Comparison of Landing Biomechanics Between Dancers and Team Sport Athletes via a BTS Bioengineering Motion Capture System

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ABSTRACT

Introduction: Motion capture, electromyography (EMG), and force data were collected on student and professional dancers, and athletes for the purpose of attempting to identify differences in EMG activity with kinetics and kinematics in relation to stiffness between professional dancers and athletes.

Methods: We examined differences in the order of muscle activation between subject groups comparing pre and post fatigue data. The study involved 20 female professional dancers, 5 female student dancers, 20 female professional collegiate athletes, 20 male professional dancers, and 20 male collegiate athletes. The motion capture system tracked movement and collected force data using infrared cameras, video cameras, and force plates. The dancers and athletes both performed 3 single legged drop landings from a 30-cm platform. Landings were defined as the period of time from initial contact with the force plate to the point at which the maximum amount of knee flexion was achieved during each trial.

Results: By comparing the landing biomechanics between several subject groups, it was determined that women land with different biomechanics than men. Women showed a greater range of motion than men, as well as lower ankle stiffness. More importantly, we saw differences in ankle mechanics and muscle activation during landing between preprofessional dancers and athletes, with student dancers often falling between the two. Professional dancers landed in a position of greater plantarflexion than did athletes (p = 0.015) and absorbed the impact with a less-stiff ankle (p < 0.001). Differences in activity of the medial gastrocnemius and peroneus muscles reflected many of these differences. Fatigue resulted in changes to ankle
kinematics and kinetics that were largely similar across groups and genders, though fatigue did seem to affect ankle plantarflexion at initial contact with the ground to a greater degree in dancers as opposed to athletes (p < 0.001).

1.0 Review of Literature

Sports medicine deals with physical fitness, and the treatment and prevention of injuries related to sports and exercise. In this branch of medicine, the term biomechanics is defined as the study of the mechanical laws relating to the movement or structure of living organisms. Biomechanics can be applied to the movement of the athlete’s body, specifically kinetics (forces acting upon and generated by the body) and kinematics (motions of the body). Dancers may be considered elite athletes based on the training they undergo and the level of skill required; the performance demands of ballet, for example, have been compared to those of American football (Nicholas, 1975). The annual rate of injury for professional dancers is reported to be between 67%–95% (Bronner et al., 2003) with the ankle being the most often injured joint (Liederbach et al., 2008). The high occurrence of these injuries can be explained by the dancer’s high degree of repetition, high level of physical demands, and environmental risk factors (Koutedakis and Jamurtas, 2004). In some cases (e.g., anterior cruciate ligament injury), dancers show much lower injury rates than do athletes (Liederbach et al., 2008) as well as a longer time to fatigue when performing a similar task (Liederbach et al., 2014). Thus, it is informative to study biomechanical differences between athletes and dancers as well as the muscle activity that results in and from these motions, which can be analyzed by electromyography (EMG).

Several studies have suggested that kinetic and kinematic variables of the lower extremities are altered when the foot is positioned on an inclined surface; dancers often perform
on inclined stages, especially in larger theaters. Floor inclination has been shown to alter kinetic and kinematic variables during gait analysis studies (Kawamura et al., 1991, Vogt and Banzer, 1999, Sun et al., 1996, McIntosh et al., 2006). Even though floor conditions had a significant effect on kinematic and kinetic variables, they did not have a significant effect on muscle activity, as measured by EMG in dancers (Hagins et al., 2009). Early detection of malalignment in the lower extremities is also important. The assessment of lower extremity alignment can be accurately performed using 3D motion analysis in a laboratory setup (Orishimo et al., 2009, Ross et al., 2016). Poor alignment is constituted as deviation from standard anatomic measures (Poggini et al., 1999) and is a risk factor for injury. Studying whether or not the athlete has poor control of their lower extremities may help detect and prevent alignment related injuries (Stensrud et al., 2011).

