AJSM PreView, published on March 4, 2014 as doi:10.1177/0363546514524525

Comparison of Landing Biomechanics Between Male and Female Dancers and Athletes, Part 2

Influence of Fatigue and Implications for Anterior Cruciate Ligament Injury

Marijeanne Liederbach,*† PhD, PT, ATC, CSCS, Ian J. Kremenic,‡ MEng, Karl F. Orishimo,‡ MS, Evangelos Pappas,§ PhD, PT, and Marshall Hagins,|| PhD, PT

Investigation performed at the Harkness Center for Dance Injuries, New York University Langone Medical Center Hospital for Joint Diseases, New York, New York

Background: Fatigue is strongly linked to an increased risk of injuries, including anterior cruciate ligament (ACL) ruptures. Part 1 of this study identified differences in the biomechanics of landing from a jump between dancers and team athletes, particularly female athletes, which may explain the epidemiological differences in ACL injuries between dancers and team athletes and the lack of a sex disparity within dancers. However, it is not known if these biomechanical variables change differently between team athletes and dancers in the face of fatigue.

Purpose/Hypothesis: The purpose of this study was to compare dancers' and team athletes' resistance to fatigue and its effect on the biomechanics of single-legged drop landings. The primary hypotheses were that dancers may be more resistant than team athletes to the onset of fatigue and/or may have different biomechanical responses than athletes in landing tasks once fatigue has been achieved.

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; National Collegiate Athletic Association Division I-III) performed single-legged drop landings from a 30-cm platform before and after a fatigue protocol consisting of step-ups and vertical jumps. Unfatigued and fatigued joint kinematics and kinetics were compared between groups and sexes with multivariate analyses of variance, followed by pairwise *t* tests as appropriate.

Results: Dancers took longer ($P = .023$) than team athletes to reach a similar state of fatigue. Multiple kinetic (eg, increased peak knee valgus moment; $P < .001$) and kinematic (eg, increased lateral and forward trunk flexion; $P < .001$ and $P = .002$, respectively) parameters of landing changed with fatigue, such that both fatigued dancers and athletes landed with mechanics that were more at risk for ACL injuries as compared with before fatigue.

Conclusion: Dancers took significantly longer to reach fatigue than team athletes. Female athletes consistently exhibited landing patterns associated with a risk for ACL injuries when compared with the other 3 groups. Fatigue changed landing mechanics similarly in both dancers and athletes, such that all groups landed with worse alignment after being fatigued.

Clinical Relevance: Dancers are more resistant to lower extremity fatigue than athletes, and this may partially explain the lower incidence of ACL injuries in both male and female dancers compared to team athletes. The extensive training in landing technique and daily practice that dancers undergo from a young age may be responsible for the higher levels of endurance.

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

Multiple variables have been linked with varying degrees of strength to an increased risk of noncontact anterior cruciate ligament (ACL) injuries in athletes, including suboptimal neuromuscular activation leading to poor limb and trunk alignment,[1,9,16,18,24,30,70] environmental and psychodynamic elements such as object handling or decision-making management of unanticipated events,[7,13,19,25] and effects of fatigue.[¶]

The American Journal of Sports Medicine, Vol. XX, No. X
DOI: 10.1177/0363546514524525
© 2014 The Author(s)

[¶]References 2, 3, 8, 14, 17, 47, 49, 54, 57, 58.

Downloaded from ajs.sagepub.com by MALACHY MCHUGH on March 27, 2014

Although there is currently a lack of direct epidemiological evidence demonstrating that fatigue increases the risk of ACL injuries, there are several types of evidence suggesting the validity of this relationship. Fatigue significantly decreases muscular force development and contraction velocity, increasing the forces seen by passive tissues,[5,23,28] adversely alters kinematics and neural feedback,[37,38,40,41,51,63] and adversely affects joint stability.[6,21,53,60,61,69] In addition, fatigue has been shown to significantly diminish dynamic balance control,[39,43] which is a variable strongly associated with an increased injury risk.[15,34,35,36,48]

More directly relevant to ACL injuries, numerous studies have shown that ACL noncontact injuries occur more frequently during a game or performance than practice, as well as closer to the end of the day and season, suggesting an effect of fatigue over time.[#] Importantly, relative to ACL injuries and fatigue, several research groups have shown, in laboratory studies examining the biomechanics of jump landings in athletes, that fatigue results in landing mechanics that mimic the position of risk for ACL ruptures.[13,17,24,49,50]

There are 2 reasons suggesting that a study of dancers in comparison with athletes may yield important information relative to fatigue. First, dancers suffer considerably fewer ACL injuries than athletes participating in team ball sports,[44] which may be explained by the major differences between the environments of sport versus dance (eg, equipment handling, anticipatory events) or by the specialized training that dancers undergo from a young age. However, dance is an activity rife with single-legged jump landings, which is the primary mechanism of injury for noncontact ACL injuries,[44,46,50] and Meuffels and Verhaar[50] found that dancers who are at risk for noncontact ACL injuries are those who are most exposed to jumps. For those ACL injuries that do occur in dancers, fatigue may play a role as, like athletes, their ACL injuries happen most often late in the day and season.[44]

