What Is Known About the Effect of Fatigue on Injury Occurrence Among Dancers?

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Abstract

Fatigue is often thought of as any transient exercise-induced reduction of work capacity. In fact, it is a complex phenomenon caused by overlapping and interacting peripheral and central mechanisms. There is a known relationship between fatigue, diminished performance, and injury. This paper reviews what is currently known about fatigue in the current literature.

Fatigue has been defined as "an acute impairment of exercise performance that includes both an increase in the perceived effort necessary to exert a desired force or power output and the eventual inability to produce that force or power output,"[1] and much of the literature is divided into two subcategories: peripheral and central.[2]

Peripheral fatigue influences function of the contractile processes in muscle that typically take place during progressive dance, fitness, and sports training, or during functional work that requires prolonged holding or repetition of a high-force isometric or isotonic contraction. It may result from impairment of neuromuscular transmission, action potential propagation, actin-myosin crossbridge interactions, or calcium release and uptake dysfunction in the sarcoplasmic reticulum.[3] Peripheral fatigue may also result from shortage of metabolic substrates or accumulation of metabolites during exercise, such as glycogen depletion in exercising muscle.[3]

Central fatigue, by way of contrast, is an inhibitory influence on the muscular system that can exist despite an individual's full motivation. It is defined as a failure to maintain the required or expected force for power output function that cannot reasonably be explained solely by dysfunction in the muscle itself; rather, the failure is associated with specific alternations in the central nervous system (CNS), with resulting decrements in muscle activation.[1,4] Cognitive and emotional factors, such as low motivation or negative stimulus, can also promote fatigue.[1,4,5-7]

The overtraining syndrome is a good example of central fatigue. Also known as "burnout" or "staleness," it is characterized by an unexpected drop in performance that cannot be attributed to illness or injury. It often occurs when performance or training loads are not matched by adequate rest periods and in many cases is preceded by a period of time during which a dancer or athlete is able to maintain his or her level of performance, but only with a sense of greater effort.[8] For example, Ross and colleagues[9] showed that cyclists racing in the Tour de France, involving repetitive bouts of exhausting cycling with only short recovery periods interspersed, experienced both peripheral and central fatigue, with central deficits persisting even two days following the end of the tour. Commonly, an individual suffering from overtraining syndrome will experience symptoms such as mood disturbances—including depression, anger, irritability, and anxiety—as well as feelings of general fatigue and malaise, diminished levels of achievement and enthusiasm associated with a loss of energy and vigor, feeling of heaviness in the limbs, and changes in sleep patterns and appetite.[10-15]

In the sports literature, Costill and associates[11] and Morgan and colleagues[8,10,15] found that the condition of overtraining commonly results among athletes who have worked in a highly intense manner that involved monotonous training and performances with insufficient rest phases. Ninety percent of the total injuries in

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these studies had a positive subjective report of fatigue at the time of injury.

Background on Fatigue

As Lambert and coworkers[16] suggest, defining fatigue can be likened to the task described in the well-known Indian fable of the blind men and the elephant. In the fable, four blind men feel different parts of the beast and describe it according to the part they are feeling. The elephant incorporates each observation, but it is only by seeing the entirety of the elephant that one can accurately understand the animal as a whole. Physiologically, Lambert and colleagues[16] hypothesize fatigue to be a centralized, homeostatic control of exercise intensity tolerance based on a black-box-like neural integration of afferent information from the periphery, influenced by such factors as prior experience and training. They suggest that this neural integration leads to an oscillatory power output and physiological responses during exercise as the result of a complex integration of inputs from multiple systems, including both feed-forward and feedback components. They consider that fatigue may be a sensory perception rather than a physical phenomenon and present evidence for a complex but centrally-integrated model of fatigue wherein variables from the periphery provide afferent feedback to the black-box for calculation, thus informing the perception of fatigue and resulting in an attenuation of work output that may be consciously or unconsciously determined.

In both sports and dance, injuries result from a complex interplay between intrinsic, extrinsic, and situational variables that come about during dynamic events that require an equally complex coordination of central and peripheral responses.[17-24] Central and peripheral processing mechanisms are both compromised during fatigue,[25-27] and numerous studies conducted on athletes[28-30] have shown that the ability to perceive *in situ* conditions well in order to perform with efficiency and the ability to make optimal decisions leading to good reaction times and resultant movement strategies, decline when the athlete is in a fatigued state.[31-33]

Fatigue as it relates to dancer health raises questions of how, why, and when a dancer's ability to adapt successfully to his or her environmental challenges ceases to function optimally. While studies showing a relationship between fatigue and injury among athletes are readily available,[34-36] the purpose of this paper is to review what has been published about the effect of fatigue on dance injury occurrence.

