AJSM PreView, published on March 3, 2014 as doi:10.1177/0363546514523928

Comparison of Landing Biomechanics Between Male and Female Dancers and Athletes, Part 1

Influence of Sex on Risk of Anterior Cruciate Ligament Injury

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Background: The incidence of anterior cruciate ligament (ACL) injuries among dancers is much lower than among team sport athletes, and no clear disparity between sexes has been reported in the dance population. Although numerous studies have observed differences in landing biomechanics of the lower extremity between male and female team sport athletes, there is currently little research examining the landing biomechanics of male and female dancers and none comparing athletes to dancers. Comparing the landing biomechanics within these populations may help explain the lower overall ACL injury rates and lack of sex disparity.

Hypothesis: The purpose was to compare the effects of sex and group (dancer vs team sport athlete) on single-legged drop-landing biomechanics. The primary hypothesis was that female dancers would perform a drop-landing task without demonstrating typical sex-related risk factors associated with ACL injuries. A secondary hypothesis was that female team sport athletes would display typical ACL risk factors during the same task.

Study Design: Controlled laboratory study.

Methods: Kinematics and kinetics were recorded as 40 elite modern and ballet dancers (20 men and 20 women) and 40 team sport athletes (20 men and 20 women) performed single-legged drop landings from a 30-cm platform. Joint kinematics and kinetics were compared between groups and sexes with a group-by-sex multivariate analysis of variance (MANOVA) followed by pairwise *t* tests.

Results: Dancers of both sexes and male team sport athletes landed similarly in terms of frontal-plane knee alignment, whereas female team sport athletes landed with a significantly greater peak knee valgus (P = .007). Female dancers were found to have a lower hip adduction torque than those of the other 3 groups (P = .003). Dancers (male and female) exhibited a lower trunk side flexion (P = .002) and lower trunk forward flexion (P = .032) compared with team sport athletes.

Conclusion: In executing a 30-cm drop landing, female team sport athletes displayed a greater knee valgus than did the other 3 groups. Dancers exhibited better trunk stability than did athletes.

Clinical Relevance: These biomechanical findings may provide insight into the cause of the epidemiological differences in ACL injuries between dancers and athletes and the lack of a sex disparity within dancers.

Keywords: anterior cruciate ligament; neuromuscular risk factors; biomechanics; dancers

The sex disparity in the incidence of noncontact anterior cruciate ligament (ACL) injuries among team sport athletes has been well documented. Adolescent and older female team sport athletes are 4 to 6 times more likely to sustain an ACL injury compared with their equivalently trained male counterparts.[2,18] Additionally, numerous studies examining landing and cutting activities have identified differences in lower extremity biomechanics between male and female team sport athletes that may place female athletes at an increased risk for ACL injuries.[5,9,15,20,21,27,31] By contrast, dance has been shown to have a much lower overall incidence of ACL injuries (0.009 ACL injuries per 1000 exposures) compared with team sports (0.07-0.31 ACL injuries per 1000 exposures), with no clear sex difference in the incidence of ACL injuries.[22] Furthermore, Orishimo et al[26] found no differences in landing biomechanics between male and female professional dancers, which suggests that the biomechanical differences typically observed between male and female athletes may not be the product of anatomic and hormonal factors that can be specifically attributed to sex. However,

The American Journal of Sports Medicine, Vol. XX, No. X
DOI: 10.1177/0363546514523928

limited research currently exists on biomechanical differences as they relate to the disparity in the ACL injury rate between dancers and team athletes. The neuromuscular deficit theories that have been proposed to explain the sex disparity in ACL injury rates include the ligament dominance, quadriceps dominance, trunk dominance, and leg dominance theories.[12] Ligament dominance results when the ligaments are relied upon excessively to absorb the high landing forces being transmitted through the body, particularly those forces experienced when the landing limb is in the malaligned position of excessive knee abduction and hip adduction/internal rotation. Quadriceps dominance is defined as the preferential use of the quadriceps muscles to stiffen and stabilize the knee joint during landings. This preferential activation of the quadriceps may result in excessive anterior translation of the tibia and strain on the ACL. This imbalance is characterized by a low knee flexion angle at landing and also higher electromyographic (EMG) activation of the quadriceps relative to the hamstrings. The trunk dominance theory refers to the inability to control or stabilize the position of the trunk in 3 dimensions. This is usually characterized by excessive trunk tilt over the supporting leg, which is related to increases in hip adduction and knee abduction, creating large external moments around the knee. Finally, the leg dominance theory refers to side-to-side kinetic and kinematic asymmetries between legs. These asymmetries may result in one leg consistently absorbing more of the impact force compared with the other, which could lead to an ACL injury. Currently, identification of 1 or any combination of these imbalances on screening tests may be used to provide specifically targeted injury prevention interventions for the athlete to correct the risky movement pattern.