Second, unlike team athletes, there is no sex disparity in the rates of ACL noncontact injuries in dancers.[44,50] This lack of a sex disparity in dancers relative to ACL injury rates may be partially explained by our previous work, which found that, in contrast to athletes, male and female dancers do not land differently from one another during a drop landing task,[55] and by the recent work by our group[56] and others,[4] which demonstrated that dancers and athletes exhibit biomechanical differences when performing landing tasks. To date, however, there has been no study that has attempted to differentiate responses to fatigue between dancers and team athletes, which may partially explain the lower rates of ACL injuries in dancers. Additionally, to our knowledge, there have been no studies that have explored fatigue as a factor relative to the sex disparity differences between these 2 groups.

[#]References 22, 26, 27, 29, 42, 44, 45, 65, 66.

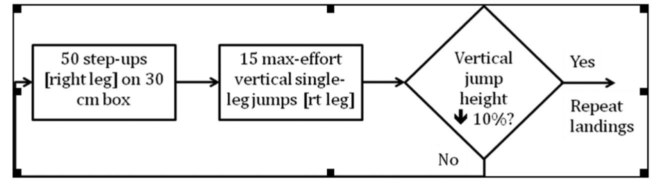

Figure 1. Flowchart of fatigue protocol.

Therefore, the purpose of this study was to compare dancers' and team athletes' resistance to fatigue and the biomechanics of a jump landing task before and after achieving fatigue relative to the risk variables associated with the ligament dominance, quadriceps dominance, and trunk dominance theories as described in our part I companion article (see the previous article in this issue).[56] We hypothesized that dancers would be more resistant than team athletes to the onset of fatigue and/or would have different biomechanical responses than these athletes in landing tasks once fatigue has been achieved. We also were interested in exploring whether responses to fatigue relative to sex would be different across groups and provide useful information relative to the known lack of an ACL injury sex disparity in dancers.

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. All participants completed a medical history questionnaire and signed an informed consent form approved by the Institutional Review Board. Demographic information including height, weight, and age at the time of testing as well as inclusion criteria can be found in the companion article within this issue.[56]

Drop Landings

The drop landing task and motion analysis methodology are described in our companion article.[56]

Fatigue Protocol

Before commencement of the experiment, each participant first practiced and then performed 3 maximal vertical

*Address correspondence to Marijeanne Liederbach, PhD, PT, ATC, CSCS, Harkness Center for Dance Injuries, New York University Langone Medical Center Hospital for Joint Diseases, 301 East 17th Street, New York, NY 10003, USA (e-mail: marijeanne.liederbach@nyumc.org).
†Harkness Center for Dance Injuries, New York University Langone Medical Center Hospital for Joint Diseases, New York, New York, USA.
‡Nicholas Institute of Sports Medicine and Athletic Trauma, Lenox Hill Hospital, New York, New York, USA.
§Discipline of Physiotherapy, Faculty of Health Sciences, University of Sydney, Lidcombe, New South Wales, Australia.
||Division of Physical Therapy, Long Island University, Brooklyn, New York, USA.
One or more of the authors has declared the following potential conflict of interest or source of funding: This work was supported by the Jacob and Valeria Langeloth Foundation.

Downloaded from ajs.sagepub.com by MALACHY MCHUGH on March 27, 2014

TABLE 1
Data Analyzed for the Ligament Dominance Theory[a]

	Male Dancers	Male Athletes	Female Dancers	Female Athletes
Peak knee abduction angle,[b] deg				
Before	–2.1 ± 1.1	–2.5 ± 1.1	0.5 ± 1.1	4.9 ± 1.0
After	–2.5 ± 1.0	–1.9 ± 1.3	0.9 ± 0.8	4.9 ± 0.9
Knee abduction angle at IC, deg				
Before	–4.3 ± 0.8	–3.9 ± 0.8	–2.2 ± 0.7	0.3 ± 0.8
After	–4.2 ± 0.6	–4.1 ± 0.9	–2.1 ± 0.6	0.8 ± 0.9
Peak knee abduction moment,[c] N·m/kg				
Before	0.08 ± 0.04	0.04 ± 0.03	0.01 ± 0.04	0.13 ± 0.07
After	0.14 ± 0.07	0.04 ± 0.05	0.07 ± 0.04	0.14 ± 0.06
Peak hip adduction angle, deg				
Before	–0.2 ± 1.2	–1.2 ± 1.1	1.7 ± 1.1	2.9 ± 1.3
After	–0.1 ± 1.1	–1.2 ± 1.1	3.2 ± 1.3	3.0 ± 1.3
Hip adduction angle at IC, deg				
Before	–9.1 ± 1.0	–9.7 ± 1.1	–10.6 ± 0.9	–7.9 ± 1.2
After	–9.2 ± 1.2	–10.3 ± 1.1	–10.9 ± 1.0	–8.0 ± 1.3
Peak hip adduction moment,[b,c] N·m/kg				
Before	3.4 ± 0.2	3.2 ± 0.2	2.4 ± 0.2	3.1 ± 0.1
After	3.0 ± 0.2	3.0 ± 0.2	2.4 ± 0.2	3.0 ± 0.2
Peak hip IR angle,[c] deg				
Before	1.2 ± 1.0	0.3 ± 0.9	–2.8 ± 1.5	–4.5 ± 1.3
After	2.8 ± 1.6	3.1 ± 1.6	–0.9 ± 1.7	–3.0 ± 1.6
Hip IR angle at IC,[c] deg				
Before	–3.7 ± 1.7	–4.7 ± 1.1	–10.8 ± 1.7	–9.4 ± 1.3
After	–1.8 ± 2.0	–3.3 ± 1.6	–8.0 ± 1.7	–8.1 ± 1.4
Peak hip IR moment,[c] N·m/kg				
Before	0.6 ± 0.1	0.6 ± 0.1	0.6 ± 0.1	0.6 ± 0.1
After	0.7 ± 0.1	0.7 ± 0.1	0.7 ± 0.1	0.7 ± 0.1