Background on Dance Injuries

The prevalence of dance injuries is reported to be as high as 75% to 97%, suggesting that participation in dance activity is very risky.[37-41] From a clinical point of view, however, prevalence values can be misleading with regard to actual activity risk because, while prevalence studies shed some light on the number of injuries present in a sample of dancers at a given point in time, they do not provide information about how many new injuries occur in dancers over a discrete time span, and they do not yield prospective, exposure-controlled data about factors associated with the onset of injury. In the 1970s, Dr. James Nicholas[42] popularized an idea that dance is as physically demanding as football and as mentally stressful as bullfighting. The aim of his expert opinion paper was to help sports medicine clinicians appreciate the different neuromuscular, environmental, and psychometric demands imposed on participants by various activities. By today's standards of evidence,[43] activities are more objectively evaluated for risk using an injury rate equivalent (IRE) scale, a 4-point classification system that evaluates the number of injuries occurring in groups of performers over 1,000 units of exposure to their activity. Injuries are counted in this system when they have resulted in at least one day of missed participation in the activity beyond the day of the injury event itself.[44] Within the IRE, an activity is considered low risk if the number of time-lost injuries that occur per 1,000 units of exposure is between 0 and 2. As the number of time-lost injuries increases, so too does the risk. An activity that yields 2.1 to 4.0 time-lost injuries is considered low to moderate risk, compared to a moderate to high risk activity that would yield between 4.1 and 6.0 injuries per 1,000 exposures, and a high risk activity that would yield 6.1 or more injuries. Using these criteria, dance falls somewhere between level 1 (low risk)[45,46] and level 2 (low to moderate risk),[47] well behind football, which qualifies as a level 4 (high risk) activity.[44,48]

Injuries in dance are similar to injuries in sports in the sense that they are activity-specific, resulting in patterns representative of the movement demands associated with the activity.[49] In numerous studies, dance injuries have been found to occur most commonly in the lower extremities, especially the foot and ankle region.[40,47,50-52]

It has been reported that most athletic injuries occur in the later stages of training and competition periods.[53-64] In the dance literature, five studies have reported that injuries occurred most often during performance seasons when dancers were engaged in work-related physical activity for approximately 4 more hours per day than at other times of the year, such as during rehearsals and layoffs.[40,47,50,65,66] Conversely, three studies found that the greatest incidence of dance injuries occurred during rehearsal periods, when new work was being learned and participation in repetitive activity was at its highest.[46,67,68] All of the dance studies regarding when injuries happen have in common the conclusion that injuries occur most often when dancers are in training or work phases that entail overload and fatigue. In the sports medicine literature, Hootman and associates[69] evaluated 182,000 injury reports from 17 different men's and women's sports over a 5-year period and found that the vast majority of sports injuries occurred during games in the competitive season versus during practice in the preseason or postseason periods, with the exception of gymnastics. Gymnasts, contrastingly, were injured three times more often during preseason practice than during competition, due either to relatively lax physical conditioning or to fatigue from increased training intensity and duration associated with returning to practice schedules following the offseason.[48]

Dancers and Fatigue

Hamilton and colleagues[41] found that frequency of dance injuries and time disabled were functions of exposure. Kadel and associates[70] and Liederbach and coworkers[71] both found that exposure time among injured dancers was significantly higher than among uninjured dancers. Kadel and colleagues surveyed 54 female dancers from two professional ballet companies and found that a total of 27 fractures had been reported in 17 of the dancers.[70] Interestingly, when they divided the whole sample of dancers into those who danced more than 5 hours per day and those who danced less than 5 hours per day, the subjects who danced more than 5 hours per day were significantly more likely to have a stress fracture than those who danced less. Dancers with stress fractures also had a significantly longer duration of amenorrhea than did those without stress fractures, a finding that corroborates the work of Warren and associates.[72]

Two other studies have shown a relationship between injury occurrence and volume of time danced. In 1994, Liederbach and colleagues[65] studied 12 professional ballet dancers over the course of an annual, 5 week New York performance season when the average number of hours of work per day was 4 more than the pre- and post-season schedule. The investigators in this study measured weekly urinary excretion of free norepinephrine and epinephrine, change in mood using the Profile of Mood States (POMS),[73] and injury onset using the International Performing Arts Injury Reporting System (IPAIRS).[74,75] Results of this analysis showed that average weekly excretion of catecholamine increased with time for norepinephrine and epinephrine. Two mood categories assessed by the POMS, fatigue and inertia and vigor and activity, changed significantly over the course of the 5-week season. Coincident with the time of change in catecholamine and mood was a significant rise in the number of injuries experienced by the dancers. At the beginning of the season, 100% of the sample dancers were injury free. By week 3 of the season, 33% of the dancers were injured, and by week 4, when the fatigue and vigor categories of the POMS changed significantly, 66% of them were injured. This study documented a change in urinary catecholamine, mood, and injury onset among dancers as the duration of their performance season progressed. The daily training schedule of a professional ballet dancer is extensive and increases remarkably in intensity as well as in duration during a performance season, as demonstrated by significantly higher heart rates in performance compared with class and rehearsal work.[76,77]

Another study that shows a relationship between injury and fatigue is one focused on the topic of anterior cruciate ligament (ACL) ruptures among dancers.[47] In the general population, it is estimated that between 100,000 and 200,000 ACL injuries occur annually in the USA, with a high risk of re-injury, and more than one half of those going to surgery.[78-80] To understand how many ACL injuries happen to dancers and their etiology, Liederbach and associates followed 298 dancers prospectively for a 5-year period of time to document injury rates and circumstances related to those injuries.[47] In this study, the results indicated that ACL injuries among dancers were not related to differences in any physical factors when compared with the dancers who did not experience an ACL injury. However, the injuries occurred most often late in the day (67%) and late in the season (75%), suggesting fatigue as a causal factor. This suggestion appears to be corroborated by the work of Mueffels and colleagues.[66] In their 10 year retrospective study, they compared ACL injury occurrence among dancers from three professional companies in the same region (two contemporary and one classical ballet), of similar size (approximately 80 dancers per company), similar number of workdays (5 to 6 per week), similar environmental conditions (flooring, etc.), and similar number of annual performances (approximately 100). Fifty percent of the ACL injuries occurred during performance, and 100% of the dancers who experienced ACL injuries (N = 6; 4 men and 2 women) were from the classical ballet company in which the repertoire included a far greater number of jumps than did the contemporary dance companies'.