Efforts to better understand the biomechanics of athletic groups such as dancers, which do not have a sex disparity in ACL injuries and which have a very low incidence, may provide useful information for the prevention and rehabilitation of ACL injuries in team sport athletes. While there are many extrinsic factors that differentiate dance from other athletic activities (ie, choreographed routines vs unanticipated movements, differences in shoe-surface interactions), landing maneuvers must be executed with proper biomechanics to avoid injuries, regardless of athletic discipline. To our knowledge, no study has directly compared landing biomechanics between dancers and team sport athletes. The purpose of this study was to compare the effects of sex and group (dancer vs team sport athlete) on single-legged drop-landing biomechanics relative to the ligament dominance, quadriceps dominance, and trunk dominance theories. As landing on a single leg appears to be the primary mechanism of injury in both dancers and team sport athletes,[22] we used a single-legged drop-landing task as our model, which precludes us from testing the limb dominance theory. Our primary hypothesis was that female dancers would perform a drop-landing task without demonstrating typical sex-related risk factors associated with an ACL injury exemplified by each theory (eg, increased knee valgus according to the ligament dominance theory, excessive trunk tilt according to the trunk dominance theory). The secondary hypothesis was that female team sport athletes would display the typical sex-related risk factors for an ACL injury during a drop-landing task.

TABLE 1
Participant Demographics[a]

	Age, y	Height, m	Weight, kg
Male dancers	27 ± 6	1.84 ± 0.07	73.5 ± 9.4
Female dancers	25 ± 5	1.70 ± 0.07	56.9 ± 6.0
Male athletes	22 ± 2	1.85 ± 0.07	78.8 ± 13.6
Female athletes	20 ± 2	1.76 ± 0.08	67.6 ± 7.5

[a]Values are expressed as mean ± standard deviation.

MATERIALS AND METHODS

Participants

Forty dancers (20 men, 20 women) and 40 team sport athletes (20 men, 20 women) were recruited to participate in this study. An a priori power analysis for the main outcome variable (knee valgus angle) was performed with standard deviations from previous similar studies on athletes and dancers in our laboratory.[26,27] It was determined that 20 participants per group are needed to achieve 80% power for an α level of .05 and a moderate effect size (partial $\eta^2 = .13$).

All participants completed a medical history questionnaire and signed an informed consent form approved by the institutional review board of the New York University Langone Medical Center Hospital for Joint Diseases. Demographic information including height, weight, and age at the time of testing is displayed in Table 1. All dancers were active in a professional ballet or modern dance company, and all athletes were competing at the collegiate level (National Collegiate Athletic Association [NCAA] Division I-III) in jumping and/or cutting sports (ie, basketball, volleyball, soccer, lacrosse, rugby). Additionally, for inclusion, all participants had no history of surgery to the lower extremities, no current lower extremity injuries, and no lower extremity injuries within the previous year.

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One or more of the authors has declared the following potential conflict of interest or source of funding: The Jacob and Valeria Langeloth Foundation supported this work.

