

[Athletic Training]



Neuroscience Application to Noncontact Anterior Cruciate Ligament Injury Prevention

Dustin R. Grooms, PhD, ATC, CSCS,*[†] and James A. Onate, PhD, ATC, FNATA[‡]

Context: Many factors, including anatomy, neuromuscular control, hormonal regulation, and genetics, are known to contribute to the noncontact anterior cruciate ligament (ACL) injury risk profile. The neurocognitive and neurophysiological influences on the noncontact ACL injury mechanism have received less attention despite their implications to maintain neuromuscular control. Sex-specific differences in neurocognition may also play a critical role in the elevated female ACL injury risk. This report serves to frame existing literature in a new light to consider neurocognition and its implications for movement control, visual-motor function, and injury susceptibility.

Evidence Acquisition: Sources were obtained from PubMed, MEDLINE, Web of Science, and LISTA (EBSCO) databases from 1990 onward and ranged from diverse fields including psychological and neuroscience reviews to injury epidemiology and biomechanical reports.

Study Design: Clinical review.

Level of Evidence: Level 5.

Results: Neurological factors may contribute to the multifactorial ACL injury risk paradigm and the increased female injury susceptibility.

Conclusion: When developing ACL injury prevention programs, considering neurocognition and its role in movement, neuromuscular control, and injury risk may help improve intervention effectiveness.

Keywords: neuromuscular; prevention; psychology; visual-motor

ANTERIOR CRUCIATE LIGAMENT INJURY

Noncontact anterior cruciate ligament (ACL) injuries continue to be a primary prevention priority for the sports medicine community. Numerous systematic reviews and meta-analyses published in recent years have established several factors that may contribute to ACL injury risk and the effectiveness of injury prevention programs.^{34,35} The current evidence-based prevention programs target neuromuscular control, strength, movement feedback, and balance to reduce the risk of ACL injury in sport.³⁴ However, despite a significant relative risk reduction (73.4%) when these known risk factors are targeted in training programs, noncontact injuries still occur.³⁵ The

remaining injury risk may be due to the failure to consider other aspects of neuromuscular control and function that play a role in injury risk susceptibility.³⁴ The relative risk reduction with the current programs may be improved by addressing additional neurological factors implicated in the noncontact ACL injury mechanism.

The noncontact ACL injury scenario itself exemplifies key components of function that are not addressed in traditional neuromuscular training.^{22,34} The video analysis of noncontact ACL injury incidents demonstrates external factors such as contact with a ball, another player, and/or distracted attention are involved in the majority of ACL noncontact events.^{6,19,28} This environmental interaction, combined with the rapid nature of

From [†]Division of Athletic Training, School of Applied Health Sciences and Wellness, Ohio University, Athens, Ohio, and [‡]Athletic Training Division, School of Health and Rehabilitation Sciences, The Ohio State University, Columbus, Ohio

*Address correspondence to Dustin R. Grooms, PhD, ATC, CSCS, Ohio University, E156 Grover Center, Athens, OH 45701 (email: groomsd@ohio.edu).

The authors report no potential conflicts of interest in the development and publication of this article.

DOI: 10.1177/1941738115619164

© 2015 The Author(s)

the injury (<50 ms after ground contact),¹⁹ may indicate that the error in motor control resulting in noncontact ACL injury is beyond the reactive capability of the central nervous system^{32,42} and may be at least partially dependent on feedforward mechanisms involving motor planning and cognition.^{23,37} Neurocognitive factors, specifically reaction time, processing speed, dual tasking, focus of attention, visual-motor control, and complex environmental interaction, all combine with biomechanical factors to directly contribute to feedback motor control and influence injury risk.^{7,28} These attentional and environmental components of neuromuscular function are largely not addressed in training programs that target strengthening, proximal control, balance, and plyometric ability.³⁴

THE “NEURO” IN NEUROMUSCULAR CONTROL

The standard neuromuscular ACL injury prevention training program typically does not incorporate the neurocognitive components associated with maintaining joint-to-joint alignment while engaging in the complex athletic environment.^{19,41} The ability to sustain motor control in the variable sport environment demands complex central nervous system (CNS) integration of a constantly changing profile of sensory inputs, including visual feedback, proprioception, and vestibular equilibrium. Biomechanical studies confirm that the incorporation of a layer of neurocognitive elements ranging from dual tasks, responding to stimuli,²⁴ anticipation,⁵ decision making,²⁰ and programming motion relative to external targets¹⁰ may degrade neuromuscular control relative to movement without such factors. Recently, examination of injury risk during ball-handling and offensive action (considered anticipatory and feedforward in nature) versus defending (considered unanticipatory and responsive in nature) demonstrated a disparity with basketball players at greater risk during defensive action.²⁷ These large-scale epidemiological data further support the possibility of increased injury risk when responding to unanticipated events or rapid visual-motor decision making is required.