While there is growing evidence that ACL injuries in sports and dance are related to fatigue, little is known about the effect of fatigue on balance. We raise this point because balance is a function essential to the mastery of dance technique[81,82] and is a skill critical to the safety of dancers (given their work on diminished bases of support such as when performing in a single leg stance in relevé posture, while wearing pointe shoes or high heeled shoes, and when performing in light-altered environments such as dim or very bright stage lighting, spot lights, or scene changing blackouts) and because it is known from the sports medicine literature that an athlete's ability to control his or her balance during activity plays a critical role in prevention of lower extremity injury.[83-85] Impaired balance has been shown to be a risk factor for traumatic non-contact rupture of the ACL.[86-90]

In a 2006 study, Liederbach and associates speculated that ACL-reconstructed (ACL-R) dancers would show impaired balance due to mechanoreceptor impairment incurred during ligament injury.[91] Because dancers rely so heavily on balance ability to successfully and safely complete their movement tasks, the investigators designed the study to determine if a difference existed in tests of balance between ACL-intact and ACL-R dancers before and after fatigue. Twenty subjects (14 women [8 ACL-intact, 6 ACL-R] and 6 men [3 ACL-intact, 3 ACL-R]) were studied for comparison of single-leg stance balance under eyes-open and eyes-closed conditions before and after completing a fatigue protocol. The results of this study showed that single leg stance balance performance was not different between ACL-R and ACL-intact subjects during any of the non-fatigue tests. During the eyes closed test, however, all subjects performed profoundly worse on the NeuroCom Balance Master (NeuroCom International Inc., Clackamas, OR) when fatigued, with the ACL-R group showing the greatest decline.

Moving from physical volume and training considerations to the psychodynamic elements associated with injury, Liederbach and Compagno studied fatigue-related findings from 500 injury reports on 644 dancers from 3 different settings who participated in an injury survey over a 2 year period.[92] In this investigation, dancers were screened at the beginning of the study for injury risks, including eating attitudes (using the Eating Disorders Inventory 2 [EDI-2])[93,94] and mood (using the POMS).[73] Psychometric data from these screenings were evaluated by sub-groupings of dancers who had experienced a reportable injury according to the IPAIRS injury data collection system during the subsequent study period and those who had not. The study's findings revealed that fatigue was indicated as a significant injury factor in several data items, including subjective perception of fatigue, POMS scores, exposure hours on day of injury occurrence, time of injury relative to season of work, and level of work intensity at the time of injury occurrence. Seventy-nine percent of the reported injuries in this study happened in the evening, all but two after the dancer had already been exposed to 5 or more hours of dance activity that day, corroborating the findings of Kadel and colleagues.[70] At the time of injury, 79% of the dancers reported they were engaged in familiar repertory work, as opposed to the creation of new choreography or technique class. Eighty percent of the injuries occurred during self-described high cardiovascular intensity dance and 67% during the middle and end of a performance season, corroborating the findings of Garrick and Requa[50] and Solomon and associates.[40] When comparing injured to non-injured dancers by the POMS categories, injured dancers scored significantly higher on the fatigue item at the start of the study than did the non-injured dancers. This finding corroborated findings by Smith and coworkers,[95] who reported that the mood state of fatigue, as measured by POMS, significantly predicted injury in high school ice hockey players.

Fatigue, Diet, and Menstrual Status

Fatigue related injuries have been reported to increase when an individual fails to maintain a good diet or experiences regular psychosocial stressors, including work or school conflicts, especially if he or she possesses poor coping ability.[10-14] For dancers undertaking prolonged submaximal or intermittent high intensity exercise bouts on successive days for several weeks, the restoration of glycogen stores is probably the single most important factor in determining their recovery time to continue or resume exercise.[96,97] In the Liederbach and Compagno study discussed above, a significant difference was found between injured and non-injured dancers with respect to dieting behaviors and eating attitudes.[92] Sixty-nine percent of injured dancers reported that they were dieting to lose weight at the time of their injury, and the injured dancer cohort had significantly higher scores for thinness, bulimic tendencies, perfectionism, and body dissatisfaction on the Eating Disorders Inventory-2 than did the non-injured cohort.[93,94]