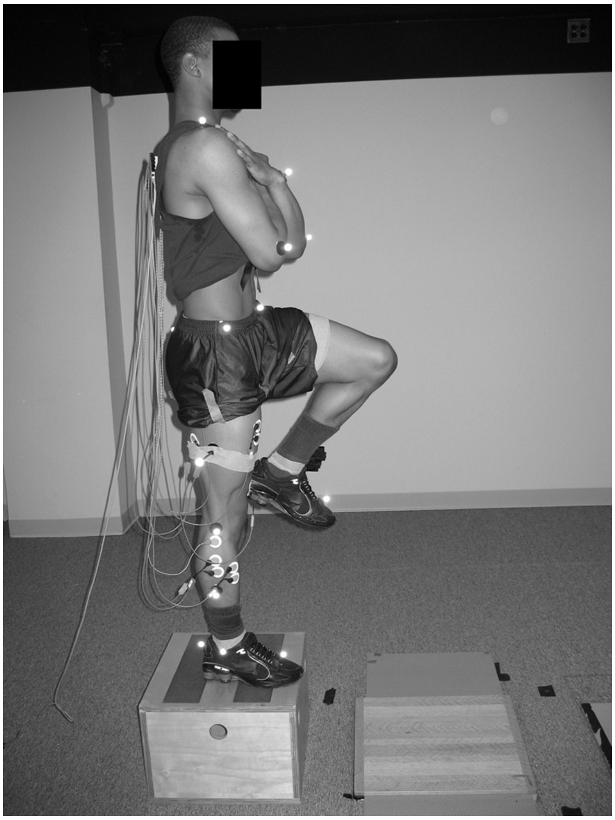

Figure 1. Laboratory setup for 30-cm drop landings. Participants crossed their arms over their chest and started each trial in a single-limb stance on the dominant leg. They then dropped off of the platform and landed on the force plate using the dominant leg.

Drop Landings

Participants performed 3 single-legged drop landings from a 30-cm platform onto a force plate. Each participant wore his or her own personal athletic shoes for the testing, and all landings were performed on the dominant leg, which was defined as the leg that would be used to kick a ball for maximal distance. As illustrated in Figure 1, participants were required to cross their arms over their chest and begin each trial in a single-limb stance on the dominant leg. They then dropped off of the platform and landed on the force plate using the same leg.

3-Dimensional Motion Analysis

Twenty reflective markers were placed bilaterally over the calcaneus, second metatarsal, lateral malleolus, lateral femoral condyle, midshank, midthigh, anterior superior iliac spine, acromion, lateral humeral epicondyle, and distal radius. Two additional markers were placed on the sacrum and the left posterior superior iliac spine as per the Helen Hayes system.[4] Marker positions were collected at 250 Hz using 8 Eagle cameras (Motion Analysis Corp, Santa Rosa, California, USA). The motion data were then filtered with a fourth-order Butterworth low-pass filter with a cutoff frequency of 10 Hz to eliminate any high-frequency noise. Ground-reaction forces were recorded at 2500 Hz with a multicomponent force plate (AMTI, Watertown, Massachusetts, USA).

Landings were defined as the period of time from initial contact with the force plate to the point in time at which the maximum amount of knee flexion was achieved during each trial. Joint angles were calculated for the ankle, knee, and hip using the motion capture data. Net joint moments were calculated for each joint by standard inverse dynamic techniques using specialized computer software (Visual 3D, C-Motion Inc, Rockville, Maryland, USA). All joint moments were reported as external moments and normalized to body mass.

EMG Analysis

The EMG data were acquired simultaneously with force and motion data using an 8-channel Myosoft 1400 surface electrode amplifier system (Noraxon Inc, Scottsdale, Arizona, USA) with a 10- to 500-Hz/channel bandwidth. After the skin was shaved, cleaned, and lightly abraded for each participant, muscle activity was sampled at 2500 Hz using disposable passive electrodes (Blue Sensor, Ambu Inc, Linthicum, Maryland, USA). Electrodes were placed over the vastus lateralis as well as semitendinosus muscle. The interelectrode distance was 20 mm, placed parallel to the muscle's fiber orientation in accordance with the standardized guidelines for anatomic landmark placement between each muscle's motor point and its distal tendon.[11,35] The EMG data were high-pass filtered at 10 Hz to eliminate motion artifact and then full-wave rectified and smoothed using a root mean square calculation with a window of 20 milliseconds. After processing, the EMG data were normalized to the maximum EMG activities recorded during the landing phase of a separately recorded single-legged vertical jump, standardized to 50% of each participant's maximal height. After normalization, the ratio of vastus lateralis activity to semitendinosus activity was calculated for each trial.

