Lower Body Stiffness and Muscle Activity Differences Between Female Dancers and Basketball Players During Drop Jumps

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Abstract:

Background: Anterior cruciate ligament (ACL) injuries often occur during landing, with female athletes at higher injury risk than male athletes. Interestingly, female dancers have lower ACL injury rates than do female athletes in general.

Hypothesis: Female dancers will have earlier and greater lower extremity muscle activity and higher sagittal knee joint and leg stiffness than will female basketball players.

Study Design: Cross-sectional group comparison.

Methods: Fifty-five healthy female athletes (35 dancers, 20 basketball players) performed 5 double-leg drop jumps from a 45-cm box. Surface electromyography (onsets and amplitudes; prelanding and postlanding) was recorded from the lateral gastrocnemius, medial and lateral hamstrings, lateral quadriceps muscles with a 3-dimensional electromagnetic tracking system, and forceplates recording biomechanics (leg spring stiffness and knee joint stiffness).

Results: Compared with basketball players, dancers had greater leg spring stiffness (P = 0.047) but similar knee joint stiffness (P = 0.44). Although no significant differences were observed in overall muscle onset times (P = 0.22) or activation amplitudes (prelanding, P = 0.60; postlanding, P = 0.78), small to moderate effect sizes (ESs) suggest trends in dancers toward earlier (ES = 0.53) and higher medial hamstrings activation pre- (ES = 0.55) and post- (ES = 0.41) landing and lower lateral quadriceps (ES = 0.30) and higher gastrocnemius (ES = 0.33) postlanding muscle activation.

Conclusions: In dancers, the higher leg spring stiffness and trends toward higher hamstrings prelanding and postlanding, as well as lower quadriceps and higher gastrocnemius activation

postlanding with similar knee joint stiffness, indicate lower extremity neuromechanical differences across other joints.

Clinical Relevance: Female dancers may have lower extremity neuromechanics that are different from those of basketball players during drop jumps. If dancers use ACL-protective strategies during activity, then their training routines should be further investigated to improve ACL injury prevention programs.

Keywords: landing | anterior cruciate ligament | knee | injury

Article:

Female athletes have higher rates of noncontact anterior cruciate ligament (ACL) injuries than do male athletes.[3,4,20] Sex differences in neuromuscular and biomechanical (neuromechanical) parameters during activity are among the potential explanations for this injury rate disparity.[20,51] Research suggests that female athletes have higher levels of quadriceps and lower levels of hamstrings muscle activity,[58] slower responses of hamstring activation to anterior stress on the ACL,[56] increased knee extensor moments, lesser total hip and knee flexion angles and time to peak flexion angles,[48] and lower sagittal and torsional knee joint stiffness and leg spring stiffness than do male athletes during activity.[11,19,24,47,49,56]

Landing is commonly associated with ACL injury.[42,51] The drop jump task of landing from a height onto the ground (initial landing), followed by an immediate maximum vertical jump and then a landing back onto the ground, is often used as a research model to investigate landing neuromechanics.[40,45,54] Leg spring stiffness reflects the resistance of the entire leg (combined ankle, knee, and hip joints) to the compression imposed during landing; it is a measure of dynamic stability.[15,24] Decreased leg spring stiffness suggests higher risk for soft tissue injury.[7,11,19,55] Knee joint stiffness is also important because the knee musculature influences joint stability during high-risk ACL injury activities, such as landing.[18,22,35,51,53]

Quadriceps, hamstrings, and gastrocnemius muscle activation increases knee joint stiffness 48% to 400%[18,34,36,56] and improves joint congruence.[5,13,36] Excessive quadriceps muscle force is known to be injurious to the ACL.[12,20,22,25,30] Quadriceps muscle fatigue leads to earlier activation of the gastrocnemius muscle, probably to compensate for the fatigued quadriceps muscles.[41] The gastrocnemius is a synergist of the quadriceps and an antagonist of the ACL.[16] Hamstring muscle forces are ACL protective.[13,14,53] Investigating knee muscles is therefore important to elucidate mechanisms that increase knee stability during activity.