From a basic science perspective, the following three final studies are of value in shedding light on fatigue-related injuries. Glace and colleagues and Liederbach and associates studied 32 professional ballet dancers to determine if gender or menstrual status, as one potential indicator of energy balance, affected muscle strength or electromyographic (EMG) activity during serial fatigue tests.[98,99] In these studies, quadriceps and hamstring peak torque, when normalized to lean body mass and when tested at 50% maximum voluntary contraction (MVC), was significantly higher in eumenorrheic women and men dancers than in amenorrheic dancers, but time to fatigue was not different between groups. The amenorrheic dancers in this study reported exercising 11.5 hours more per week than their eumenorrheic counterparts and 20.7 hours more than the men. Higher injury rates seen in amenorrheic dancers may be due to exercise exposures that exceed an optimal dose-response for good health, corroborating the work of Kadel and coworkers,[70] or to inadequate strength to meet the demands of dance.[71] Caloric intakes of amenorrheic women have been reported to be less than those of eumenorrheic women,[100] and since estrogen is an anabolic steroid associated with osteoblastic activity, muscle substrate utilization, and hypertrophy, its diminution in amenorrheic dancers may be related to an underlying pathophysiologic mechanism for injury. Finally, Cohen and colleagues[101] found that the prevalence of secondary amenorrhea induced by physical and emotional stress and fatigue increased significantly in female dancers during performance seasons, which in turn increased their risk of bone injuries and other health problems.[72,102,103]

Summary

The deleterious effects of fatigue on human performance have been well documented.[33,104-114] It is known, for example, that lower extremity kinematics and kinetics associated with landing from a single leg jump—the mechanism of injury for the most common of all traumatic injuries in dance, the ankle sprain, as well as for rupture of the ACL—change under the condition of fatigue such that there is an increase in three-dimensional motions and loads and a deterioration from neutral to non-neutral alignment.[31,115-120]

Fatigue significantly decreases muscular force development and contraction velocity,[121] increases the forces imposed on passive tissues,[122] adversely alters neural feedback,[123-126] and has a negative effect on joint stability.[1,111,113] In addition, fatigue has been shown to significantly alter, in a suboptimal direction, dynamic balance control.[91,127]

More work remains to be done in dance for us to understand fully the complex interactions between emotions, personality, behavior, and health outcomes in dancers, but there are some clear lessons to be gleaned from the above body of work. Risk for injury increases with dance exposure not only because of neuromuscular fatigue associated with the nature and repetition of the movement involved, but also because of the opportunity for psychodynamic fatigue to set in.

The transition from appropriate training to overtraining is gradual and difficult to diagnose in the early stages. Teachers and artistic staff should be encouraged to think routinely of ways to bring variety to their technique and rehearsal schedules to avoid the monotony component of overtraining. Leaders in the field of dance must consider how to superimpose periodization onto dancer schedules and supervise training exposures, specificity, and overloads, ensuring adequate rest between training bouts and between high intensity performance weeks over long-lasting performance seasons.[128] Cardiovascular conditioning, hydration, healthy eating, and weight management behaviors must be properly taught and implemented. Complaints of fatigue and perceptions of increased exertion beyond what has been typical for a given task should be taken seriously, especially if observed with changes in mood, sleep patterns, diet, or other life events, as they may well be indicative of increased vulnerability to injury.[128-131]