Statistical Analysis

Three separate multivariate analyses of variance (MANOVAs) were performed (1 for each of the theories that we examined). To test the ligament dominance theory, the following variables were entered in the MANOVA: knee abduction, hip adduction, and internal rotation angles (all at initial contact and peak values) and knee abduction, hip adduction, and hip internal rotation moments (all peak values). To test the trunk dominance theory, the following variables were entered in the MANOVA: trunk flexion and right side flexion angles (peak values). To test the quadriceps dominance theory, the following variables were entered in the MANOVA: knee flexion angle (at initial contact and peak value), knee flexion moment (peak value), and normalized EMG ratio of the vastus lateralis to the semitendinosus (averaged over 100 milliseconds before initial contact).[35] Univariate analyses of variance (ANOVAs)

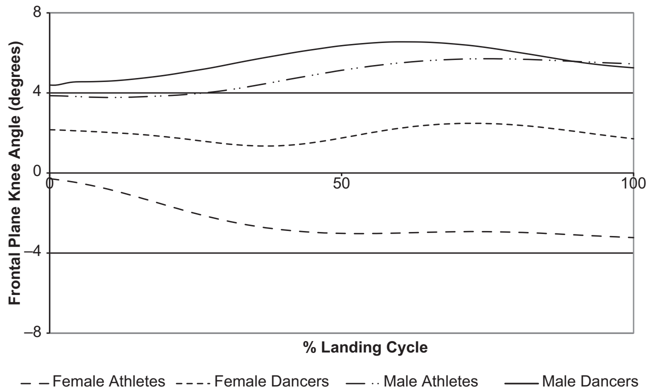

Figure 2. Ensemble averages of frontal-plane knee angle during drop landings. Negative values denote knee abduction (valgus). Female athletes showed a greater peak knee valgus angle than all others, per the ligament dominance theory (P = .007).

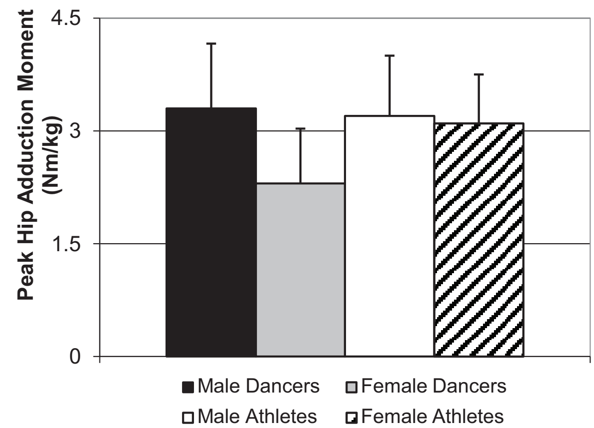

Figure 3. Comparison of peak hip adduction moments. Female dancers showed a lower peak hip adduction moment than all others, per the ligament dominance theory (P = .003).

and pairwise tests were used as post hoc tests when the MANOVA identified statistically significant differences (P < .05) for the main effects of group (dancers vs team sport athletes), sex (male vs female), or their interaction.

RESULTS

The MANOVA on the ligament dominance theory revealed an interaction effect of group by sex (P = .049). Post hoc tests revealed that peak knee valgus angle and peak hip adduction moment were different as follows: female team sport athletes demonstrated a higher peak knee valgus angle than those of the other 3 groups (P = .007) (Figure 2), whereas female dancers demonstrated a lower peak hip adduction moment than those of the other 3 groups (P = .003) (Figure 3).

The MANOVA on the trunk dominance theory demonstrated a main group effect (P = .002). Post hoc tests revealed that dancers landed with a lower peak trunk forward flexion (P = .032) and lower right trunk side flexion (P = .002) than did team sport athletes. Female dancers demonstrated a lower trunk side flexion than did female team sport athletes (P = .011) and male team sport athletes (P = .001) (Figure 4). Additionally, male dancers landed with a lower trunk forward flexion than did male team sport athletes (P = .017) and female team sport athletes (P = .046).

The MANOVA on the quadriceps dominance theory revealed that there was no statistical effect for group, sex, or interaction (P = .088) (Table 2).