[a]Data are expressed as mean ± standard error of the mean. IC, initial contact; IR, internal rotation.
[b]Significant for group × sex interaction.
[c]Significant effect of fatigue.

TABLE 2
Data Analyzed for the Trunk Dominance Theory[a]

	Male Dancers	Male Athletes	Female Dancers	Female Athletes
Lateral trunk lean,[b] deg				
Before	4.2 ± 0.6	5.9 ± 0.6	2.5 ± 0.7	5.2 ± 0.7
After	5.3 ± 0.6	7.7 ± 1.0	3.3 ± 0.7	6.7 ± 0.7
Forward trunk flexion,[b] deg				
Before	–4.4 ± 1.5	0.6 ± 1.5	–1.4 ± 0.4	–0.5 ± 1.2
After	–0.5 ± 1.8	5.3 ± 2.2	2.3 ± 1.7	0.4 ± 1.4

[a]Data are expressed as mean ± standard error of the mean. For lateral lean, a positive value indicates lean to the right.
[b]Significant effect of fatigue and of group.

single-legged jumps to determine his or her maximal single-legged jump height using the Vertec Jump Measure Performance Device (Gill Athletics, Champaign, Illinois, USA). Participants performed sets of a stepping and jumping protocol designed to induce fatigue until a 10% decrement in their vertical jump height was documented. The fatigue protocol consisted of 50 step-ups onto a 30-cm box, followed by 15 maximal-effort single-legged vertical jumps. At the end of each set, participants' maximum vertical jump height was assessed, and participants rated their subjective sensation of fatigue using the Borg CR-10 scale.[10-12] If fatigue did not occur after the first set of step-ups and single-legged jumps, participants repeated sets of the fatigue protocol until their maximum vertical jump height was decreased by 10% from baseline. When participants attained a 10% decrement in vertical jump height, they repeated the single-legged drop-jump landings performed before fatigue (Figure 1).

Statistical Analysis

Similarly to our companion article,[56] 3 separate multivariate analyses of variance (MANOVAs) were performed. Univariate ANOVAs and pairwise tests were used as post

Downloaded from ajs.sagepub.com by MALACHY MCHUGH on March 27, 2014

TABLE 3
Data Analyzed for the Quadriceps Dominance Theory[a]

	Male Dancers	Male Athletes	Female Dancers	Female Athletes
Knee flexion angle at IC,[b,c] deg				
Before	10.1 ± 1.3	11.5 ± 1.2	10.8 ± 0.9	13.0 ± 1.1
After	9.6 ± 1.1	13.4 ± 1.5	10.0 ± 1.2	14.2 ± 1.3
Peak knee flexion angle,[d] deg				
Before	54.3 ± 1.4	54.2 ± 2.0	57.2 ± 1.6	56.2 ± 1.2
After	57.6 ± 1.7	61.2 ± 3.0	63.8 ± 1.6	60.4 ± 1.9
Peak knee flexion moment,[d] N·m/kg				
Before	2.7 ± 0.1	2.8 ± 0.2	2.5 ± 0.1	2.9 ± 0.1
After	2.4 ± 0.1	2.3 ± 0.3	2.3 ± 0.1	2.9 ± 0.1
Quadriceps:hamstring ratio				
Before	0.95 ± 0.17	0.74 ± 0.16	0.72 ± 0.12	0.50 ± 0.06
After	0.96 ± 0.12	0.79 ± 0.13	0.71 ± 0.07	0.49 ± 0.05

[a]Data are expressed as mean ± standard error of the mean. IC, initial contact.
[b]Significant for group × fatigue interaction.
[c]Significant effect of group.
[d]Significant effect of fatigue.