With the continued promotion of informed behavior with food and water, balanced work and rest schedules, regulated incorporation of modern conditioning principles, and the development of social support systems, many dance injuries may be avoided without compromise to technical and artistic excellence.[128-131]

References

1. Davis JM, Bailey SP. Possible mechanisms of central nervous system fatigue during exercise. Med Sci Sports Exerc. 1997 Jan;29(1):45-57.
2. Knicker A, Renshaw I, Oldham AR, Cairns SP. Interactive processes link the multiple symptoms of fatigue in sport competition. Sports Med. 2011 Apr 1;41(4):307-28.
3. Rauch HG, St Clair Gibson A, Lambert EV, Noakes TD. A signaling role for muscle glycogen in the regulation of pace during prolonged exercise. Br J Sports Med. 2005 Jan;39(1):34-8.
4. Young SN. The clinical psychopharmacology of trypotophan. *In*: Wurtman RJ, Wurtman JJ (eds): *Nutrition and the Brain*. New York: Raven, 1986, pp. 49-88.
5. Gabriel HHW, Urhausen A, Valet G, et al. Overtraining and immune system: a prospective longitudinal study in endurance athletes. Med Sci Sports Exerc. 1998 Jul;30(7):1151-7.
6. Gastmann UA, Lehmann MJ. Overtraining and the BCAA hypothesis. Med Sci Sports Exerc. 1998 Jul;30(7):1173-8.
7. Snyder AC. Overtraining and glycogen depletion hypothesis. Med Sci Sports Exerc. 1998 Jul;30(7):1146-50.
8. Morgan WP, Brown DR, Raglin JS, et al. Psychological monitoring of overtraining and staleness. Br J Sports Med. 1987 Sep;21(3):107-13.
9. Ross EZ, Gregson W, Williams K, et al. Muscle contractile function and neural control after repetitive endurance cycling. Med Sci Sports Exerc. 2010 Jan;42(1):206-12.
10. Morgan WP, Costill DL, Flynn MG, et al. Mood disturbance following increased training in swimmers. Med Sci Sports Exerc. 1988 Aug;20(4):408-14.
11. Costill DL, Flynn MG, Kirwin JP, et al. Effect of repeated days of intensified training on muscle glycogen and swimming performance. Med Sci Sports Exerc. 1988 Jun;20(3):249-54.
12. Krieder RB, Fry AC, O'Toole ML. *Overtraining in Sport*. Champaign, IL: Human Kinetics Publishers, Inc., 1998.
13. Kuipers H. Training and overtraining: an introduction. Med Sci Sports Exerc. 1998 Jul;30(7):1137-9.
14. O'Connor PJ. Overtraining and staleness. *In*: Morgan WP (ed): *Physical Activity and Mental Health*. Washington, DC: Taylor & Francis, 1997, pp. 145-160.
15. Morgan WP. Physical fitness and emotional health: a review. Am Corr Ther J. 1969 Jul-Aug;23(4):124-7.
16. Lambert EV, St Clair Gibson A, Noakes TD. Complex systems model of fatigue: integrative homeostatic control of peripheral physiological systems during exercise in humans. Br J Sports Med. 2005 Jan;39(1):52-62.
17. Meeuwisse WH. Assessing causation in sport injury: a multifactorial model. Clin J Sport Med. 1994;4:166-70.
18. Murphy DF, Connolly DJ, Beynnon BD. Risk factors for lower extremity injury: a review of the literature. Br J Sports Med. 2003 Feb;37(1):13-29.
19. Backx FG. *Sports Injuries in Youth: Etiology and Prevention* [thesis]. Utrecht, The Netherlands: University of Utrecht, 1991.
20. Bol E, Schmiokli, SL, Backx FJG, van Mechelen W. *Sportblessures Onder de Knie*. Papendaf, The Netherlands: Nationaal Instituut voor SportGezonheidsZorg; 1991:publication 38.
21. Junge A. The influence of psychological factors on sports injuries. Review of the literature. Am J Sports Med. 2000;28(5 Suppl):S10-5.
22. MacMahon B, Pugh TF (eds). *Epidemiology: Principles and Methods*. Boston, MA: Little Brown, 1970.
23. van Mechelen W, Hlobil H, Kempner HC. Incidence, severity, etiology and prevention of sports injuries. A review of concepts. Sports Med. 1992 Aug;14(2):82-99.
24. 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 (Bristol, Avon). 2008 Jan;23(1):81-92.
25. Gandevia SC. Spinal and supraspinal factors in human muscle fatigue. Physiol Rev. 2001 Oct;81(4):1725-89.
26. Lorist MM, Boksem MA, Ridderink-