Understanding leg and joint stiffness during a hopping task can provide information for developing more effective training methods for dancers and other athletes. For these purposes, the lower extremity of an athlete or dancer can be modeled as a simple linear spring, and the stiffness of this “leg spring” computed based on measurements carried out in a biomechanics lab. Similarly, joints in the body can be modeled as torsional springs (i.e., the moment or torque required to cause the joint to rotate is proportional to the amount of rotation; the constant of proportionality is the stiffness of the joint). It has been shown that ankle stiffness has a major influence on spring-mass dynamics during hop tests (Mrdakovic et al., 2014).

The connection between the musculoskeletal system and the environment plays a key role in landing biomechanics. Research has shown that leg spring stiffness adapts to surface stiffness such that the combined stiffness of the leg and the surface remains constant (Ferris, 1997). In 2016, Ross et al., studied ankle stiffness specifically in relation to time to stability. They found
that subjects with lower ankle stiffness values took longer to stabilize after a drop landing than those with increased ankle stiffness. Both kinetics and kinematics can demonstrate the strategies used by the subjects in an attempt to maintain joint stability during activity (Ross et al., 2005). Caulfield (2002) analyzed patterns of lower extremity motion prior to and following the landing of a single leg jump in subjects with functional instability of the ankle and uninjured subjects. Their study showed that subjects with functional ankle instability performed the landing task in a unique way that contributed to the different results. If an individual is in a position where he or she cannot stay upright (attempting to stand or maneuver on a Swiss ball), the amount of resistance that can be applied to the muscle will be negligible because all focus is on balance (Behm et., al 2002).

Landing tasks are a valid metric in the examination of various landing techniques used by dancers and athletes. Jumping and landing are common tasks and provide detail on the use of lower extremities (Liederbach, 2000). The ability to stabilize quickly is a desirable characteristic for many dancers because they often have to change from one balance task to another without falling. Orishimo et al., (2014) showed that dancers with greater experience demonstrated more biomechanical characteristics that are protective for ACL injury during landing. This research aims to build on these studies and compares the order of muscle activation and its relation to fatigue between dancers and athletes at the same stage in their career. If the order of muscle activation does differ between subject groups, this could provide information to help reduce the risk of injury.

2.0 Research Questions and Hypotheses
Knowing that dancers have a lower rate of specific injuries, means that if a dancer activates his/her muscles in a different order than athletes, than it is likely an athlete could be taught to land similarly to a dancer and avoid those same injuries.

This study hypothesized that during a landing task, professional dancers would display different landing mechanics than those of team-sport athletes, who have not undergone the same thorough training in jumping and landing as the dancers; additionally, student-level dancers would display these differences, but not to the same degree as professionals. Specifically, we believe that there will be changes in the time and amount of muscle activation, between dancers and athletes; and that these differences will become more extreme when fatigue is a factor. Both male and female subjects were tested and data was processed based on time, vocation, and gender.

3.0 Methods

3.1 Participants

This study had five groups of participants including 20 female professional dancers, 20 male professional dancers, 20 female professional athletes, 20 male professional athletes, and 5 student dancers. All subjects completed a medical history questionnaire and signed a consent form to participate in the study. Demographic information including height, weight, and age were collected.

3.2 Motion Capture

The BTS Bioengineering SMART DX-700 motion capture system and six P-6000 force plates were used to capture motion and force data on both the dancers and athletes for the
purpose of attempting to identify differences in joint stiffness and muscle activation between professional dancers and professional athletes. Specifically, we examined differences in the order of muscle activation and its relation to fatigue. Subjects were brought to the lab and instrumented for motion capture using reflective markers. 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 (Figure 2). All kinematic data were sampled at 500 frames/sec, while force plate data were from the medial gastrocnemius (GAS) and peroneus (PER) muscles, also sampled at 1000 Hz. EMG data was collected simultaneously and later averaged to find maximum the force, height, and propulsion for the three landing tasks.