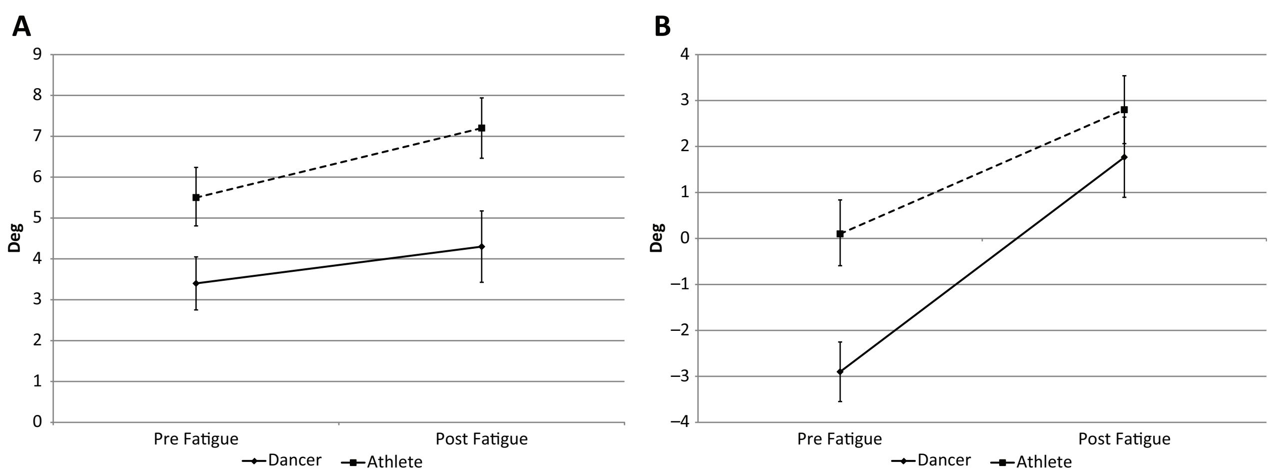

Figure 2. (A) Lateral trunk lean and (B) forward trunk flexion before and after fatigue for dancers and athletes. There were significant main effects of fatigue and of group.

hoc tests when the MANOVA identified statistically significant differences ($P \leq .05$) for the main effects of group (dancers/athletes), sex (male/female), time (before/after fatigue), or their interactions. Additionally, a univariate ANOVA was used to test whether there were differences between groups or sexes on the number of sets of the fatigue protocol required to induce fatigue or in the subjective ratings of fatigue.

RESULTS

Dancers took significantly more exertional bouts to fatigue (approximately 40%) than did team athletes (mean sets of fatigue protocol, 2.7 ± 1.8 vs 1.9 ± 1.3, respectively; P = .023). However, there was no effect of sex (P = .208), nor was there a sex × group interaction (P = .782). There were no significant main or interaction effects on Borg CR-10 scale subjective ratings of fatigue achieved, with dancers rating their fatigue as a mean of 7.4 ± 0.3 and athletes as 7.2 ± 0.3 (P = .755). Similarly, there was no effect of sex (P = .157) or sex × group (P = .998).

The MANOVA on the ligament dominance theory showed a main effect of fatigue ($P < .001$). Post hoc testing showed that fatigue increased the peak knee valgus moment (P = .047), decreased the peak hip adduction moment (P = .044), decreased the hip external rotation angle (at initial contact and peak; $P < .001$ and P = .002, respectively) (external rotation is reported here as participants landed in an externally rotated position and progressed toward a position of internal rotation with fatigue), and increased the peak hip internal rotation moment (P = .001). There were no interactions with fatigue relative to sex or group. As in our companion article within this issue,[56] group × sex interactions were significant (P = .039), with post hoc tests showing similar results (Table 1).

Downloaded from ajs.sagepub.com by MALACHY MCHUGH on March 27, 2014

The MANOVA on the trunk dominance theory showed a main effect of fatigue ($P < .001$). Post hoc tests revealed that fatigue increased both forward trunk flexion ($P = .002$) and lateral trunk lean ($P < .001$). An analysis unrelated to fatigue but that examined the main effect of group was significant ($P < .001$), with results similar to those of our companion study within this issue.[56] There were no significant interaction effects (Table 2).

The MANOVA on the quadriceps dominance theory showed a group × fatigue interaction ($P = .043$) and main effects of group ($P = .018$) and fatigue ($P < .001$). Post hoc tests showed that athletes landed with significantly more knee flexion at initial contact than did dancers ($P = .017$). Dancers responded to fatigue by slightly decreasing knee flexion at initial contact, whereas athletes slightly increased knee flexion at initial contact (group × fatigue interaction; $P = .001$). Fatigue also caused increased peak knee flexion angles ($P < .001$) and decreased knee flexion moments ($P = .003$) during landing (Table 3).

DISCUSSION

To our knowledge, this is the first study to compare the fatigability and landing biomechanics of dancers and team athletes after a fatiguing protocol. The main findings are that (1) dancers required significantly more exercise bouts (almost 40%) to achieve a similar level of fatigue (defined by jumping height decrement and confirmed by subjective ratings) as the athletes; (2) after the fatigue protocol, both dancers and athletes had significantly increased faulty alignment; and (3) fatigue largely had similar effects to both groups and both sexes.

