Lower Extremity Kinetics in Tap Dance

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Abstract

Tap dance is a unique performing art utilizing the lower extremities as percussion instruments. In a previous study these authors reported decreased injury prevalence among tap dancers compared to other dance and sports participants. No biomechanical analyses of tap dance exist to explain this finding. The purpose of the current pilot study was to provide a preliminary overview of normative peak kinetic and kinematic data, based on the hypothesis that tap dance generates relatively low ground reaction forces and joint forces and moments. Six professional tap dancers performed four common tap dance sequences that produced data captured by the use of a force platform and a five-camera motion analysis system. The mean vertical ground reaction force for all sequences was found to be 2.06 ± 0.55 BW. Mean peak sagittal, frontal, and transverse plane joint moments (hip, knee, and ankle) ranged from 0.07 to 2.62 N·m/kg. These small ground reaction forces and joint forces and moments support our hypothesis, and may explain the relatively low injury incidence in tap dancers. Nevertheless, the analysis is highly complex, and other factors remain to be studied and clarified.

Injuries occur frequently in ballet and modern dance,[1-9] with incidence and prevalence similar to that found in inter-collegiate sports[10] and high risk occupations.[11] Reported ballet and modern dance injury rates range from 0.62 to 18.3/1000 hours of exposure. The existing research strongly indicates that dance injuries predominantly involve the lower extremity and lumbar spine, and are mainly the result of cumulative microtrauma (overuse).

In a previous retrospective survey of experienced tap dancers we found a relatively low injury prevalence and occurrence rate (0.31/1000 exposures) among the cohort.[12] No biomechanical analyses of tap dance were available at that time to explain this finding, nor have any appeared since. Interestingly, studies of the dance styles that are most similar to tap (due to emphasis on percussive footwork), flamenco[13] and Irish dance,[14] are equally devoid of such analysis. The purpose of the current study was to provide normative kinetic and kinematic data to explain our previous findings. We conducted a descriptive pilot study of common tap dance sequences based on the hypothesis that tap dancers are relatively free of injury because their art form generates low peak ground reaction forces and joint forces and moments.

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Methods

Participants

Six professional tap dance performers (3 males and 3 females) volunteered to participate in this study. Each subject was currently employed as a tap dance performer or teacher and was between the ages of 18 and 50. Criteria for exclusion included any musculoskeletal injury in the previous six months that caused the dancer to miss dancing for one or more weeks. The subjects mean age was 24.5 ± 10.6 years, and they had 14.0 ± 7.3 years of tap dance experience (Table 1).

Each subject gave informed written consent in accordance with University Internal Review Board guidelines.

A power analysis (power 0.80) using pilot data to calculate one and two-tailed test sample size determined that six subjects were sufficient for the study.[15]

Experimental Protocol

Four commonly performed tap dance sequences were selected for study: flaps, cramprolls, pullbacks, and one self-selected sequence considered by the subject to be technically demanding. *Flaps* are performed by alternating the feet brushing forward and down

Table 1 Mean (SD) Subject Demographics

Gender	Female	Male	Total
Number	3	3	6
Age (yrs)	20.0 (4.4)	29.0 (14.2)	24.5 (10.6)
Height (cm)	168.0 (8.7)	180.0 (4.4)	173.5 (9.4)
Weight (kg)	58.7 (4.7)	81.0 (12.2)	69.8 (14.8)
Dance experience (yrs)	14.3 (5.9)	13.7 (9.9)	14.0 (7.3)

with weight landing on the ball of the foot. *Cramprolls* involve alternating four taps (toe-toe, heel-heel) with each foot. During both of these sequences weight is shifted from side to side with a hop. The *Pullback* is a backward jump with weight landing on the balls of both feet simultaneously. The self-selected sequences involved combinations of steps. These movements were repeated 4 to 8 times within each sequence, and a tape recording of a metronome with voice instruction overlay provided the tempo. Subjects practiced each sequence prior to data collection to synchronize their movements with the metronome.

The subjects warmed up at their preferred intensity on a cycle ergometer for five minutes and stretched in their usual manner prior to data collection. They wore dark colored Spandex clothing and their own tap shoes.