Prospective evidence of depressed aspects of neurocognitive function increasing the risk of noncontact ACL injury further highlights the implications of visual-motor integration on noncontact ACL injury risk.³⁶ Specifically, reaction time, visual processing, and memory measured via a computerized concussion baseline assessment (IMPACT) were significantly lower in those that went on to experience a noncontact ACL injury than matched controls.³⁶ Visual processing speed is imperative to successful sport function whereby complex sensory and visual feedback must be handled with minimal preparation time.^{15,19} The ability to keep the constantly changing environment (player or ball positions) in short-term visual memory also plays a vital role in feedforward motor planning during activity.³³ Thus, visual-motor function and reaction time may influence musculoskeletal injury risk in the ability to anticipate and prepare for high-risk situations.^{15,25} Faster

reaction time or processing speed may improve preparation for incoming perturbations while maintaining neuromuscular integrity and avoiding compromising knee positions (eg, excessive valgus). If visual-motor processing is suboptimal, this will decrease the ability to compensate for external stimuli and/or attenuate the rapid maneuvers that depend on quick visual-motor interaction.^{8,17,24}

SEX DIFFERENCES IN NEUROCOGNITION-NEUROPHYSIOLOGY

Neurological factors may also contribute to the greater relative noncontact ACL injury rate in female athletes.^{1,3} The greater female ACL risk profile has been attributed to factors ranging from hormonal, skeletal alignment, muscular strength, neuromuscular, and biomechanical differences.¹⁶ Aspects of physiology that have not been attributed to the sex disparity in injury risk, are neurocognitive and neurophysiological sex differences,²⁶ which influence motor control and visual processing interaction in the spatially complex sport environment.

Altered neuromuscular control during visual-motor environmental interaction increases injury risk and is supported by extensive biomechanical evidence.^{7,8,10,24,29} The addition of an external target or stimulus that must be visually attended to during landing or change of direction maneuvers has a more pronounced effect on knee control related to injury risk in women compared with men.^{10,16,24} Women also experience greater alterations in knee neuromuscular control during movement that requires responding to an anticipatory component that integrates visual processing and reaction time.⁸ Incorporating short-term memory and online decision making also demonstrate sex-specific adaptations in the maintenance of joint-to-joint alignment during complex athletic maneuvers such as cutting or sidestepping.^{7,29} This evidence may represent a sex disparity in visual-motor-related neurocognition contributing to knee neuromuscular control.

The sex-related disparity in neuromuscular control when spatial attention is challenged may have a neurophysiologic mechanism. Investigations into brain function and anatomy have demonstrated sex differences in nervous system function and structure^{13,14} that may influence noncontact ACL injury risk. Diffusion tensor imaging has demonstrated that the male brain is structured to facilitate perception and coordinated action (intrahemispheric connectivity), whereas the female brain is structured to facilitate analytical and intuitive processing (interhemispheric connectivity).¹⁸ Men also tend to have a larger angular gyrus and visual cortices relative to overall brain mass.^{11,12} The functional role of these areas are spatial and visual processing, and visuospatial performance tends to favor men.^{4,40} This visuospatial processing functionality in men may assist in navigation through a chaotic athletic field while maintaining knee alignment and avoiding high injury-risk positions.²⁸

The sex differences in cognition, visual-motor function, and movement control are likely due to a complex and not entirely understood combination of biological, psychological,

physiological, societal, and cultural factors.^{9,26,30,43} The sex-specific visuospatial ability and brain anatomy may be due to evolutionary history for selecting men for hunting-related skills, creating a biological advantage for increased development of visuospatial abilities.³¹ Male sex hormones, specifically testosterone, influence brain function to shift cognition away from the left hemisphere and toward the right, increasing a task- and/or spatial-oriented distribution that may improve visuospatial ability.^{9,39} Experiential factors also play a role, for example, London taxi drivers have greater hippocampal gray matter volume consistent with their constant exposure to the complex visual-spatial problems of navigating a complex city.²¹ Along similar lines, exposure to specific toys (construction, blocks, etc) and/or action video games has been shown to improve visuospatial skills, and men tend to engage in these activities to a much greater degree.^{2,38} In light of the typical high spatial demands during sport and the noncontact ACL injury event, the male predisposition to improved spatial cognition⁴⁰ may play a role in the relatively higher rate of female noncontact ACL injury.

CONCLUSION

The tools of neuroscience will continue to help uncover how the nervous system generates motor control and the mechanistic errors in motor control resulting in noncontact ACL injury. Adding neurocognitive elements to injury prevention programs may reduce motor control errors during sport when visuospatial responsibilities are in high demand. Adding dual tasks such as memory recall, environmental stimulus (ball or partner perturbations), or direct visual perturbations can supplement interventions. Recognition of the neurological implications for maintaining neuromuscular control and injury avoidance may help to mitigate injury risk and improve intervention effectiveness.