It is unclear why dancers required more exercise bouts to achieve fatigue (as measured by jump height and subjective reports of the perceived level of difficulty). One possibility is the amount of specific jump training that dancers receive. Dancers perform approximately 200 jumps per 1.5 hours in their daily technique class and typically go on to perform more jumps throughout the day during their rehearsals and performances.[46] Furthermore, dancers begin training before adolescence and are not promoted to the next level of technique class until they master neutral trunk and lower extremity alignment and exemplary balance control.[44,55] It is possible that the increased resistance to fatigue found in dancers is related to differences in the ACL injury risk between dancers and team athletes. Future studies should use more ecologically valid methods to examine this issue.

In general, participants performed postfatigue landings with increased faulty alignment in biomechanical measures associated with each of the 3 theories examined. These findings may provide a biomechanical explanation to the previously reported suggestion that fatigue is associated with an increased likelihood of ACL injuries. Within the ligament dominance theory, several measures were significantly altered because of fatigue. However, knee valgus and moment are highly correlated[52] and most clearly associated with ACL injuries,[36] and consequently, our discussion focuses on these variables relative to the ligament dominance theory.

Our findings are in agreement with those of Chappell et al,[17] who reported an increased knee valgus moment after fatigue in athletes; the present study extends these findings to dancers. Other studies did not find an effect of fatigue on knee valgus.[8,14,57,58] The explanation for this discrepancy may have been described in the conclusions of a recent systematic review,[62] which reported wide variability in the methodology used to collect biomechanical variables as well as in the fatigue protocols used between studies. It is also important to note that some studies found trends but not statistical significance for some of the variables.[57,58] The current study provides additional data on the effects of fatigue that can be used in a meta-analysis that will provide more conclusive answers. Additionally, the current study provides novel data on the effects of fatigue on the biomechanics of landing in dancers, which have not been previously reported.

Similarly, we found increased faulty trunk posture after fatigue (Figure 2). To our knowledge, this is the first study of drop landings that focused on trunk kinematics after a functional fatigue protocol. Thus, no direct comparisons can be made with other studies. However, a study on firefighters investigating the effect of fatigue on firefighting tasks also found increased trunk flexion after fatigue.[31] The findings from these 2 studies should be interpreted as preliminary, but they suggest that trunk posture, which has a large effect on the center of mass, deteriorates after fatigue. It is also important to note that landing from a jump is a complex task. The response of the locomotor system to fatigue may be difficult to discern when looking at individual biomechanical variables. For example, we found that participants landed with decreased hip adduction after fatigue, which may be related to the significant finding for increased lateral trunk lean after fatigue. We speculate that athletes and dancers lean the trunk to the supporting leg side in an attempt to control undesirable forces along the lower extremity, and as a consequence, the contralateral pelvis moves superiorly, creating decreased hip adduction. This compensatory mechanism has been previously suggested as a possible explanation in a similar study that also found decreased hip adduction moments,[59] although the investigators did not measure trunk kinematics. The complex interplay between the trunk and lower extremity after fatigue needs to be further explored by studies that also use full-body marker systems and evaluate multiple joints.

Of the 3 biomechanical models used for the analysis (ligament, quadriceps, and trunk dominance theories), only 1, the quadriceps dominance theory, showed a significant fatigue × group interaction. Taking into consideration that the difference in knee flexion after fatigue was of a very small magnitude (0.7° in dancers and 1.5° in athletes) and that knee flexion was 1 of 15 examined variables, we suggest that these findings support the view that the biomechanical responses of dancers and team athletes to a drop landing task are not significantly different once the state of neuromuscular fatigue has been reached.

The primary hypothesis of this study was that fatigue would create significant differences between team athletes and dancers, providing information to explain the differences in ACL injuries between these groups. However, we found

Downloaded from ajs.sagepub.com by MALACHY MCHUGH on March 27, 2014

that fatigue had a similar effect on both groups by increasing the presence of faulty mechanics associated with ACL injuries. Effects of fatigue are multifactorial, and a study of this nature that is focused exclusively on a selected array of biomechanical variables may not capture factors related to fatigue that are associated with an ACL injury risk. Several authors suggest that much evidence exists in support of there being a temporal nature to the occurrence of ACL noncontact injuries, specifically when training intensities are highest, cumulative features of combined physiological mechanisms from central and peripheral levels occur, and athletes succumb to the mental and physiological demands of the game.[32,33,49] Previous research on dancers[44,45] and athletes[20,64,67,68] that has looked at both physiological and psychodynamic variables in relation to injuries or performance outcomes supports this assertion. Therefore, we suggest that future research incorporate a biopsychosocial approach to better understand which athletes in any given activity are most vulnerable to an ACL injury risk.

The secondary hypothesis of this study, that dancers would be more resistant to the onset of fatigue, was supported in that we found dancers required 40% more exertional bouts to reach the same state of fatigue as team athletes. This raises the possibility that the reason that dancers suffer fewer ACL injuries may be that they are more resistant to fatigue and its deleterious effects on alignment.