Instrumentation and Data Analysis

Kinetic data sampled at 1080 Hz were acquired using a single force platform (AMTI OR6, Advanced Mechanical Technology, Inc., Watertown, MA). The analog signal was amplified using the associated signal conditioner (MCA-6, AMTI) and connected via a 12-bit A-D card to the motion capture system. Three-dimensional kinematic data were acquired using a five-camera motion capture system (Vicon, Oxford Metrics Ltd, Oxford, UK) sampled at 120 Hz. A modified Helen Hayes marker set comprised of 39 reflective spherical markers, 25 mm in diameter, was used to create an 11-segment model. Data collection was synchronized and acquired through the motion capture system. Prior to each testing session the motion capture system and force plate were calibrated.

Kinetic data were reported about anatomically oriented axes using an x (flexion–extension), y (adduction–abduction) and z (axial rotation) Cardan rotation sequence. Three-dimensional net joint forces and moments and ground reaction forces (GRFs) were calculated from the position and force data using an inverse dynamics approach with BodyBuilder software (Vicon, Oxford Metrics Ltd, Oxford, UK) that incorporated the body anthropometrics entered for each subject. Hip, knee, and ankle joint forces and external moments were reported with respect to the local body reference frame. Kinetic data were low-pass filtered using a zero-lag 4th-order Butterworth filter with cut-off frequency of 25 Hz. To report joint moments, hip and knee extension and ankle plantar flexion in the sagittal plane, hip and knee abduction and ankle eversion in the frontal plane, and hip and knee external rotation and ankle abduction in the transverse plane were defined as negative in all Tables.

Given the constraint of using only one force platform, flaps and cramprolls were analyzed in three foot conditions: left foot only, right foot only, and two feet on the force platform. Examination of joint kinematics and forces found distinct angular displacements and forces that were equivalent for the unilateral foot condition and same foot in the bilateral condition (e.g., left unilateral=left bilateral, and so forth). Furthermore, with the exception of the pullback, the steps had only one foot in contact with the force platform when peak amplitude was determined. Because pullback is a bilateral movement, we made the assumption that moments and forces were evenly distributed between the two limbs. Therefore, the pullback is the sequence with the greatest limitation for left-right limb calculations and was not included in the statistical analysis for limb.

The intent of tap dance is to create percussive sound syncopation, which occurs by striking the forefoot or heel against the ground. Therefore, we analyzed forces and moments in all directions. Peak vertical, anterior-posterior, and medial-lateral ground reaction forces (GRFs) in Newtons (N) and 3-D hip, knee, and ankle net external joint forces (N) and moments (N·m/kg) were scored for each sequence using a custom program in LabVIEW (LabVIEW 7.1, National Instruments Corp., Austin, TX). All forces were normalized to body weight (BW).

Statistical Analysis

Means for each kinetic variable (peak vertical, anterior-posterior, and medial-lateral GRFs, and hip, knee, and ankle joint net forces and moments) were calculated for each subject to minimize intra-subject variability. Descriptive statistics were calculated for each sequence. We thought it important to test for gender differences to eliminate this as a factor in our results, as differences have been found between genders in jump landing that subsequently correlated with increased incidence of musculoskeletal injury.[16] A two-way analysis of variance was used to calculate differences between gender and limb for each joint variable in flaps and cramprolls, with significance set at $p < 0.05$. Pullbacks were not compared, as this was a bilateral movement and we were less confident of the left-right limb partitioning of forces. The optional sequences were also not compared for gender and limb as each dancer performed different steps. As there were no differences between gender or limb for those sequences, all data were merged. Because our major focus was to describe a range of forces and moments in tap dance, not to compare one movement to another, only vertical GRFs were examined for differences between sequences. A one-way repeated measures ANOVA was used to assess differences in the vertical GRFs between the four sequences, with significance set at $p < 0.05$. Post hoc comparisons using Bonferroni corrections were conducted.