DISCUSSION

The objective of this study was to compare landing task biomechanics of dancers and team sport athletes relative to sex-related neuromuscular deficits. In particular, we investigated if female dancers would demonstrate typical

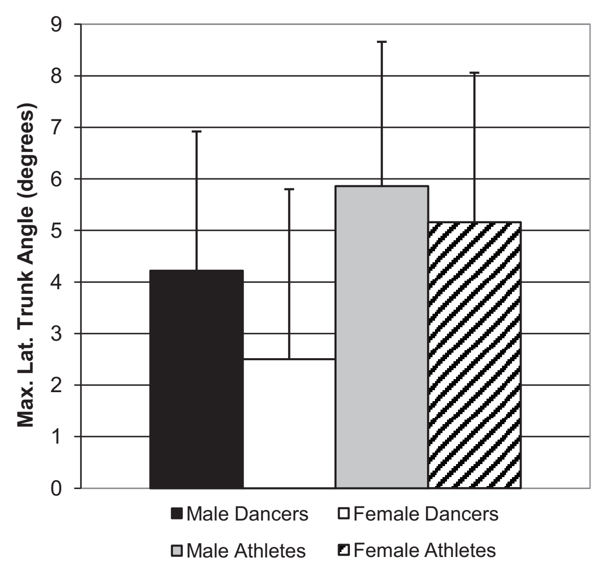

Figure 4. Comparison of peak lateral trunk angles. Dancers showed a lower peak lateral trunk angle than did athletes, per the trunk dominance theory (P = .002).

neuromuscular risk factors related to ACL injury risk found in female team sport athletes. This study found that female dancers landed with a significantly lower knee valgus angle, hip adduction moment, and trunk side flexion than female team sport athletes. Thus, female dancers did not demonstrate neuromuscular deficits consistent with the ligament and trunk dominance theories that are present in female team sport athletes. This may partially explain the low ACL injury rate among female dancers. Conversely, no significant differences were found for variables that are part of the quadriceps dominance theory.

Several implications can be derived from these findings. First, it is likely that the extensive training in landing technique that professional dancers undergo from a young

TABLE 2
Quadriceps Dominance Theory[a]

	Male Dancers	Female Dancers	Male Athletes	Female Athletes
Knee flexion at initial contact, deg	10.1 ± 5.7	10.7 ± 4.1	11.5 ± 5.5	13.1 ± 4.9
Peak knee flexion, deg	54.3 ± 6.3	57.0 ± 6.1	54.2 ± 9.1	56.0 ± 5.4
Peak knee flexion moment, N·m/kg	2.8 ± 0.4	2.5 ± 0.4	2.8 ± 0.6	2.9 ± 0.3
Quadriceps/hamstring ratio	0.95 ± 0.75	0.72 ± 0.51	0.74 ± 0.71	0.53 ± 0.31

[a]Values are expressed as mean ± standard deviation.

age is partially responsible for the protective biomechanics that they exhibit during landing. This is particularly encouraging for the potential of injury prevention programs to effect changes in movement patterns and ultimately decrease ACL injury rates among female team sport athletes. A variety of different programs have been developed, and many of them have been shown to be effective in reducing ACL injury rates.[13] Those programs that are most effective include correction of biomechanical faults as one of their elements but almost universally focus on sports-specific exercises.[13] It may be worth investigating dance training and the possibility of incorporating some of its elements into injury prevention programs for team sport athletes.

Dancers practice hundreds of jumps each day from an early age as part of their routine technique training and maintain an upright and square torso while performing their movements.[22,23] Accomplishment of aesthetically precise balance and jumping skills is indistinguishably necessary for both men and women in dance to advance to the professional ranks. Unlike many sports, where jumping is practiced as a means toward a specific point-scoring task, jumping in dance is utilized in and of itself solely for the purpose of helping to convey a story and/or for displaying technical virtuosity.[22]

Longitudinal studies have shown that male team sport athletes demonstrate neuromuscular adaptations after puberty that are considered to be protective for an ACL injury while female team sport athletes demonstrate increases in faulty landing patterns from before to after puberty.[10,14,16,30] These studies suggest that injury prevention programs need to be introduced before puberty to maximize their effect. Dancers who go on to perform professionally typically start training at a very young age and are consistently exposed to the requirement for neutrally aligned limbs during jumping and all movement tasks from the very beginning of their training.[6] This may be one of the reasons that female dancers demonstrate proper landing mechanics and have low ACL injury rates.[26]

Second, female dancers had a lower hip adduction moment compared with those in all other groups. The importance of minimizing hip adduction during landing from a jump has been previously discussed, and sex differences between athletes have been identified.[3,19,29,34] This finding in female dancers may help explain the lower incidence of ACL injuries compared with that of female athletes. However, it is unclear why female dancers have a lower hip adduction moment than male dancers when the ACL injury risk is equal for these groups. It may be that controlling hip adduction moments is a different mechanical task for female dancers, necessitating the increased control of hip motion to improve lower extremity alignment as required by dance performance.