CONCLUSION

Fatigue had a significant effect on biomechanical variables across all 3 foci of analysis, although there were no significant differences in biomechanical responses to fatigue between team athletes and dancers. However, dancers took significantly longer to reach fatigue than did athletes, suggesting that future research examine fatigue resistance as a potential explanation for differences in ACL injury rates between team athletes and dancers.

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. This study was selected for presentation at the 2013 annual conference of the International Association for Dance Medicine and Science.

REFERENCES

1. Agel J, Arendt EA, Bershadsky B. Anterior cruciate ligament injury in National Collegiate Athletic Association basketball and soccer: a 13-year review. *Am J Sports Med*. 2005;33(4):524-530.
2. Alentorn-Geli E, Myer GD, Silvers HJ, et al. Prevention of non-contact anterior cruciate ligament injuries in soccer players, part 1: mechanisms of injury and underlying risk factors. *Knee Surg Sports Traumatol Arthrosc*. 2009;17(7):705-729.
3. Alentorn-Geli E, Myer GD, Silvers HJ, et al. Prevention of non-contact anterior cruciate ligament injuries in soccer players, part 2: a review of prevention programs aimed to modify risk factors and to reduce injury rates. *Knee Surg Sports Traumatol Arthrosc*. 2009;17(8):859-879.
4. Ambegaonkar JP, Shultz SJ, Perrin DH, Schmitz RJ, Ackerman TA, Schulz MR. Lower body stiffness and muscle activity differences between female dancers and basketball players during drop jumps. *Sports Health*. 2011;3(1):89-96.
5. Asmussen E. Muscle fatigue. *Med Sci Sports Exerc*. 1979;11(4):313-321.
6. Baratta R, Solomonow M, Zhou BH, Letson D, Chuinard R, D'Ambrosia R. Muscular coactivation: the role of the antagonist musculature in maintaining knee stability. *Am J Sports Med*. 1988;16(2):113-122.
7. Beiser TF, Lloyd DG, Ackland TR, Cochrane JL. Anticipatory effects on knee joint loading during running and cutting maneuvers. *Med Sci Sports Exerc*. 2001;33:1176-1181.
8. Benjaminse A, Habu A, Sell TC, et al. Fatigue alters lower extremity kinematics during a single-leg stop-jump task. *Knee Surg Sports Traumatol Arthrosc*. 2008;16:400-407.
9. Bittencourt NF, Ocarino JM, Mendonca LD, Hewett TE, Fonseca ST. Foot and hip contributions to high frontal plane knee projection angle in athletes: a classification and regression tree approach. *J Orthop Sports Phys Ther*. 2012;42(12):996-1004.
10. Borg E, Borg G, Larsson K, Letzter M, Sundblad BM. An index for breathlessness and leg fatigue. *Scand J Med Sci Sports*. 2012;20(4):644-650.
11. Borg G. A category scale with ratio properties for intermodal and inter-individual comparisons. In: Geissler HG, Petzold P, eds. *Psychophysical Judgment and the Process of Perception*. Berlin, Germany; VEB; 1982:25-34.
12. Borg G. A general scale to the rate symptoms and feelings related to problems of ergonomic and organizational importance. *G Ital Med Lav Ergon*. 2008;20(1):A8-A10.
13. Borotikar BS, Newcomer R, Koppes R, McLean SG. Combined effects of fatigue and decision making on female lower limb landing postures: central and peripheral contributions to ACL injury risk. *Clin Biomech*. 2008;23:81-92.
14. Brazen DM, Todd MK, Ambegaonkar JP, Wunderlich R, Peterson C. The effect of fatigue on landing biomechanics in single-leg drop landings. *Clin J Sport Med*. 2010;20(4):286-292.
15. Caraffa A, Cerulli G, Projetti M, Aisa G, Rizzo A. Prevention of anterior cruciate ligament injuries in soccer: a prospective controlled study of proprioceptive training. *Knee Surg Sports Traumatol Arthrosc*. 1996;4(1):19-21.
16. Carson DW, Ford KR. Sex differences in knee abduction during landing: a systematic review. *Sports Health*. 2011;3(4):373-382.
17. Chappell JD, Herman DC, Knight BS, Kirkendall DT, Garrett WE, Yu B. Effect of fatigue on knee injuries and kinematics in stop-jump tasks. *Am J Sports Med*. 2005;33(7):1022-1029.
18. Chappell JD, Yu B, Kirkendall DT, Garrett WE. A comparison of knee kinetics between male and female recreational athletes in stop-jump tasks. *Am J Sports Med*. 2002;30:261-267.
19. Chaudhari AM, Hearn BK, Andriacchi TP. Sport-dependent variations in arm position during single-limb landing influence knee loading: implications for anterior cruciate ligament injury. *Am J Sports Med*. 2005;33(6):824-830.
20. Cooke A, Kavussanu M, McIntyre D, Ring C. Psychological, muscular and kinematic factors mediate performance under pressure. *Psychophysiology*. 2010;47:1109-1118.
21. Davis JM, Bailey SP. Possible mechanisms of central nervous system fatigue during exercise. *Med Sci Sports Exerc*. 1997;29(1):45-57.
22. Feagin JA, Lambert KL, Cunningham RR, et al. Consideration of the anterior cruciate ligament injury in skiing. *Clin Orthop Rel Res*. 1987;216:13-18.
23. Fitts RH. Muscle fatigue: the cellular aspects. *Am J Sports Med*. 1996;24(6):S9-S13.
24. Ford KR, Myer GD, Hewett TE. Valgus knee motion during landing in high school female and male basketball players. *Med Sci Sports Exerc*. 2003;35:1745-1750.