Results

Mean peak vertical GRFs differed between sequences ($p < 0.026$), with cramprolls and optional sequence forces greater than flaps ($p < 0.006$ and $p < 0.015$, respectively; Table 2). For flaps, vertical GRFs ranged from 1.12 to 2.12 BW (mean 1.53 ± 0.39). For cramprolls, vertical GRFs ranged from 2.13 to 2.82 BW (mean 2.39 ± 0.26). For pullbacks, vertical GRFs ranged from 1.52 to 2.53 BW (mean 1.96 ± 0.36). For the optional self-selected sequence chosen by each performer (n = 4, as two records were technically inadequate for analysis), vertical GRFs ranged from 1.72 to 3.47 BW (mean 2.36 ± 0.80). The mean vertical GRF for all sequences measured in all subjects was 2.06 BW ± 0.55. Mean peak horizontal GRFs (anterior-posterior and medial-lateral) for the six subjects were relatively small (< 0.50 BW) for all tap dance sequences.

Ankle peak horizontal shear forces (anterior-posterior and medial-lateral) were minimal (< 0.60 BW) for all sequences (mean posterior → anterior 0.44, anterior → posterior 0.25, lateral → medial 0.23, and medial → lateral 0.08, respectively; Table 3). Only peak ankle vertical axial compression forces exceeded 1 BW (mean of all sequences was 1.47 BW). Mean peak knee shear forces were also minimal for all sequences (mean posterior → anterior 0.58, anterior → posterior 0.19, lateral → medial 0.18, and medial → lateral 0.10, respectively). Mean peak knee vertical axial compression forces were near or exceeded 1 BW (mean of all sequences was 1.26 BW). Mean peak hip shear forces were minimal for all sequences (mean posterior → anterior 0.19 and anterior → posterior 0.57, lateral → medial 0.13, and medial → lateral 0.27 BW, respectively). Mean peak hip vertical compression forces were about 1 BW (mean of all sequences was 1.07 BW).

Mean peak ankle moments (N·m/kg) for the four sequences were dorsiflexion-plantar flexion 0.67 and -0.33, inversion-eversion 1.71 and -0.58, and adduction-abduction 0.82 and -1.56 (Table 4). Mean peak knee moments (N·m/kg) for the four sequences were flexion-extension 1.70 and -0.62, adduction-abduction 1.58 and -0.75, and internal rotation-external rotation 0.71 and -0.29. Mean

Table 2 Mean (SD) Peak Ground Reaction Forces (BW)

Sequence	Flaps	Cramprolls	Pullbacks	Optional
Vertical*	1.53 (0.39)*	2.39 (0.26)*	1.96 (0.36)	2.36 (0.80)*
Anterior	0.06 (0.02)	0.19 (0.41)	0.25 (0.10)	0.17 (0.08)
Posterior	0.10 (0.07)	0.41 (0.21)	0.36 (0.12)	0.40 (0.28)
Medial	0.09 (0.02)	0.16 (0.05)	0.08 (0.03)	0.15 (0.05)
Lateral	0.10 (0.02)	0.14 (0.03)	0.05 (0.01)	0.16 (0.11)

Note: *ANOVA Vertical GRF: $F(1,3) = 3.95$, $p < 0.026$; post hoc Cramprolls v. Flaps $p < 0.006$ and Optional v. Flaps $p < 0.015$.

Table 3 Mean (SD) Peak Joint Forces (BW)