hof KR. Impaired cognitive control and reduced cingulated activity during mental fatigue. Brain Res Cogn Brain Res. 2005 Jul;24(2):199-205.
27. Miura K, Ishibashi Y, Tsuda E, et al. The effect of local and general fatigue on knee proprioception. Arthroscopy. 2004 Apr;20(4):414-8.
28. Chappell JD, Herman DC, Knight BS, et al. Effect of fatigue on knee injuries and kinematics in stop-jump tasks. Am J Sports Med. 2005 Jul;33(7):1022-9.
29. Madigan ML, Pidcoe PE. Changes in landing biomechanics during a fatiguing activity. J Electromyogr Kinesiol. 2003 Oct;13(5):491-8.
30. McLean SG, Felin RE, Suedekum N, et al. Impact of fatigue on gender-based high-risk landing strategies. Med Sci Sports Exerc. 2007 Mar;39(3):502-14.
31. Beiser TF, Lloyd DG, Ackland TR, Cochrane JL. Anticipatory effects on knee joint loading during running and cutting maneuvers. Med Sci Sports Exerc. 2001 Jul;33(7):1176-81.
32. Houck JR, Duncan A, De Haven KE. Comparison of frontal plane trunk kinematics and hip and knee moments during anticipated and unanticipated walking and side step cutting tasks. Gait Posture. 2006 Nov;24(3):314-22.
33. Pollard CD, Davis IM, Hamill J. Influence of gender on hip and knee mechanics during a randomly cued cutting maneuver. Clin Biomech (Bristol, Avon). 2004 Dec;19(10):1022-31.
34. King DA, Gabbett TJ, Dreyer C, Gerrard DF. Incidence of injuries in the New Zealand national rugby league sevens tournament. J Sci Med Sport. 2006 May;9(1-2):110-8.
35. Meyers MM, Laurent CM, Higgins RW, Skelly WA. Downhill ski injuries in children and adolescents. Sports Med. 2007;37(6):485-99.
36. Orlando C, Levitan EB, Mittleman MA, et al. The effect of rest days on injury rates. Scand J Med Sci Sports. 2011 Dec;21(6):e64-71.
37. Krasnow D, Kerr G, Mainwaring L. Psychology of dealing with the injured dancer. Med Probl Perform Art. 1994;9:7-9.
38. Byhring S, Bo K. Musculoskeletal injuries in the Norwegian National Ballet: a prospective cohort study. Scand J Med Sci Sports. 2002 Dec;12(6):365-70.
39. Ramel EM, Moritz U, Gun-Britt J. Recurrent musculoskeletal pain in professional ballet dancers in Sweden: a six year follow up. J Dance Med Sci. 1999;3(3):93-100.
40. Solomon R, Solomon J, Micheli LJ, McGray E. The cost of injuries in a professional ballet company: a five year study. Med Probl Perform Art. 1999;14:164-9.
41. Hamilton LH, Hamilton WG, Meltzer JD, et al. Personality, stress and injuries in professional ballet dancers. Am J Sports Med. 1989 Mar-Apr;17(2):263-7.
42. Nicholas JA. Risk factors, sports medicine and the orthopedic system: an overview. J Sports Med. 1975 Sep-Oct;3(5):243-59.
43. Sackett DL, Rosenberg WM, Gray JA, et al. Evidence-based medicine: what it is and what it isn't. BMJ. 1996 Jan 13;312(7023):71-2.
44. NCAA injury surveillance system: 1997-98. Overland Park, KS: National Collegiate Athletic Association, 1999.
45. Nilsson C, Leanderson J, Wykman A, Strender L. The injury panorama in a Swedish professional ballet company. Knee Surg Sports Traumatol Arthrosc. 2001 Jul;9(4):242-6.
46. Bronner S, Ojofeitimi S, Rose D. Injuries in a modern dance company: effect of comprehensive management of injury incidence and time loss. Am J Sports Med. 2003 May-Jun;31(3):365-73.
47. Liederbach M, Dilgen FE, Rose DJ. Incidence of anterior cruciate ligament injuries among elite ballet and modern dancers: a five-year prospective study. Am J Sports Med. 2008 Sep;36(9):1779-88.
48. Marshall SW, Covassin T, Dick R, et al. Descriptive epidemiology of collegiate women's gymnastics injuries. National Collegiate Athletic Association injury surveillance system: 1988-1989 through 2003-2004. J Athl Train. 2007 Apr-Jun;42(2):234-40.
49. Noyes FR, Albright JP. Forward: sports injury research. Am J Sports Med. 1988;16(suppl 1):Svi-Sx.
50. Garrick JG, Requa RK. Ballet injuries: analysis of epidemiology and financial outcome. Am J Sports Med. 1993 Jul-Aug;21(4):586-90.
51. Liederbach M. Performance demands of ballet: a general overview. Kinesiol Med Dance. 1985;8:6-9.
52. Quirk R. Injuries in classical ballet. Aust Fam Physician. 1984 Nov;13(11):802-4.
53. Gabbett TJ. Incidence, site, and nature of injuries in amateur rugby league over three consecutive seasons. Br J Sports Med. 2000 Apr;34(2):98-103.
54. Gabbett TJ. Incidence of injury in amateur rugby league sevens. Br J Sports Med. 2002 Feb;36(1):23-6.
55. Gabbett TJ. Incidence of injury in junior and senior rugby league players. Sports Med. 2004;34(12):849-59.
56. Lyman S, Fleisig GS, Waterbor JW, et al. Longitudinal study of elbow and shoulder pain in youth baseball pitchers. Med Sci Sports Exerc. 2001 Nov;33(11): 1803-10.
57. Pinto M, Kuhn JE, Greenfield ML, Hawkins RJ. Prospective analysis of ice hockey injuries at the junior level over the course of one season. Clin J Sport Med. 1999 Apr; 9(2):70-4.
58. Rahnama N, Reilly T, Lees A. Injury risk associated with playing actions during competitive soccer. Br J Sports Med. 2002 Oct;36(5):354-9.
59. Price RJ, Hawkins RD, Hulse MA, Hodson A. The Football Association medical research programme: an audit of injuries in academy youth football. Br J Sports Med. 2004 Aug;38(4):466-71.
60. Rodacki AL, Fowler NE, Bennett SJ. Multi-segment coordination: fatigue effects. Med Sci Sports Exerc. 2001 Jul;33(7):1157-67.
61. Feagin JA, Lambert KL, Cunningham RR, et al. Consideration of the anterior cruciate ligament injury in skiing. Clin Orthop Rel Res. 1987 Mar;(216):13-18.
62. Molsa J, Airaksinen O, Nasman O, Torstila I. Ice hockey injuries in Finland. A prospective epidemiologic study. Am J Sports Med. 1997 Jul-Aug;25(4):495-9.
63. Pettrone FA, Ricciardelli E. Gymnastic injuries: the Virginia experience 1982-1983. Am J Sports Med. 1987 Jan-Feb;15(1):59-62.
64. Stuart MJ, Smith A. Injuries in Junior A ice hockey. A three-year prospective study. Am J Sports Med. 1995 Jul-Aug;23:458-61.
65. Liederbach M, Gleim G, Nicholas J. Physiologic and psychological measurements of performance stress and onset of injuries in professional ballet dancers. Med Probl Perform