Downloaded from ajs.sagepub.com by MALACHY MCHUGH on March 27, 2014

25. Ford KR, Myer GD, Toms HE, Hewett TE. Gender differences in the kinematics of unanticipated cutting in young athletes. *Med Sci Sports Exerc*. 2005;37:124-129.
26. Gabbett TJ. Incidence of injury in amateur rugby league sevens. *Br J Sports Med*. 2002;36:23-26.
27. Gabbett TJ. Incidence, site, and nature of injuries in amateur rugby league over three consecutive seasons. *Br J Sports Med*. 2000;34:98-103.
28. Gandevia SC. Spinal and supraspinal factors in human muscle fatigue. *Physiol Rev*. 2001;81:1725-1789.
29. Garrick JG, Requa RK. Ballet injuries: analysis of epidemiology and financial outcome. *Am J Sports Med*. 1993;21:586-590.
30. Geiser CF. Effects of isolated hip abductor fatigue on frontal plane knee mechanics. *Med Sci Sports Exerc*. 2010;42(3):535-545.
31. Gregory DE, Narula S, Howarth SJ, Russell C, Callaghan JP. The effect of fatigue on trunk muscle activation patterns and spine postures during simulated firefighting tasks. *Ergonomics*. 2008;51(7):1032-1041.
32. Hawkins RD, Fuller CW. A prospective epidemiological study of injuries in four English professional football clubs. *Br J Sports Med*. 1999;33:196-203.
33. Hawkins RD, Hulse MA, Wilkinson C, Hodson A, Gibson M. The association football medical research programme: an audit of injuries in professional football. *Br J Sports Med*. 2001;35:43-47.
34. Hertel J, Buckley WE, Denegar CR. Serial testing of postural control after acute lateral ankle sprain. *J Athl Train*. 2001;36(4):363-368.
35. Hewett TE, Lindenfeld TN, Riccobene JV, Noyes FR. The effect of neuromuscular training on the incidence of knee injury in female athletes: a prospective study. *Am J Sports Med*. 1999;27(6):699-706.
36. Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes. *Am J Sports Med*. 2005;33(4):492-501.
37. Hiemstra LA, Lo IK, Fowler PJ. Effect of fatigue on knee proprioception: implications for dynamic stabilization. *J Orthop Sports Phys Ther*. 2001;31:598-605.
38. Horita T, Komi P, Nicol C, et al. Effect of exhausting stretch-shortening cycle exercise on the time course of mechanical behavior in the drop jump: possible role of muscle damage. *Eur J Appl Physiol*. 1999;79:160-167.
39. Johnston RB, Howard ME, Cawley PW, Losse GM. Effect of lower extremity muscular fatigue on motor control performance. *Med Sci Sports Exerc*. 1998;30:1703-1707.
40. Lattanzio PJ, Petrella RJ. Knee proprioception: a review of mechanisms, measurements, and implications of muscular fatigue. *Orthopedics*. 1998;21:463-470.
41. Lattanzio PJ, Petrella RJ, Fowler PF. Effects of fatigue on knee proprioception. *Clin J Sport Med*. 1997;7:22-27.
42. Liederbach M, Compagno JM. Psychological aspects of fatigue-related injuries in dancers. *J Dance Med Sci*. 2001;5(4):116-120.
43. Liederbach M, Dilgen FE, Rose DJ. Effect of fatigue on balance in dancers with and without anterior cruciate ligament reconstruction. Abstract published in the proceedings booklet of the American Physical Therapy Association Annual Meeting, Orlando, Florida, June 2006. Available at: http://apps.apta.org/Custom/abstracts/pt2006/abstractsPt.cfm?pubNo=PL-RR-174-SA.
44. Liederbach M, Dilgen FE, Rose DJ. Incidence of anterior cruciate ligament injury among elite ballet and modern dancers: a five-year prospective study. *Am J Sports Med*. 2008;36(9):1779-1788.
45. Liederbach M, Gleim GW, Nicholas JA. Physiologic and psychological measurements of performance stress and onset of injuries in professional ballet dancers. *Med Probl Perform Art*. 1994;9:10-14.
46. Liederbach M, Richardson M, Rodriguez M, Compagno J, Dilgen FE, Rose DJ. Jump exposures in the dance training environment: a measure of ergonomic demand. *J Athl Train*. 2006;41(2):S85.
47. Madigan ML, Pidcoe PE. Changes in landing biomechanics during a fatiguing activity. *J Electromyogr Kinesiol*. 2003;13:491-498.
48. McGuine TA, Greene JJ, Best T, Leverson G. Balance as a predictor of ankle injuries in high school basketball players. *Clin J Sport Med*. 2000;10(4):239-244.