Sequence	Flaps	Cramprolls	Pullbacks	Optional
Ankle				
Post→Ant	0.36 (0.21)	0.43 (0.25)	0.52 (0.24)	0.49 (0.23)
Ant→Post	0.16 (0.18)	0.13 (0.16)	0.27 (0.34)	0.25 (0.28)
Lat→Med	0.27 (0.10)	0.31 (0.13)	0.21 (0.09)	0.25 (0.13)
Med→Lat	0.04 (0.04)	0.11 (0.11)	0.08 (0.09)	0.12 (0.11)
Compression	1.03 (0.48)	1.75 (0.55)	1.54 (0.50)	1.57 (0.56)
Knee				
Post→Ant	0.40 (0.22)	0.53 (0.37)	0.76 (0.27)	0.65 (0.39)
Ant→Post	0.11 (0.08)	0.21 (0.18)	0.25 (0.26)	0.23 (0.14)
Lat→Med	0.21 (0.11)	0.18 (0.15)	0.14 (0.12)	0.23 (0.08)
Med→Lat	0.06 (0.04)	0.17 (0.19)	0.09 (0.05)	0.10 (0.05)
Compression	0.96 (0.46)	1.61 (0.56)	1.40 (0.51)	1.07 (0.28)
Hip				
Post→Ant	0.10 (0.04)	0.20 (0.13)	0.22 (0.12)	0.28 (0.11)
Ant→Post	0.19 (0.12)	0.63 (0.33)	0.82 (0.21)	0.74 (0.33)
Lat→Med	0.10 (0.05)	0.14 (0.06)	0.13 (0.08)	0.18 (0.07)
Med→Lat	0.07 (0.05)	0.24 (0.22)	0.20 (0.16)	0.11 (0.05)
Compression	1.07 (0.48)	1.23 (0.63)	1.13 (0.47)	0.87 (0.35)

Note: Horizontal shear forces: Posterior to Anterior (Post→Ant), Anterior to Posterior (Ant→Post), Lateral to Medial (Lat→Med), Medial to Lateral (Med→Lat). Vertical axial loading forces: Compression (Compression).

Table 4 Mean (SD) Peak Joint Moments (N·m/kg)

Sequence	Flaps	Cramprolls	Pullbacks	Optional
Ankle				
Dorsiflexion	0.44 (0.36)	0.78 (0.49)	0.65 (0.25)	0.91 (0.60)
Plantar flexion	-0.21 (0.23)	-0.31 (0.28)	-0.33 (0.45)	-0.59 (0.96)
Inversion	1.59 (0.56)	1.48 (0.82)	1.67 (1.04)	2.32 (0.96)
Eversion	-0.12 (0.20)	-0.30 (0.46)	-1.34 (1.63)	-0.50 (0.47)
Adduction	1.04 (0.54)	0.98 (0.75)	0.48 (0.51)	0.77 (0.63)
Abduction	-0.55 (0.59)	-2.42 (0.16)	-1.55 (0.72)	-2.09 (1.93)
Knee				
Flexion	0.83 (0.66)	2.50 (1.64)	2.01 (0.63)	1.49 (0.47)
Extension	-0.42 (0.65)	-0.93 (0.92)	-0.47 (0.61)	-0.82 (0.59)
Adduction	0.56 (0.64)	1.56 (1.04)	2.62 (0.75)	1.55 (0.66)
Abduction	-0.98 (0.69)	-0.71 (0.65)	-0.50 (0.35)	-0.82 (0.77)
Internal rotation	0.32 (0.29)	0.88 (0.63)	0.88 (0.23)	0.87 (0.38)
External rotation	-0.24 (0.27)	-0.28 (0.29)	-0.38 (0.43)	-0.26 (0.15)
Hip				
Flexion	0.78 (0.45)	1.25 (0.95)	1.12 (0.39)	1.12 (1.36)
Extension	-0.37 (0.62)	-0.76 (0.49)	-0.36 (0.42)	-1.01 (0.68)
Adduction	1.31 (0.56)	1.69 (1.28)	1.74 (0.86)	2.35 (0.82)
Abduction	-0.29 (0.13)	-0.70 (0.34)	-1.43 (1.03)	-1.21 (0.67)
Internal rotation	0.14 (0.15)	0.29 (0.22)	0.07 (0.61)	0.34 (0.24)
External rotation	-0.24 (0.16)	-1.15 (0.74)	-0.72 (0.45)	-0.77 (0.22)

peak hip moments (N·m/kg) for the four sequences were flexion-extension 1.05 and -0.56, adduction-abduction 1.69 and -0.87, and internal rotation-external rotation 0.19 and -0.69. These results are summarized in Table 4.

Discussion

As mentioned earlier, our literature search revealed no previous studies that analyzed biomechanical aspects of tap dance or other percussive dance forms such as flamenco or Irish dance. Thus, to interpret our results, we compared them to those reported for other dance forms, sports, and activities of daily living.