Female dancers (who regularly perform multiple landing and jumping activities) do not injure their ACLs as frequently as female athletes in sports that involve jumping and landing.[2,32,38] Sex differences were not noted in a recent comparison of landing biomechanics in professional dancers,[44] but dancers display differing neuromuscular characteristics (eg, smaller H-reflexes)[39] than active individuals.

Increased activation of knee musculature is protective during activity by reducing the probability of knee joint subluxation following joint loading.[53] Higher stiffness via greater muscle activation may be ACL protective by reducing external force resisted by the ACL.[56] Female athletes may expose their knee joints to greater ligamentous strain than that of male athletes during landing.[8,23,48] However, examinations are still lacking of possible neuromechanical differences between female dancers and athletes (eg, basketball players) during high-risk ACL injury activities (eg, landing).

This study compared knee muscle activation, leg spring stiffness, and knee joint stiffness between female dancers and basketball players during the initial landing of drop jumps. We hypothesized that female dancers will have earlier and greater lower extremity muscle activity and higher torsional sagittal knee joint and leg stiffness than female basketball players.

METHODS

Fifty-five healthy athletes participated: 35 dancers (20.7 ± 2.3 years, 164.3 ± 6.7 cm, 62.2 ± 1.9 kg, years of experience =13.9 ± 5.2) and 20 basketball players (20.1 ± 2.0 years, 170.5 ± 6.1 cm, 72.6 ± 11.4 kg, years of experience = 10.7 ± 3.5). Only those whose primary form of activity was dance or basketball for at least the past 2 years were recruited, including dance or basketball at least 3 days per week for at least 30 minutes per day.

All surface electromyography (sEMG) data were collected using a 16-channel Myopac sEMG unit (Run Technologies, Mission Viejo, California). The sEMG unit and surface electrode specifications have been described elsewhere.[1] A Biodex System 3 dynamometer (Biodex Medical Systems Inc, Shirley, New York) was used to position the participant at a fixed knee flexion angle of 30° during the maximum voluntary isometric contraction (MVIC) trials. The sEMG data were acquired, stored, and analyzed using the Datapac 2K2 Lab Application Software (Run Technologies); furthermore, sEMG activity was synchronized with a type 4060 nonconducting forceplate (Bertec Corporation, Columbus, Ohio) where foot contact exceeding 10 N triggered sEMG data collection at 1000 Hz.

Kinematic data were collected at 120 Hz using a 3-dimensional electromagnetic tracking system (MotionStar hardware, Ascension Technology, Burlington, Vermont; Motion Monitor software, Innovative Sports Training, Chicago, Illinois), and kinetic data were collected at 1000 Hz using the type 4060 nonconducting forceplate.[50] Kinematics setup included the attachment of 4 six degrees of freedom position sensors (Ascension Technologies) on the preferred landing leg to record the movement of the lower extremity during the drop jumps using previously published methods.[48]

Participants completed a university-approved informed consent form, after which demographics were recorded. All measurements were taken on the preferred landing leg. The process of determining the preferred leg has been described elsewhere.[1] The effects of footwear on movement mechanics have been documented.[6] Unlike athletes who always play with footwear, dancers may or may not use it, depending on the dance form. To partially account for the effects of this factor, all testing was done barefoot.

The participant stood on a 45-cm box, extended her preferred leg, and dropped off the box, performing a double-leg landing, with each foot landing on a separate forceplate. The participant then immediately performed a maximal vertical jump upon ground contact, again landing on the forceplates. To control for the potential effects of hand position on landing and movement neuromechanics,[9,10] participants were asked to look forward at a marker placed at eye level in front of them and to keep their hands on their hips at all times. Sufficient practice was allowed for participants, and the number of practice familiarization trials was recorded (dance, 3.9 ± 1.7; basketball, 3.9 ± 1.8).