Art. 1994;9:10-4.
66. Meuffels DE, Verhaar JA. Anterior cruciate ligament injury in professional dancers. Acta Orthop. 2008 Aug;79(4):515-8.
67. Scialom M, Goncalves A, Padovani CR. Work and injuries in dancers: survey of a professional dance company in Brazil. Med Probl Perform Art. 2006;21:29-33.
68. Evans RW, Evans RI, Carvajal S, Perry S. A survey of injuries among Broadway performers. Am J Public Health. 1996 Jan;86(1):77-80.
69. Hootman JM, Dick R, Agel J. Epidemiology of collegiate injuries for 15 sports: summary and recommendations for injury prevention initiatives. J Athl Train. 2007 Apr-Jun;42(2):311-9
70. Kadel J, Teitz CC, Kronmal RA. Stress fractures in ballet dancers. Am J Sports Med. 1992 Jul-Aug;20(4):445-9.
71. Liederbach M, Glace BW, Kremenic IJ, McHugh MP. Muscle performance in amenorrheic versus eumenorrheic and male ballet dancers. *In*: Solomon R, Solomon J (eds): *Proceedings of the 15th Annual Meeting of the International Association for Dance Medicine and Science*. Stockholm, Sweden: IADMS, 2005, pp. 109-113.
72. Warren MP, Brooks-Gunn J, Fox R, et al. Lack of bone accretion and amenorrhea: evidence for a relative osteopenia in weight bearing bones. J Clin Endocrinol Metab. 1991 Apr;72(4):847-53.
73. McNair DM, Lorr M, Droppleman LF. *Profile of Mood States Manual*. San Diego, Educational and Industrial Testing Service, 1977.
74. Liederbach M. IPAIRS: an injury tracking system for dance. *Proceedings of the 5th Annual Meeting of the International Association for Dance Medicine and Science*. Tel Aviv, Israel: 1995.
75. Liederbach M, Richardson M. The importance of standardized injury reporting in dance. J Dance Med Sci. 2007:11(2):45-8.
76. Cohen JL, Gupta PK, Lichstein E, Chadda KD. The heart of a dancer: noninvasive cardiac evaluation of professional ballet dancers. Am J Cardiol. 1980 May;45(5):959-65.
77. Cohen JL, Segal KR, McArdle WD. Heart rate response to ballet stage performance. Phys Sportsmed. 1982;10(11):120-33.
78. Brown CH, Carson EW. Revision anterior cruciate ligament surgery. Clin Sports Med. 1999 Jan;18(1):109-71.
79. Lyman S, Koulouvaris P, Sherman S, et al. Epidemiology of anterior cruciate ligament reconstruction: trends, readmissions, and subsequent knee surgery. J Bone Joint Surg Am. 2009 Oct;91(10):2321-8.
80. Duquin TR, Wind WM, Fineberg MS, et al. Current trends in anterior cruciate ligament reconstruction. J Knee Surg. 2009 Jan;22(1):7-12.
81. Liederbach M. Movement and function in dance. *In*: Brownstein B, Bronner S (eds): *Evaluation, Treatment and Outcomes of Functional Movement in Orthopaedic and Sports Physical Therapy*. New York: Churchill Livingstone, 1997, pp. 253-310.
82. Liederbach M. The effect of shoe heel height and floor incline on the biomechanics of landing from a single leg jump in elite female dancers. Doctoral Dissertation in Biomechanics and Ergonomics, New York University. New York, NY, 2008.
83. Boden BP, Dean GS, Feagin JA, Garrett WE. Mechanisms of anterior cruciate ligament injury. Orthopedics. 2000 Jun;23(6):573-8.
84. 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: a prospective study. Am J Sports Med. 2005 Apr;33(4):492-501.
85. Caraffa A, Cerulli G, Projetti M, et al. 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.
86. Hertel J, Buckley WE, Denegar CR. Serial testing of postural control after acute lateral ankle sprain. J Athl Train. 2001 Dec;36(4):363-8.
87. Tropp H, Ekstrand J, Gillquist J. Factors affecting stabilometry recordings of single limb stance. Am J Sports Med. 1984 May-Jun;12(3):185-8.
88. 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 Oct;10(4):239-44.
89. Hewett TE, Ford KR, Hoogenboom BJ, Myer GD. Understanding and preventing ACL injuries: current biomechanical and epidemiologic considerations - update 2010. N Am J Sports Phys Ther. 2010 Dec;5(4):234-51.
90. Myer GD, Ford KR, McLean SG, Hewett TE. The effects of plyometric versus dynamic stabilization and balance training on lower extremity biomechanics. Am J Sports Med. 2006 Mar;34(3):445-55.
91. Liederbach M, Dilgen FE, Rose DJ. Effect of fatigue on balance in dancers with and without anterior cruciate ligament reconstruction. *Proceedings of the American Physical Therapy Association Annual Meeting*. Orlando, FL: June, 2006.
92. Liederbach M, Compagno J. Psychological aspects of fatigue-related injuries in dancers. J Dance Med Sci. 2001;5(4):116-20.
93. Garner DM, Garfinkel PE. The eating attitudes test: an index of the symptoms of anorexia nervosa. Psychol Med. 1979 May;9(2):273-9.
94. Garner DM. *Eating Disorder Inventory-2 Professional Manual*. Odessa, FL: Psychological Assessment Resources, Inc., 1991.
95. 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 Jul-Aug;25(4):500-7.
96. Costill DL, Bowers R, Branam G, Sparks K. Muscle glycogen utilization during prolonged exercise on successive days. J Appl Physiol. 1971 Dec;31(6):834-8.
97. McInerney P, Lessard SJ, Burke LM, et al. Failure to repeatedly supercompensate muscle glycogen stores in highly trained men. Med Sci Sports Exerc. 2005 Mar;37(3):404-11.
98. Glace B, Kremenic I, Liederbach M. Energy conservation in amenorrheic ballet dancers. Med Probl Performing Art. 2006;21(3):97-104.
99. Liederbach M, Kremenic IJ, Glace BW, et al. The effect of amenorrhea on strength and fatigue in ballet dancers [Abstract]. Med Sci Sports Exerc. 2000 Jun;32:S279.
100. Nelson ME, Fisher EC, Catsos PD, et al. Diet and bone status in amenorrheic runners. Am J Clin Nurt. 1986 Jun;43(6):910-6.
101. Cohen JL, Segal KR, Witriol I, McArdle WD. Cardiorespiratory responses to ballet exercise and maximum oxygen consumption of