GRFs have been measured in numerous studies involving walking,[17] dance leaps,[18] aerobic dance,[19-21] running,[22-24] hop for distance,[25] drop landings, [26-29] vertical dance jumps,[30] gymnastics,[31] and various other sports activities.[32-35] Vertical GRFs measured for the four tap dance sequences were in the lower range of those previously reported for the various activities (Fig. 1). Tap dance vertical GRFs most closely resembled those measured in low impact aerobic dance[20] and shorter dance leaps.[18] However, the tap dance sequences with the greatest vertical GRFs (cramprolls and the optional sequence) equaled those reported during large dance leaps,[18] running,[22-24] and high impact aerobic dance.[19,20,36]

Lower extremity joint shear forces were all relatively small. Among studies of ankle joint vertical compression forces, tap dance activity was comparable to low impact aerobic dance,[19] but lower than high impact aerobics[19] or dance leaps[18] (Fig. 2). Compared with studies of hip and knee joint compression forces occurring during various activities, our findings again

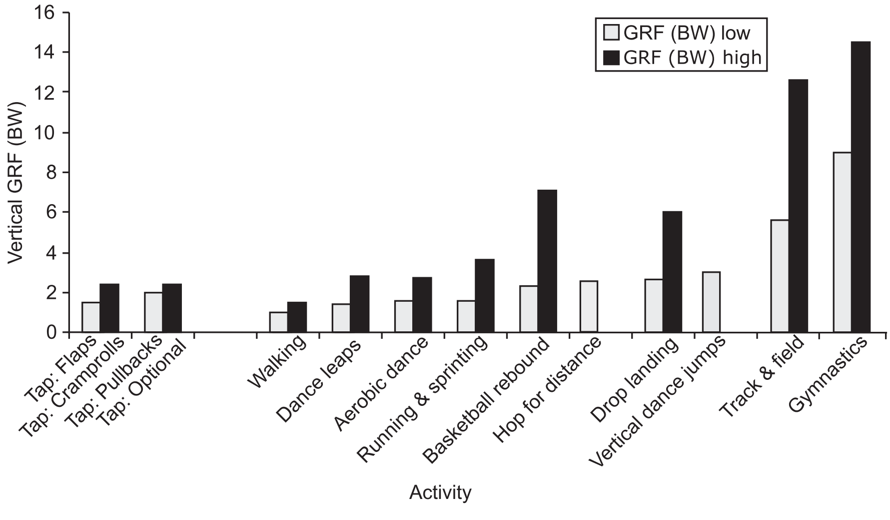

Figure 1 Vertical ground reaction forces (BW) measured during various activities. The range of values is represented by the high and low GRF (BW). Tap dance: flaps, cramprolls, pullbacks, and optional (current study); walking[17]; dance leaps[18]; aerobic dance[19,20,36]; running and sprinting[22-24]; basketball rebound[35]; hop for distance[25]; drop landing[26-29]; vertical dance jumps[30]; track and field: high jump[32] and triple jump[33]; and gymnastic back flips.[31]

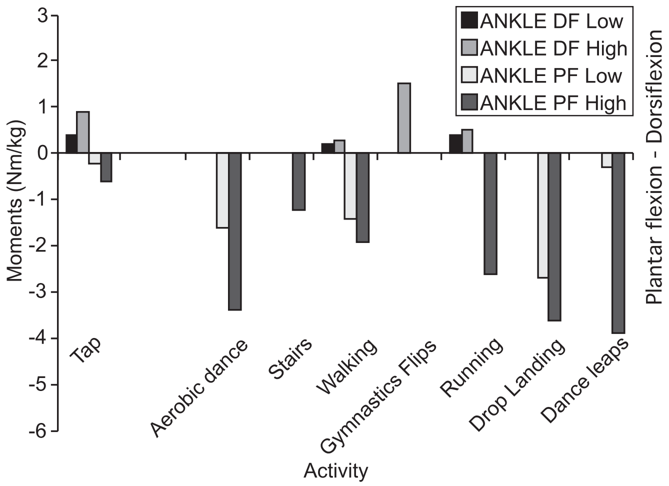

Figure 2 Vertical force comparisons for the ankle, knee, and hip joints. The range of values is represented by the high and low Fz (BW). Tap dance (current study), walking,[37] stairs,[37,45] aerobic dance,[19] and dance leaps.[18]