Third, female dancers landed with a lower trunk side flexion compared with male and female athletes, while male dancers landed in a more erect position than those in both groups of team sport athletes. This is likely because of the aesthetics of dancing that requires dancers to land with a straight trunk. Dancers train specifically for many years to maintain an upright and square torso during all of their jumping activities and, by and large, are not permitted to utilize forceful, free arm swings to generate momentum for their jumps. Rather, dancers' upper extremities are typically choreographed to reach a precise posture in aesthetic coordination with the overall style of each particular jump in their repertoire. We speculate that the dancers had less trunk deviation than the athletes because of the unique way in which they train jumps with respect to intentional trunk stability and precision of the upper extremity position. Studies have shown that a lack of trunk control is linked to ACL injuries in female team sport athletes.[17,32,33] The difference in trunk posture between groups is an additional and novel finding that may help explain the lower incidence of ACL injuries in female dancers compared with female team sport athletes and the lack of sex disparity among dancers.

Unlike the ligament and trunk dominance theories, no group or sex differences were found with respect to the quadriceps theory. Several studies have shown that female team sport athletes exhibit preferential quadriceps activation compared with male team sport athletes and that, among female athletes, it is a predisposing factor for ACL injuries.[8,25,35] The methodology used in the present study is consistent with that of the prospective study by Zebis et al[35] in that we used EMG activity during the preparation phase of an athletic task to assess the quadriceps dominance theory. It is unclear if using the more traditional isokinetic measurements[1,24] would have been a more sensitive measure to detect group or sex differences.

The implications of this work should be interpreted in light of several limitations. Biomechanical differences are not the only reason that may account for the difference in ACL injury rates between female team sport athletes and dancers. The activities performed in dance and sports such as basketball are different in many ways, among them that many forms of dance are heavily choreographed.

On the other hand, many team sports, for example, basketball, have the element of the unpredictability of ball and player motion, which may account for a large part of the high ACL injury rates. However, this alone does not explain why women in such sports are different than men as those extrinsic variables should be the same between sexes.

Another limitation is the difference in age and weight between the female dancers and team sport athletes. The population of team sport athletes was composed of collegiate athletes, while the dancer population was taken from the professional ranks. Given the amount of time spent training and perfecting their craft to achieve technical virtuosity and professional status, we would expect the female dancers to be older than the female team sport athletes. Additionally, many of the female dancers' primary style was ballet. Given the typical body type of professional ballet dancers, we would expect that the female team sport athletes would be heavier. To minimize this potentially confounding factor, all impact forces and joint moments were normalized to body mass. Additionally, over the course of training and performance, dancers are selected for body type, ability to perform specific postures, and aesthetics in general. Consequently, this may have eliminated dancers who exhibit poor landing mechanics as opposed to athletes who can still progress in their career as long as they are effective players. Finally, a limitation of examining unilateral landings is that differences in the leg dominance theory could not be assessed. As neuromuscular deficits that are part of this theory have also been linked to sex differences among athletes[7,28] and to ACL injuries,[15] future studies should include bilateral tasks and assess side-to-side differences between athletes and dancers.

The main and novel finding of the present study is that female dancers do not exhibit several neuromuscular deficits that are evident in female team sport athletes and that would predispose them to ACL injuries. Specifically, female dancers exhibited similar biomechanical profiles to the male dancers and landed with a significantly lower knee valgus angle, hip adduction moment, and trunk side flexion than female team sport athletes. Thus, female dancers did not demonstrate neuromuscular deficits consistent with the ligament and trunk dominance theories that are present in female team sport athletes. These findings may be related to the lower ACL injury rate that female dancers experience compared with female team sport athletes and the lack of sex disparity in ACL injury rates among dancers.[26]

ACKNOWLEDGMENT

The authors thank the Jacob and Valeria Langeloth Foundation for its support of this work. They also thank Emily Junct, MD, and Megan Richardson, MS, ATC, of the Motion Capture Laboratory at the Harkness Center for Dance Injuries, New York University Langone Medical Center Hospital for Joint Diseases, for their major assistance with data collection.

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