3.3 Drop Landing Task

The dancers and athletes performed 3 single-legged drop landings from a 30-cm platform onto a force plate. Each participant wore his/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. Participants dropped off of the platform and landed on...
the force plate using the same leg. The participant balanced for at least 10 seconds upon landing. The researcher described and demonstrated the single-legged drop-jump task, and then the participant performed 3 trials. In addition to the drop landing task, participants completed 3 vertical jumps to measure their maximum jump height, and three horizontal jumps to measure the maximum distance that each subject could propel themselves forward. Following these landings, subjects were then instructed to perform a fatigue protocol. Fatigue was defined as a 10% decrease in vertical jump height. The fatigue protocol (see flowchart, Figure 3) consisted of sets 50 step-ups onto a 30-cm box, followed by 15 maximal-effort single-legged vertical jumps; students did not perform the jumps, in order to compensate for the difference in platform height. Following this, vertical jump height was measured. If it did not decrease by at least 10%, subjects repeated the set of the fatigue protocol until a 10% decrement was achieved. Subjects then repeated the three landing tasks in the fatigued state.

![Figure 2: Flowchart of Fatigue Protocol](image)

3.4 Data Processing

All marker data were filtered with a fourth-order Butterworth low-pass filter with a cutoff frequency of 10 Hz to eliminate any high-frequency noise. EMG data were rectified and smoothed by using a Butterworth lowpass filter with a cutoff frequency of 10 Hz.
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 using the motion capture data. Net ankle moments were calculated for the ankle by standard inverse dynamic techniques using specialized computer software (Visual 3D, C-Motion Inc, Rockville, Maryland, USA). Ankle moments were reported as external moments and normalized to body mass.

Stiffness for a linear spring would be calculated using the relationship \[ k = \frac{-F}{x} \], where \( k \) is the stiffness of the spring, \( F \) is the force on the spring and \( x \) is the displacement of the spring. For angular motion such as the ankle, stiffness is computed analogously with the ankle moment substituting for the force, and angular motion for displacement. Average ankle stiffness was computed for the landing phase by using the change in ankle moment and angle from the start to the end of the landing phase.

3.5 Statistical Analysis

Data from the three landings were averaged for each subject prior to and following fatigue. Variables we analyzed were ankle plantarflexion at initial contact with the ground, peak ankle dorsiflexion, ankle range of motion (the difference between these two angles), average ankle stiffness during landing, peak ankle moment, and activity of the PER and GAS at initial contact with the ground and at their respective maxima. All kinematic, kinetic, and time to stability(TTS) variables were compared using 3x2 mixed-model ANOVA to test the effect of vocation or skill level (collegiate team-sport athlete, professional dancer, student dancer), sex (male, female) and fatigue (pre- and post-fatigue). A p-value of 0.05 was set as the threshold for
Statistical significance. Post-hoc t-tests with Bonferroni corrections were run as appropriate when differences were found in the ANOVA (main effects or interactions).

4.0 Results

Ankle plantarflexion at initial contact was different between sexes (P < 0.001) and vocations (P = 0.020) and increased with fatigue (P < 0.001). Women contacted the ground with greater plantar flexion than did men. Professional dancers contacted the ground with greater plantar flexion than athletes (P = 0.015), but did not differ from student dancers. Fatigue resulted in approximately 1.5° less plantar flexion at initial contact across all subjects, though this seemed mainly to affect the dancers and not the athletes (time x vocation, P < 0.001).

(Figures X,Y)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Men</th>
<th>Women</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak plantarflexion</td>
<td>18.3 ± 0.7°</td>
<td>22.5 ± 0.8°</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Peak dorsiflexion</td>
<td>17.8 ± 0.7°</td>
<td>19.8 ± 0.8°</td>
<td>0.058</td>
</tr>
<tr>
<td>Range of motion</td>
<td>36.1 ± 0.9°</td>
<td>42.3 ± 1.1°</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Peak moment</td>
<td>2.01 ± 0.07 Nm/kg</td>
<td>2.05 ± 0.08 Nm/kg</td>
<td>0.751</td>
</tr>
<tr>
<td>Stiffness</td>
<td>2.66 ± 0.12 Nm/°</td>
<td>1.80 ± 0.14 Nm/°</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>IC GAS</td>
<td>0.29 ± 0.02 mV</td>
<td>0.30 ± 0.02 mV</td>
<td>0.786</td>
</tr>
<tr>
<td>Max GAS</td>
<td>0.34 ± 0.02 mV</td>
<td>0.33 ± 0.02 mV</td>
<td>0.709</td>
</tr>
<tr>
<td>IC PER</td>
<td>0.24 ± 0.01 mV</td>
<td>0.15 ± 0.01 mV</td>
<td>0.003</td>
</tr>
<tr>
<td>Max PER</td>
<td>0.41 ± 0.02 mV</td>
<td>0.28 ± 0.02 mV</td>
<td>0.017</td>
</tr>
</tbody>
</table>
Figure ABC: Sex differences between kinematic, kinetic and EMG variables. While sex differences were noted, men and women behaved similarly across vocations and with fatigue (i.e., no statistical interactions).