Electrodes were placed on the skin over the muscle bellies of the lateral quadriceps, medial hamstrings, lateral hamstring, and lateral gastrocnemius muscles and the anteromedial aspect of the tibia (reference electrode) using previously published methods.[1,52] Participants then performed three 5-second MVICs of each muscle for normalization purposes while seated in a Biodex dynamometer in knee extension (quadriceps), knee flexion (hamstrings), and ankle plantar flexion (gastrocnemius). Kinematic data were collected with position sensors on the lower extremity, followed by standard digitization procedures.[26,29,48]

Participants performed 5 double-leg drop jumps from the 45-cm box (Figure 1). A rest interval of 10 seconds was provided between each trial. A trial was discarded and participants were asked to repeat the trial if they lost their balance, if their hands came off their hips at any point during the trial, or if they failed to land back onto the forceplates.

Figure 1. Drop jump task performance. Note direction of movement indicated by arrow line.

Data Processing

Muscle activity during the first and last second of each MVIC trial was discarded before analysis to ensure steady state results. MVIC trials were digitally processed with a band pass filter from 10 to 350 Hz using a fourth-order, zero-lag Butterworth filter and a centered root mean square

(RMS) algorithm with a 100-millisecond time constant.[52] The absolute peak RMS amplitude (in volts) obtained over 3 trials was used to normalize the muscle activity data during the drop jumps.[52]

The sEMG signals during the initial landing of the drop jumps were digitally processed with a band pass filter from 10 to 350 Hz using a fourth-order, zero-lag Butterworth filter and a centered RMS algorithm with a 25-millisecond time constant. Five trials for each participant were then ensemble averaged to obtain 1 representative trial (Figure 2). A mean ± standard deviation interval event buffer extracted onset times (in milliseconds), defined as the time point when the muscle activity first exceeded 5 standard deviations above quiet standing baseline muscle activity for at least 25 milliseconds or longer. For the amplitude data, a time interval buffer extracted the mean amplitudes 150 milliseconds before ground contact (prelanding) and 50 milliseconds after (postlanding). Mean amplitudes were normalized to each participant's peak RMS value obtained during the MVIC trials and are reported as a percentage of the MVIC.

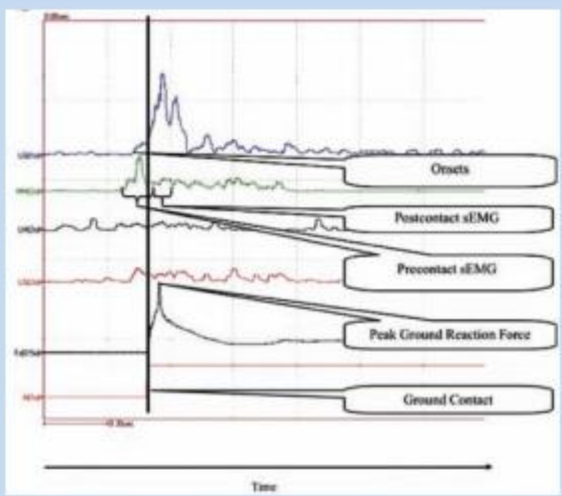

Figure 2. Neuromuscular-dependent variables during the drop jumps. sEMG, surface electromyography.

Force and position data from the initial landing of the drop jumps were used to calculate knee joint stiffness and were filtered using a fourth-order, zero-lag low-pass Butterworth filter at 60 and 12 Hz, respectively.[48] Figure 3 presents a representative trial showing biomechanical-dependent variables during the drop jump.

The net sagittal knee moments at the point of ground contact and the point of maximum knee flexion angle during the initial landing of the drop jumps were extracted to record the change in knee joint moment (ΔM; Nm). The knee moment was normalized to each participant's mass (Nm/kg). Sagittal knee flexion angles were recorded at initial ground contact and at maximum knee flexion angle and recorded as the change in knee joint angle ($\Delta\Theta$). Knee joint stiffness was then calculated by dividing the change in the net knee moment (with positive values indicating a net knee extensor moment) by the change in the knee flexion angle from ground contact to maximum knee flexion ($\Delta M/\Delta\Theta$), Nm/(kg · angle). This validated model describes the function of the knee as a spring mass system, with linear regression equations demonstrating highly linear moment-displacement relationships for the knee joint (R^2 = 0.90).[49]

Figure 3. Temporal sequence of biomechanical events during the drop jumps: A, takeoff from box (first change in center of mass); B, initial ground contact (first change in vertical ground reaction force); C, peak knee flexion (lowest point of braking phase before upward movement); D, leaving ground for vertical jump (absence of vertical ground reaction force). B → C, braking phase. C → D, propulsive phase.