elite dancers. Med Sci Sports Exerc. 1982;14(3):212-7.

102. Brooks-Gunn J, Warren M, Hamilton L. The relation of eating problems and amenorrhea in ballet dancers. Med Sci Sports Exerc. 1987 Feb;19(1):41-4.

103. DeCherney A. Physiologic and pharmacologic effects of estrogen and progestins on bone. J Reprod Med. 1993 Dec;38(12 Suppl):1007-14.

104. McLean SG, Samorezov JE. Fatigue-induced ACL injury risk stems from a degradation in central control. Med Sci Sports Exerc. 2009 Aug;41(8):1661-72.

105. Orishimo KF, Kremenic IJ. Effect of fatigue on single-leg hop landing biomechanics. J Appl Biomechs. 2006 Nov;22(4):245-54.

106. Skinner HB, Wyatt MP, Hodgdon JA, et al. Effect of fatigue on joint position sense of the knee. J Orthop Res. 1986;4(1):112-8.

107. Hardin JA, Blackburn TA, Canner GC, et al. The effects of muscle fatigue on and the relationship of arm dominance to shoulder proprioception. J Orthop Sports Phys Ther. 1996 Jun;23(6):348-52.

108. Häkkinen K, Komi PV. Electromyographic and mechanical characteristics of human skeletal muscle during fatigue under voluntary and reflex conditions. Electroencephalogr Clin Neurophysiol. 1983 Apr;55(4):436-44.

109. 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.

110. Huston LJ, Wojtys EM. Neuromuscular performance characteristics in elite female athletes. Am J Sports Med. 1996 Jul-Aug;24(4):427-36.

111. 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 Sep-Oct;24(5):615-21.

112. Nyland JA, Shapiro R, Stine RL, et al. Relationship of fatigued run and rapid stop to ground reaction forces, lower extremity kinematics, and muscle activation. J Orthop Sports Phys Ther. 1994 Sep;20(3):132-7.

113. Nyland JA, Shapiro R, Caborn DN, et al. The effect of quadriceps femoris, hamstring, and placebo eccentric fatigue on knee and ankle dynamics during crossover cutting. J Orthop Sports Phys Ther. 1997 Mar;25(3):171-84.

114. Baratta R, Solomonow M, Zhou BH, et al. Muscular coactivation: the role of the antagonist musculature in maintaining knee stability. Am J Sports Med. 1988 Mar-Apr;16(2):113-22.

115. 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 Biomechs (Bristol, Avon). 2008 Jan;23(1):81-92.

116. Brazen DM, Todd MK, Ambegaonkar JP, et al. The effect of fatigue on landing biomechanics in single-leg drop landings. Clin J Sport Med. 2010 Jul;20(4):286-92.

117. Kernozek TW, Torry MR, Iwasaki M. Gender differences in lower extremity landing mechanics caused by neuromuscular fatigue. Am J Sports Med. 2008 Mar;36(3):554-65.

118. Geiser CF. Effects of isolated hip abductor fatigue on frontal plane knee mechanics. Med Sci Sports Exerc. 2010 Mar;42(3):535-45.

119. Ortiz A, Olson SL, Etnyre B, et al. Fatigue effects on knee joint stability during two jump tasks in women. J Strength Cond Res. 2010 Apr;24(4):1019-27.

120. Tsai L, Sigward SM, Pollard CD, et al. Effects of fatigue and recovery on knee mechanics during side-step cutting. Med Sci Sports Exerc. 2009 Oct;41(10):1952-7.

121. Fitts RH. Muscle fatigue: the cellular aspects. Am J Sport Med. 1996;24(6):S9-13.

122. Kremenic IJ. How do dancers fatigue compared with athletes? *Proceedings of the 2011 Annual Meeting of the Greater New York Regional Chapter of the American College of Sports Medicine*. New York, NY: New York University Langone Medical Center, March 2011.

123. Skinner HB, Wyatt MP, Hodgdon JA, et al. Effect of fatigue on joint position sense of the knee. J Orthop Res. 1986;4(1):112-8.

124. 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 Occup Physiol. 1999 Jan;79(2):160-7.

125. Hardin JA, Blackburn TA, Canner GC, et al. The effects of muscle fatigue on and the relationship of arm dominance to shoulder proprioception. J Orthop Sports Phys Ther. 1996 Jun;23(6):348-52.

126. Linnamo V, Bottas R, Komi P. Force and EMG power spectrum during and after eccentric and concentric fatigue. J Electromyogr Kinesiol. 2000 Oct;10(5):293-300.

127. Johnston RB, Howard ME, Cawley PW, Losse GM. Effect of lower extremity muscular fatigue on motor control performance. Med Sci Sports Exerc. 1998 Dec;30(12):1703-7.

128. Liederbach M. General considerations for guiding dance injury rehabilitation. J Dance Med Sci. 2000;4(2):54-65.

129. Liederbach M. Screening for functional capacity in dancers: designing standardized, dance-specific injury prevention screening tools. J Dance Med Sci. 1997;1(3):93-106.

130. Frankenhauaser M, Dunne E, Lundberg U. Sex differences in sympathetic-adrenal medullary reactions induced by different stressors. Psychopharacology (Berl). 1976 May 5;47(1):1-5.

131. Liederbach M. Epidemiology of dance injuries: biopsychosocial considerations in the management of dancer health. *Dance Medicine: Strategies for the Prevention and Care of Injury to Dancers.* American Physical Therapy Association Orthopaedic Section Monograph. Independent Study Course 18.3.1, La Crosse, WI, 2008.