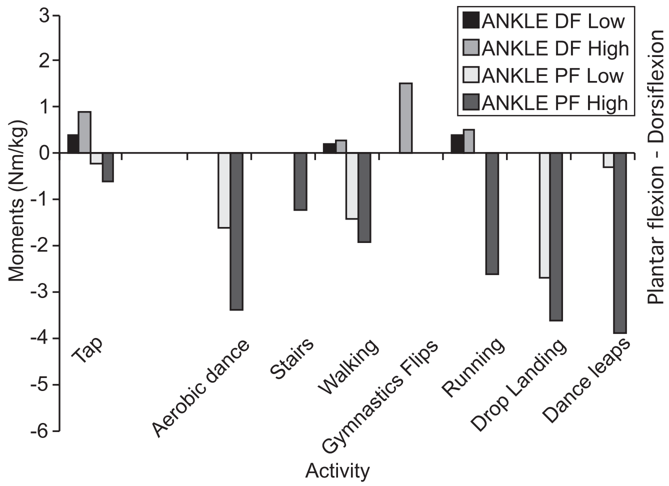

Figure 3 Ankle moment comparisons in the sagittal plane. The range of values is represented by the low and high flexion (Flex) and extension (Ext) bars (BW). Tap dance (current study), aerobic dance,[19] stairs,[37,45] walking,[40,44] gymnastic flips,[42] running,[38] drop landing,[47] and dance leaps.[18]

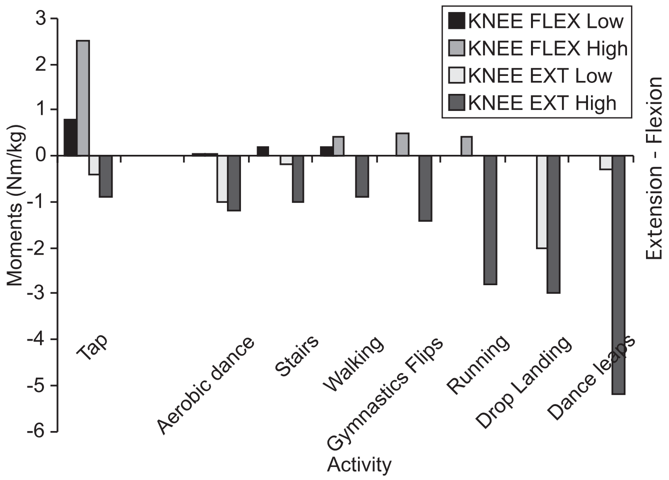

Figure 4 Knee moment comparisons in the sagittal plane. The low and high flexion (Flex) and extension (Ext) bars (BW) represent the range of values. Tap dance (current study), aerobic dance,[19] stairs,[37,45] walking,[40,41] gymnastic flips,[42] running,[38,46] drop landing,[47] and dance leaps.[18]

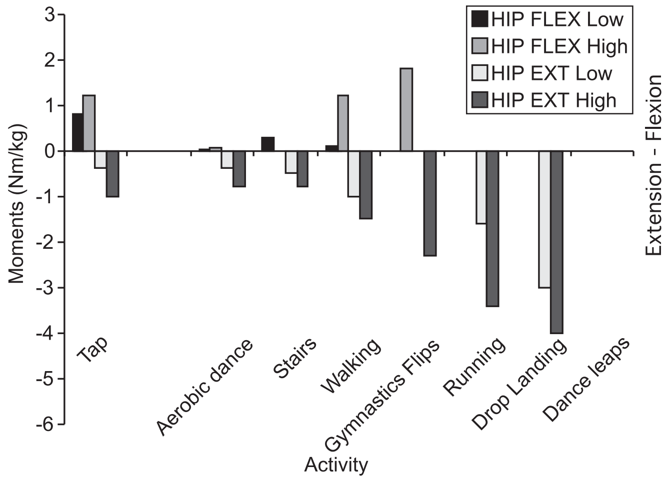

Figure 5 Hip moment comparisons in the sagittal plane. The low and high flexion (Flex) and extension (Ext) bars (BW) represent the range of values. Tap dance(current study), aerobic dance,[19] stairs,[37,45] walking,[40,41,45] gymnastic flips,[42] running,[38,46] drop landing,[47] and dance leaps.[18]

most closely resembled measurements during low impact aerobic dance,[19] and only slightly exceeded those occurring during walking and stair climbing.[37] Tap dance knee joint compression forces were considerably lower than those occurring during dance leaps.[18]