Leg spring stiffness, N/(kg · m), was calculated as the peak vertical ground reaction force divided by the maximal vertical displacement of the center of mass during ground contact—that is, change in total body center of mass (as determined by inverse dynamics) from ground contact to lowest point during the landing.[37] All variables were averaged across all 5 trials for each participant, and group variables were averaged across all participants in each group.

Statistical Analyses

Separate 2 × 4 analyses of variance compared dancers and basketball players on muscle onset times and prelanding (150 milliseconds) and postlanding (50 milliseconds) muscle activation amplitudes. Separate 1-way analyses of variance examined group differences in knee joint stiffness and leg spring stiffness. If significant interactions were noted, Bonferroni pairwise comparisons with corrections determined where the differences existed. All analyses were conducted using the SPSS 14.0 with an alpha level of 0.05.

RESULTS

Group differences were not observed in muscle onset times, $F(1, 53) = 1.56$, $P = 0.22$, $1 - \eta^2 = 0.03$, $1 - \beta = 0.23$, prelanding activation amplitudes, $F(1, 53) = 0.28$, $P = 0.60$, $1 - \eta^2 = 0.01$, $1 - \beta = 0.08$, or post landing activation amplitudes, $F\ (1, 53) = 0.07$, $P = 0.78$, $1 - \eta^2 = 0.00$, $1 - \beta = 0.06$. Between-group effect size calculations indicated that dancers had trends toward earlier medial hamstrings muscle onsets, higher muscle activation in the medial hamstrings before and after landing, and lower lateral quadriceps and higher gastrocnemius activation after landing (Tables 1 and 2).

Table 1. Muscle activation onset times (in milliseconds) during the drop jumps (mean ± SD).[a]

	Dance	Basketball	Totals	Between-Group ES
LG	146.5 ± 52.1	140.9 ± 52.6	144.5 ± 51.9[b]	0.11
MH	158.2 ± 50.2	131.4 ± 44.2	148.4 ± 49.4[b]	0.53
LH	132.1 ± 41.5	127.4 ± 50.8	130.4 ± 44.7[b]	0.09
LQ	96.8 ± 69.0	87.0 ± 53.2	93.2 ± 63.3	0.14
Total	133.4 ± 53.2	121.6 ± 50.2	129.1 ± 33.7	

[a]ES, effect size; LG, lateral gastrocnemius; MH, medial hamstrings; LH, lateral hamstring; LQ, lateral quadriceps. Bonferroni adjustment for multiple comparisons at $P = 0.05$.
[b]Indicates significantly greater than LQ.

Table 2. Muscle activation amplitudes (% maximum voluntary isometric contraction) during drop jumps (mean ± SD).[a]

	Prelanding				Postlanding			
	Dance	Basketball	Totals	Between-Group ES	Dance	Basketball	Totals	Between-Group ES
LG	39.8 ± 18.1	38.8 ± 19.8	39.4 ± 18.5[b,c,d]	0.05	45.1 ± 29.2	35.5 ± 10.9	41.6 ± 24.5	0.33
MH	34.0 ± 14.2	26.3 ± 10.9	31.2 ± 13.5[c,d]	0.55	38.2 ± 32.7	24.9 ± 13.7	33.4 + 28.0	0.41
LH	20.6 ± 7.3	21.7 ± 11.4	21.0 ± 8.9	0.10	31.0 ± 25.4	29.3 ± 25.6	30.4 ± 25.3	0.07
LQ	18.1 ± 9.6	20.3 ± 12.7	18.9 ± 10.7	0.17	89.6 ± 44.0	108.5 ± 63.7	96.5 ± 51.2[e]	0.30
Total	28.1 ± 8.7	27.7 ± 10.5	27.6 ± 9.3		51.0 ± 17.3	49.6 ± 21.4	50.5 ± 18.7	

[a]ES, effect size; LG, lateral gastrocnemius; MH, medial hamstrings; LH, lateral hamstring; LQ, lateral quadriceps. Bonferroni adjustment for multiple comparisons at $P = 0.05$.
[b]Indicates significantly greater than prelanding MH, LH, and LQ.
[c]Indicates significantly greater than prelanding LH and LQ.
[d]Indicates significantly greater than prelanding LQ.
[e]Indicates significantly greater than postlanding LG, MH, and LH.