![Ankle PF at IC](image)

Figure X: Ankle Plantarflexion at Initial Contact

Similar findings applied to peak dorsiflexion angle (i.e., ankle position at the end of the impact-absorption phase), with professional dancers having greater peak dorsiflexion than athletes ($P = 0.001$), but not being different from student dancers ($P = 0.885$). There was a trend toward women having greater peak dorsiflexion than men ($P = 0.061$). Finally, fatigue resulted in an increase in peak dorsiflexion angle ($P < 0.001$), but this did not differ between the groups (time x vocation, $P = 0.102$). (Figure Z)
Together, the fatigue-related decrease in plantarflexion angle at initial contact and increase in dorsiflexion angle at the end of impact absorption resulted in no change of ankle range of motion during landing with fatigue ($p = 0.397$) across all subjects. However, women showed overall greater range of motion during landing than men ($P < 0.001$), and both professional and student dancers showed greater ankle range of motion than did athletes ($p = 0.001$ and $P = 0.014$, respectively), with no difference between the two levels of dancers ($p = 0.855$). (Figure XY, XZ)
Peak ankle moment decreased with fatigue in all groups ($P = 0.003$) with student dancers showing a greater decrease than either professional dancers or athletes (time x vocation, $P = 0.034$). Ankle stiffness, however, did not change with fatigue ($P = 0.487$), but was lower for women than men ($P < 0.001$) and for dancers than for athletes ($P < 0.001$). (Figure YX)
Muscle activity of the medial gastrocnemius at initial contact with the ground decreased with fatigue ($P = 0.30$), and was greater in professional dancers than athletes ($P = 0.018$). Student dancers’ gastrocnemius activity was not different than professional dancers, and numerically was between that of professional dancers and athletes (Figure ZZZ). Maximal activity of the gastrocnemius did not change with fatigue ($P = 0.246$), but showed the same pattern of being greater in professional dancers vs athletes ($P = 0.021$) and similar between both levels of dancers. (Figure ZZX)
Muscle activity of the peroneus at initial contact with the ground did not change with fatigue ($P = 0.528$), but was greater in men than women ($P = 0.003$). It was also greatest in athletes vs any dancers ($P > 0.026$), with student dancers being lower than professional dancers ($P = 0.003$) (Figure ZZ). Similarly, maximal activity of the peroneus was not affected by fatigue ($P = 0.974$), but was greater in men than women ($P = 0.017$) and, similar to initial contact, was lower in student dancers than either professional dancers ($P < 0.001$) or athletes ($P = 0.001$). (Figure ZY)
5.0 Discussion and Conclusions

Confirming our hypothesis, we saw significant differences in landing mechanics at the ankle between professional and student dancers, and athletes. EMG of the GAS and PER were also different between dancers and athletes, suggesting that firing patterns of these muscles play a large role in the biomechanical differences we saw. Women also landed differently than men, and fatigue created profound changes in landing mechanics.