An overview of the tap dance joint moment results revealed that, in the sagittal plane, it is a flexion-biased activity (i.e., hip and knee flexion and ankle dorsiflexion), unlike most sports, which are extension dominant (i.e., plantar flexion and extension moments exceed dorsiflexion and flexion moments). This is most likely because heel tapping produces a greater percussive sound than toe tapping; therefore, ankle dorsiflexion and knee and hip flexion moments are emphasized. Furthermore, tap dance does not travel forward, resulting in lower extension moments.

Tap dance frontal plane moments, in particular hip and knee adduction and ankle inversion moments, generally exceeded flexion moments. Again, because the creation of modulated sound and rhythm is the purpose of tap dance, this contrasts with maximum take off and landing efforts to achieve height or distance in other dance forms or sports. In the sagittal and frontal planes knee moments tended to be larger than hip and ankle moments.

It has been reported that sagittal plane moments generally exceed those of the frontal and transverse planes.[38] However, most studies have focused on sagittal plane dominant activities (e.g., walking, running, stair climbing, aerobic dance, gymnastic flips, and similar movements). Peak ankle joint moments measured during the four tap dance sequences were relatively low in the sagittal plane and greatest in the frontal and transverse planes. Hip moments in the frontal plane were greater than those in the sagittal plane.

The greater ankle moments found in inversion may place the ankle at high risk for sprain, as suggested by our previous finding that ankle sprain is the most frequent injury in tap dancers.[12] The inversion and abduction moments may reflect those necessary to produce certain sounds. [It is important to note that there is currently no accepted standard for reporting 3-D joint moments. Different reference frames may be used in other studies, but are not always reported.] Increased variability has been reported between subjects in the frontal and transverse planes.[38,39]

Comparison of tap dance sagittal plane moments for the ankle, knee, and hip is made with other activities in Figures 3, 4, and 5. Tap dance ankle dorsiflexion moments exceeded those of walking[40,41] and running,[38] but not gymnastic flips[42] (Fig. 3). Compared with prior studies of ankle plantar flexion moments during various activities, tap dance ankle plantar flexion moments were less than those found in stair climbing,[37,43,45] walking,[40,44] gymnastic flips,[42] running,[38,46] drop landings,[47] or dance leaps.[18] Tap dance plantar flexion moments only resembled the lower values reported for dance leaps.[18]

Tap dance knee flexion moments greatly exceeded those reported for aerobic dance,[19] walking,[40,41] gymnastic flips,[42] and running[38] (Fig. 4). Tap dance knee extension moments resembled those reported for stairs[37] and walking,[40,41] but were lower than values reported for gymnastic flips,[42] running,[38,46] drop landing,[47] and dance leaps.[18] Tap dance hip flexion moments exceeded those reported for aerobic dance[19] and stair climbing[37] and closely resembled those found in walking[41,48] (Fig. 5). Tap dance hip extension moments most closely resembled those reported for aerobic dance[19] and stair climbing.[37]

There were relatively large standard deviations in all joint force and moment data, demonstrating considerable inter-subject variability. Yu and colleagues[49] analyzed variance in kinetic data, and concluded that variation in motor performance is the major factor involved. These investigators found that when tracking errors in three-dimensional coordinates, those involving location of center of pressure and skin motion were too small to account for the observed variance.