49. McLean SG, Felin RE, Suedekum N, Calabrese G, Passerallo A, Joy S. Impact of fatigue on gender-based high-risk landing strategies. *Med Sci Sports Exerc*. 2007;39(3):502-514.
50. Meuffels DE, Verhaar JA. Anterior cruciate ligament injury in professional dancers. *Acta Orthop*. 2008;79(4):515-518.
51. Miura K, Ishibashi Y, Tsuda E, Okamura Y, Otsuka H, Toh S. The effect of local and general fatigue on knee proprioception. *Arthroscopy*. 2004;20:414-418.
52. Myer GD, Ford KR, Khoury J, Succop P, Hewett TE. Biomechanics laboratory-based prediction algorithm to identify female athletes with high knee load that increase risk of ACL injury. *Br J Sports Med*. 2011;45:245-252.
53. Nyland JA, Shapiro R, Caborn DN, Nitz AJ, Malone TR. The effect of quadriceps femoris, hamstring, and placebo eccentric fatigue on knee and ankle dynamics during crossover cutting. *J Orthop Sports Phys Ther*. 1997;25(3):171-184.
54. Orishimo KF, Kremenic IJ. Effect of fatigue on single-leg hop landing biomechanics. *J Appl Biomech*. 2006;22:245-254.
55. Orishimo KF, Kremenic IJ, Pappas E, Hagins M, Liederbach M. Comparison of landing biomechanics between male and female professional dancers. *Am J Sports Med*. 2009;37(11):2187-2193.
56. Orishimo KF, Liederbach M, Hagins M, Kremenic IJ, Pappas E. Comparison of landing biomechanics between male and female dancers and team sport athletes, part I: influence of sex on risk of anterior cruciate ligament injury. *Am J Sports Med*. In press.
57. Ortiz A, Olson SL, Etnyre B, Trudelle-Jackson EE, Bartlett W, Venegas-Rios HL. Fatigue effects on knee joint stability during two jump tasks in women. *J Strength Cond Res*. 2010;24(4):1019-1027.
58. Pappas E, Sheikhzadeh A, Hagins M, Nordin M. The effect of gender and fatigue on the biomechanics of bilateral landings from a jump: peak values. *J Sports Sci Med*. 2007;6:77-84.
59. Patrek MF, Kernozek TW, Willson JD, Wright GA, Doberstein ST. Hip-abductor fatigue and single-leg landing mechanics in women athletes. *J Athl Train*. 2011;46(1):31-42.
60. Rodacki AL, Fowler NE, Bennett SJ. Multi-segment coordination: fatigue effects. *Med Sci Sports Exerc*. 2001;33:1157-1167.
61. Rozzi SL, Lephart SM, Fu FH. Effects of muscular fatigue on knee joint laxity and neuromuscular characteristics of male and female athletes. *J Athl Train*. 1989;24:106-114.
62. Santanaria LJ, Webster KE. The effect of fatigue on lower-limb biomechanics during single-limb landings: a systematic review. *J Orthop Sport Phys Ther*. 2010;40(8):464-472.
63. Skinner HB, Wyatt MP, Hodgdon JA, Conard DW, Barrack RL. Effect of fatigue on joint position sense of the knee. *J Orthop Res*. 1986;4(1):112-118.
64. Smith AM, Stuart MJ, Wiese-Bjornstal DM, Gunnon C. Predictors of injury in ice hockey players: a multivariate, multidisciplinary approach. *Am J Sports Med*. 1997;25(4):500-507.
65. Solomon R, Solomon J, Micheli LJ, McGray E. The cost of injuries in a professional ballet company: a five year study. *Med Probl Perform Artists*. 1999;14:164-169.
66. Stuart MJ, Smith A. Injuries in Junior A ice hockey: a three-year prospective study. *Am J Sports Med*. 1995;23:458-461.
67. Swanik CB, Covassin T, Stearne DJ, Schatz P. The relationship between neurocognitive function and noncontact anterior cruciate ligament injuries. *Am J Sports Med*. 2007;35(6):943-948.
68. Thomée P, Währborg P, Börjesson M, Thomée R, Eriksson BI, Karlsson J. Self-efficacy, symptoms and physical activity in patients with an anterior cruciate ligament injury: a prospective study. *Scand J Med Sci Sports*. 2007;17:238-245.
69. Wojtys EM, Wylie BB, Huston LJ. The effects of muscle fatigue on neuromuscular function and anterior tibial translation in healthy knees. *Am J Sports Med*. 1996;24(5):615-621.
70. Zazulak BT, Hewett TE, Reeves NP, Goldberg B, Cholewicki J. The effects of core proprioception on knee injury: a prospective biomechanical-epidemiological study. *Am J Sports Med*. 2007;35(3):368-373.

For reprints and permission queries, please visit SAGE's Web site at http://www.sagepub.com/journalsPermissions.nav

Downloaded from ajs.sagepub.com by MALACHY MCHUGH on March 27, 2014