gait. Interestingly, foot pronation did not significantly affect knee adduction/abduction movements or pelvic drop during mid-stance; an increase in knee adduction during mid-stance was noted bilaterally when compared to normative values (Buldt *et al.*, 2015). The lack of correlation may reflect adaptive dissociation between foot and knee mechanics in trained dancers. Hraste *et al.* (2023) framework supports the idea that movement efficiency can be maintained through alternative joint strategies, even when distal alignment is altered. This reinforces the need

to assess whole-body coordination, not just isolated joint relationships.

Russo *et al.* (2020) explored how foot mechanics influence motor control and gait variability, emphasizing the role of rhythmic lower limb coordination in stabilizing movement. Foot-ground interaction affects the entire kinetic chain, influencing joint angles, muscle activation patterns, and postural control. Altered foot posture can lead to increased variability in gait cycles, which may compromise stability and increase injury risk.

Like rhythmic gymnasts, Kathak dancers undergo rigorous, repetitive training that may foster adaptive resilience in the face of structural deviations. The maintenance of tibialis posterior strength and nonlinear joint compensation patterns observed in our study could reflect performance-driven adaptations, rather than dysfunction. Esposito *et al.*'s (2024) findings support a broader view of biomechanical plasticity, where competitive or performance-based training leads to functional adaptations that differ from general population norms.

This study acknowledges several limitations that may influence the generalizability and depth of its findings. First, the number of hours of weekly practice among participants was not considered, which could affect the degree of foot pronation and muscle strength adaptations. Second, the study exclusively included female Kathak dancers, omitting potential gender-based biomechanical variations. Finally, participants were recruited solely from a single locality, limiting the diversity of training backgrounds and regional dance styles. The FPI represents a static assessment, while gait kinematics reflect dynamic movement. This difference limits the direct comparability of the two measures and should be considered when interpreting correlation results.

To enhance future research, it is recommended to broaden the study to encompass a larger and more diverse population of Kathak dancers across various Indian states, including male dancers, to capture a broader spectrum of biomechanical adaptations. Future studies should include male dancers to understand potential gender-based biomechanical differences. Employing more reliable and validated measures (instruments like dynamometry) can improve the assessment of tibialis posterior muscle strength. In addition, comparing the tibialis posterior muscle length between dancers with pronated feet and those with neutral foot posture could provide deeper insights into structural adaptations associated with prolonged dance practice. A follow-up study incorporating an appropriate control group and detailed documentation of training variables (such as frequency, intensity, duration, and specific training components) is recommended to strengthen the validity of these preliminary findings and

allow for more robust comparisons across participant groups. Implementing these recommendations will contribute to a more comprehensive understanding of the impact of Kathak dance on lower extremity biomechanics.

Finally, our study found that FPI scores were not significantly influenced by age or years of Kathak practice, suggesting that factors such as daily practice duration and consistency may play a more critical role in the development of foot postural deviations.

6. Conclusion

This study concludes that the tibialis posterior muscle may exhibit a mild decrease in strength. But significant changes in lower limb kinematics are associated with many factors, particularly affecting gait parameters in the frontal plane more than in the sagittal plane. These adaptations may increase injury risk and impact performance efficiency. The FPI represents a static standing measure while gait kinematics reflect dynamic movement; hence, the study was interpreted with caution. Future research should focus on targeted interventions, including intrinsic foot muscle strengthening, to mitigate these changes and enhance the musculoskeletal health and longevity of Kathak dancers.

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Author contributions

In terms of the research's conception or design, data collection, analysis, or interpretation, and writing or critical review for pertinent intellectual content, the authors

stated that they had significantly contributed to the work. All authors agreed to accept public responsibility for every facet of the study and gave their approval for the final version to be published.

Conflict of interest statement

No financial, legal, or political conflicts involving third parties (government, private companies, and foundations, etc.) were declared for any aspect of the submitted work.

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