Dancers had significantly higher leg spring stiffness ($P = 0.047$; Figure 4), but no significant group differences were observed in knee joint stiffness, $F\ (1, 53) = 0.61$, $P = 0.44$, $1 - \eta^2 = 0.01$, $1 - \beta = 0.12$ (Figure 5).

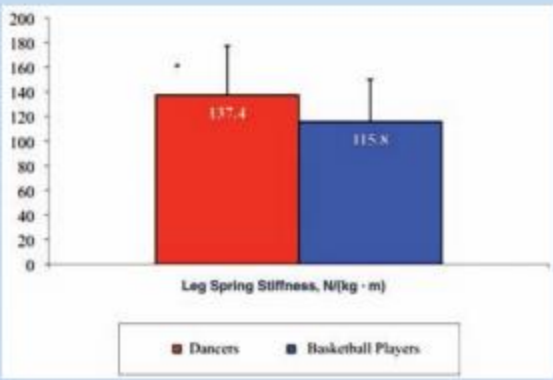

Figure 4. Leg spring stiffness, N/(kg·m), during the drop jumps (mean ± SD).
*Indicates significantly greater than basketball players.

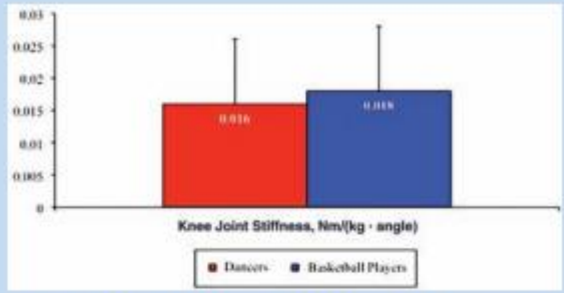

Figure 5. Knee joint stiffness, Nm/(kg · angle), during the drop jumps (mean ± SD).

DISCUSSION

Compared with basketball players, dancers had higher leg spring stiffness but similar knee joint stiffness during the initial landing of drop jumps. Dancers also had trends toward earlier onsets and higher activity in the medial hamstrings and lower lateral quadriceps and higher gastrocnemius activity postlanding, which may represent neuromechanical differences across the hip and ankle joints between groups.

Neuromuscular Patterns

The differences in muscle activation between groups did not reach statistical significance (prelanding, $P = 0.60$; postlanding, $P = 0.78$). This lack of group differences in knee muscle activation may be due to the nature of the drop jump task. Muscle activation during landing is modulated on the basis of drop height and the stiffness of the landing surface.[31,46] Research suggests that landing performance can be altered using specific instructions.[28,43] Both groups were given the same standardized set of instructions, were highly trained in their respective activities (10 to 14 years of experience), and required the same amount of familiarization (3.9 practice trials). Therefore, dancers and basketball players may have modulated muscle activity in comparable patterns during the drop jump task.

In contrast, during novel and unfamiliar tasks, muscle activation and co-contraction levels are higher as the body attempts to protect itself.[17,33] Therefore, the observed trends may become pronounced in more challenging tasks.

Excessive quadriceps and gastrocnemius activation may be ACL harmful,[12,16,30] whereas hamstring activation may be ACL protective.[13,14,53] Dancers appear to activate the medial hamstrings earlier and the lateral quadriceps later. Harleyet al[21] noted that dancers have similar jump heights but lesser quadriceps sEMG activity during jumping than do nondancers, suggesting a down modulation in quadriceps muscle activity in dancers. This down modulation of quadriceps muscle activity during jumping in dancers may be ACL protective. However, whether this actually occurs in landing tasks needs further study. Overall, dancers learning specific landing and jumping techniques for performance and aesthetic appearance during their years of training[21,32,44] may contribute to their ACL-protective neuromuscular strategies during movement.