Although our results appear to confirm the initial hypothesis for this study—that tap dancing generates relatively low GRFs and joint forces and moments, thereby decreasing injury risk for tap dancers—additional factors need to be considered. First, we studied experienced professional performers. Less skillful dancers may demonstrate higher peak forces and incur more frequent injuries, although this possibility seems unlikely in light of prior studies of vertical GRFs in gymnasts versus recreational athletes[50] and in parachutists versus novice jumpers.[51] Both of these studies found that more experienced subjects produced higher vertical GRFs during drop landings than untrained subjects. It appears, therefore, that increased skill and fitness levels promote increased accommodation of musculoskeletal stress during activity. Alternatively, subjects who are constitutionally able to tolerate higher impacts may survive to become expert in the task. A future investigation comparing novice and experienced tap dancers could resolve this question.

We believe that the relatively low peak vertical GRFs measured in our subjects reflect task specificity. Unlike jumping in sports or leaping in ballet and modern dance, where height, distance, or movement aesthetic is the goal, the purpose in tap dance is to create tasteful percussive sound syncopation. Musculoskeletal forces generated by experienced tap dancers are modulated according to the sound produced. Supporting this premise is the small variability of peak vertical GRFs among subjects.

Second, vertical GRF measurements reflect overall impact force experienced by the musculoskeletal system, but may not be identical to the forces experienced by individual components of the system. This raises the potential need for a measurement technique that is more sensitive to detail than the one used in this study. Nevertheless, our analysis of individual joint forces and moments suggests that these components of the kinetic chain are not inordinately stressed during tap dancing, with most subjects scoring less than 1.0 BW during the different tap dance sequences studied.

Third, the assumption that landing force impacts occurring during physical activity directly relate to injury is too simplistic. Nigg[24] found no significant difference in injury occurrence between subjects with high, medium, or low impact forces during running. In fact, subjects who manifested higher loading rates had significantly fewer injuries than those with lower loading rates. Nigg suggested that the locomotor system "pretunes" muscles to minimize soft tissue vibrations, and that both "impact" and "movement control" are involved in the protective adjustments to ground contact before and during landing. In addition, Elliot[23] emphasized that external forces measured on the force platform may produce different internal forces (responsible for overuse injury) consequent to anatomic and technique variations. Although we did not find this to occur among our subjects, our joint force calculation methodology might not provide a complete analysis since it calculates net forces rather than partitioned internal forces.

Fourth, varying pre-task warm-up practices, fatigue,[52] and the use of orthotics[53] can affect landing forces. Since we employed a standardized brief warm-up protocol and none of our subjects used orthotics, these factors were partially controlled for in our study. We cannot determine, however, whether the subjects' use of their preferred tap dance shoes may have influenced the measurements.

Fifth, Barr and colleagues[54,55] elegantly demonstrated in rodents that repetitive negligible force tasks induce local musculoskeletal injury and generate inflammatory cytokines and chemokines resulting in distant joint pathology in non-working limbs. These findings extend Nigg's concept that impact forces are only one component of the injury paradigm. The possibility exists, therefore, that the "negligible" forces and moments that we measured might, if repeatedly applied, result in injury. For instance, it is important to emphasize that we have measured and reported mean *peak* forces and moments for all sequences, but that multiple peaks occur during each step. It is therefore possible that the summation of these forces combined with multiple repetitions may produce overuse injury. In this pilot study we have provided normative data for GRFs, joint forces, and moments produced during common tap dance sequences. Measuring repetitions to create a semi-quantitative prediction paradigm for overuse injury could enhance the utility of further analysis of individual joint forces. Future studies tracking cytokines and chemokines through blood analysis similar to the research of Barr and associates[55] might shine further light on this link.[56]

A limitation of this study was the constraint of having only one force platform. Future studies should preferably use two force platforms to optimize partitioning of forces and moments to each limb. Also, as this was a pilot study, we analyzed healthy, young, professional tap dancers. Our results cannot be assumed to apply to tap dancers of other ages or levels.

Conclusion

As anticipated, we found relatively small joint landing forces and moments for the four sequences performed by experienced tap dancers. These findings may help to explain the low injury incidence reported in our previous study. Nevertheless, the analysis is highly complex, and many other factors remain to be studied and clarified. In particular, further research is warranted to compare the effects of age and skill level on tap kinematics and kinetics, as well as to investigate phase-specific loading and impact rates (e.g., force time curves).

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