Overall, women’s biomechanics during the landing task were different from men’s. They contacted the ground with greater plantar flexion of the ankle, showed a trend toward ending the landing with greater dorsiflexion, and thus showed greater range of motion. Consequently, they exhibited lower ankle stiffness than did men, requiring a greater range of motion to absorb the impact of landing. Women showed similar activity in the medial gastrocnemius muscle (the primary decelerator and energy absorber about the ankle in landing) as men, but greater activity of the peroneus muscle, suggesting that women needed to recruit other muscles to help absorb the impact of landing. Importantly, there was no difference (statistical interaction) between sex with respect to vocation, nor with respect to fatigue (i.e., men and women responded to the fatiguing task similarly). This may be unusual, as women are typically reported as being more resistant to fatigue than men [Hunter, 2009]. However, the studies in this area typically use static, isometric contractions, whereas both our fatigue protocol and landing task were of an intermittent, dynamic nature. A study using dynamic activity (cycling) showed no difference in fatigue between men and women (Glace at al., 2013) and previously published work based on a cohort of this sample (Liederbach et al., 2014) showed the same result with respect to fatigue and sex. Based on this and the fact that we did not use a time-based criterion for fatigue (i.e.,
maintain a force until no longer able to do so), but rather a performance criterion (10% decrement in vertical jump height), we are confident in this finding.

Fatigue resulted in several expected changes to ankle biomechanics in the landing task. Ankle posture was changed both at initial contact (less plantarflexion) and end of landing (more dorsiflexion); these changes offset each other such that ankle range of motion remained the same. Because of the unchanging range of motion with fatigue, ankle stiffness also remained the same. Peak ankle moment decreased with fatigue, as reflected by the lower activity of the gastrocnemius muscle. The gastrocnemius is the primary muscle used for plantarflexion of the ankle, thus lower activity in this muscle should result in decreased moment about the ankle. There are differences to note between dancers and athletes, as well as between different levels of experience of dancers. Dancers landed with the ankle in greater plantarflexion than did athletes, reflective of the technique training that they do. This is likely the cause for the greater gastrocnemius activity at initial contact seen in the dancers, as the gastrocnemius muscle must be active to pull the ankle into plantarflexion. Notably, the decrease in plantarflexion with fatigue affected dancers far more than athletes, suggesting that with fatigue, their practiced form begins to change. Similarly, professional dancers ended the landing in greater dorsiflexion than did athletes, again likely reflecting their high level of training and form. Hence, dancers overall showed greater ankle range of motion than did athletes, using their ankles to absorb more of the energy of impact than athletes as seen in a previous study conducted by Orshimo et al., (2014). This greater range of motion is reflected by the lower ankle stiffness in dancers.

The differences in firing patterns of the peroneus muscle across groups may be related to injury avoidance. The peroneus should contract to resist the ankle rolling, resulting in ankle sprain. Landing in greater plantarflexion, as dancers do, can put the ankle at greater risk for a
sprain. Greater activity of the peroneus at initial contact in athletes as compared to dancers may indicate that during landing, athletes place a greater emphasis on avoidance of injury vs form as compared to dancers. Additionally, the lower activity of the peroneus in student dancers compared to all other subjects could be indicative of weakness or a lower level of training as compared to professional dancers. It could also be that dancers who are able to “make it” professionally are those best able to avoid injury such as ankle sprain; hence the professional population “selects” those with preferential muscle firing patterns. The greater decrease in ankle moment for student dancers vs any other subjects is likely explained by similar factors.

The conclusions we are able to draw in this study with regard to student dancers are limited by the low number of subjects, as well as the fact that they were all female. However, as we did not note any differences between how women behave across vocations or with fatigue as compared to men (i.e., women overall may have been different from men, but that difference was unchanged based on vocation or fatigue) that may not affect the generalizability of the results. Another issue is that the fatigue protocol was slightly different between the student dancers and other subjects; this was unavoidable, as the step used for the previous subjects had been removed from the lab by the time the student dancers were recruited. We attempted to compensate for the greater height of the step by eliminating the vertical jump part of the fatigue protocol, and fatigue was defined in the same way (10% decrement in vertical jump height). However, we cannot discount the fact that any differences with fatigue seen in student dancers as compared to others could be partially due to this change. An additional weakness of the study is the small number of student dancers; we had difficulty recruiting more given time constraints. Further work could examine differences in these groups during landing at the knee and the hip.