Stiffness Patterns

The female dancers had higher leg spring stiffness than female basketball players. This finding supports observations[19,24] that male athletes, who are known to have lower risk for ACL injury than that of female athletes, have higher leg spring stiffness.

Knee joint stiffness did not differ between dancers and basketball players.[11,24,47,56] This finding may be partially due to the knee joint stiffness calculation method that focused on only knee motion.[15] The knee joint stiffness measure could not account for stiffness variations across all the lower extremity joints. Because knee joint stiffness did not differ but overall leg spring stiffness was greater in dancers, dancers probably had different joint stiffnesses at these other lower extremity joints (ankle and hip) than basketball players.

The higher overall leg spring stiffness in dancers may be due to higher ankle joint stiffness because they likely had several years of ballet dance experience during their extensive years of training (13 to 14 years, on average, for study participants). In ballet, dancers often maintain a stiff ankle when dancing demi pointe or en pointe (rising on the balls of the feet or onto the toes). Thus, over years of practicing maintaining a stiff ankle when dancing, the dancers in this study may have developed a strategy of higher ankle stiffness levels during landing, as compared with the basketball players. This suggestion of possibly higher ankle joint stiffness is partially supported by the nonsignificant trends noted in dancers toward increased lateral gastrocnemius muscle activity postlanding. Further support to this possibility may be in the suggestion by Harley et al[21] of greater use of ankle muscles by dancers. This suggestion needs to be tempered, however, by the absence of significant observed group differences for muscle activity. Also, how these higher trends of gastrocnemius muscle activity influence ACL injury risk in dancers needs further study—specifically, how much does it reduce the potentially ACL-protective combination of lower quadriceps and higher hamstrings activity trends noted in dancers?

The other mechanism allowing for the higher leg spring stiffness observed in dancers may be that of increased hip joint stiffness. Dancers are known to perform pilates exercises,[27,57] which focus on trunk and hip musculature, potentially altering hip muscle strength and activation during movement. This may be in contrast to basketball players, who often perform structured programs that may include machine exercises and free weights (to strengthen and condition trunk and hip musculature) but not pilates methods. Dancers may thus have different hip muscle strength and activation than basketball players, altering hip joint neuromechanics during landing. Overall, compensations across the entire leg and not just at the knee joint need to be examined further during high-risk ACL injury activities to elucidate relationships between leg spring stiffness and individual joint stiffness and their influence on injury risk in dancers and basketball players.

Limitations and Recommendations

Because hip and ankle neuromechanics were not measured, limited assumptions can be made about combined lower body movement from our results. All participants performed the drop jumps barefoot. Whereas basketball players always use footwear, dancers may or may not use footwear, depending on the type of dance. This factor potentially changed the way that basketball players and some dancers performed the landing. We also did not model the trunk and thorax in our biomechanical model. However, given that the research design was a comparison between 2 groups, we are reasonably confident that both groups were equally affected by the noninclusion of the trunk and thorax in the biomechanical model. We tried to control trunk and upper extremity movement by asking all participants to keep their hands on their hips and to look at a marker at all times; trials where these conditions were not met were discarded. The joint stiffness model that we used (which has been used for hopping tasks[15]) appears to be valid for drop jumps[9]. Still, it is important to appreciate that we modeled the knee joint with a torsional spring constant, and research is needed to examine whether this model represents average stiffness across the entire landing rather than a torsional spring constant during a specific portion of the landing.

The small to moderate between-group effect sizes noted suggest that an examination of a larger number of participants may have yielded different findings. Power analyses are needed to determine adequate sample sizes for comparisons of landing neuromechanics. Finally, the task demands of dancers and land-and-jump athletes are different. Dancers seldom run at top speeds during dance routines. Also, dancers are exposed to high knee joint physical demands while working in carefully choreographed movements that are repetitively practiced, whereas athletes such as basketball players may exert themselves in a more reactive and less planned manner. Therefore, dancers may not attempt to control and manipulate the same body momentum as athletes.

Conclusions

Female dancers had higher leg spring stiffness and trends toward differing muscle activation but no differences in knee joint stiffness compared to female basketball players during the initial landings of drop jumps. Neuromechanical differences across the hip and ankle joints may exist between female dancers and basketball players during activity.

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