REFERENCES

- Allen JS, Damasio H, Grabowski TJ, Bruss J, Zhang W. Sexual dimorphism and asymmetries in the gray-white composition of the human cerebrum. *Neuroimage*. 2003;18:880-894.
- Appelbaum LG, Cain MS, Darling EF, Mitroff SR. Action video game playing is associated with improved visual sensitivity, but not alterations in visual sensory memory. *Atten Percept Psychophys*. 2013;75:1161-1167.
- Arendt EA, Agel J, Dick R. Anterior cruciate ligament injury patterns among collegiate men and women. *J Athl Train*. 1999;34:86-92.
- Astur RS, Ortiz ML, Sutherland RJ. A characterization of performance by men and women in a virtual Morris water task: a large and reliable sex difference. *Behav Brain Res*. 1998;93:185-190.
- Besier 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.
- Boden BP, Torg JS, Knowles SB, Hewett TE. Video analysis of anterior cruciate ligament injury: abnormalities in hip and ankle kinematics. *Am J Sports Med*. 2009;37:252-259.
- 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;23:81-92.
- Brown TN, Palmieri-Smith RM, McLean SG. Sex and limb differences in hip and knee kinematics and kinetics during anticipated and unanticipated jump landings: implications for anterior cruciate ligament injury. *Br J Sports Med*. 2009;43:1049-1056.
- Ellis L. Evolutionary neuroandrogenic theory and universal gender differences in cognition and behavior. *Sex Roles*. 2011;64:707-722.
- Ford KR, Myer GD, Smith RL, Byrnes RN, Dopirak SE, Hewett TE. Use of an overhead goal alters vertical jump performance and biomechanics. *J Strength Cond Res*. 2005;19:394-399.
- Goldstein JM, Seidman LJ, Horton NJ, et al. Normal sexual dimorphism of the adult human brain assessed by in vivo magnetic resonance imaging. *Cereb Cortex*. 2001;11:490-497.
- Goldstein JM, Seidman LJ, O'Brien LM, et al. Impact of normal sexual dimorphisms on sex differences in structural brain abnormalities in schizophrenia assessed by magnetic resonance imaging. *Arch Gen Psychiatry*. 2002;59:480-480.
- Gur RC, Gunning-Dixon FM, Turetsky BI, Bilker WB, Gur RE. Brain region and sex differences in age association with brain volume: a quantitative MRI study of healthy young adults. *Am J Geriatr Psychiatry*. 2002;10:72-80.
- Gur RC, Turetsky BI, Matsui M, et al. Sex differences in brain gray and white matter in healthy young adults: correlations with cognitive performance. *J Neurosci*. 1999;19:4065-4072.
- Harpham JA, Mihalik JP, Littleton AC, Frank BS, Guskiewicz KM. The effect of visual and sensory performance on head impact biomechanics in college football players. *Ann Biomed Eng*. 2014;42:1-10.
- Hewett TE, Myer GD, Ford KR. Anterior cruciate ligament injuries in female athletes: part 1, mechanisms and risk factors. *Am J Sports Med*. 2006;34:299-311.
- Houck JR, De Haven KE, Maloney M. Influence of anticipation on movement patterns in subjects with ACL deficiency classified as noncopers. *J Orthop Sports Phys Ther*. 2007;37:56-64.
- Ingalhalikar M, Smith A, Parker D, et al. Sex differences in the structural connectome of the human brain. *Proc Natl Acad Sci U S A*. 2014;111:823-828.
- Krosshaug T, Nakamae A, Boden BP, et al. Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases. *Am J Sports Med*. 2007;35:359-367.
- Lee MJ, Lloyd DG, Lay BS, Bourke PD, Alderson JA. Effects of different visual stimuli on postures and knee moments during sidestepping. *Med Sci Sports Exerc*. 2013;45:1740-1748.
- Maguire EA, Gadian DG, Johnsrude IS, et al. Navigation-related structural change in the hippocampi of taxi drivers. *Proc Natl Acad Sci U S A*. 2000;97:4398-4403.
- McLean SG. The ACL injury enigma: we can't prevent what we don't understand. *J Athl Train*. 2008;43:538-540.
- McLean SG, Borotikar B, Lucey SM. Lower limb muscle pre-motor time measures during a choice reaction task associate with knee abduction loads during dynamic single leg landings. *Clin Biomech (Bristol, Avon)*. 2010;25:563-569.
- McLean SG, Lipfert SW, van den Bogert AJ. Effect of gender and defensive opponent on the biomechanics of sidestep cutting. *Med Sci Sports Exerc*. 2004;36:1008-1016.
- Mihalik JP, Blackburn JT, Greenwald RM, Cantu RC, Marshall SW, Guskiewicz KM. Collision type and player anticipation affect head impact severity among youth ice hockey players. *Pediatrics*. 2010;125:E1394-E1401.
- Miller DI, Halpern DF. The new science of cognitive sex differences. *Trends Cogn Sci*. 2014;18:37-45.
- Monfort SM, Comstock RD, Collins CL, Onate JA, Best TM, Chaudhari AM. Association between ball-handling versus defending actions and acute noncontact lower extremity injuries in high school basketball and soccer. *Am J Sports Med*. 2015;43:802-807.
- Olsen OE, Myklebust G, Engebretsen L, Bahr R. Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. *Am J Sports Med*. 2004;32:1002-1012.
- Pollard CD, Heiderscheit BC, van Emmerik RE, Hamill J. Gender differences in lower extremity coupling variability during an unanticipated cutting maneuver. *J Appl Biomech*. 2005;21:143-152.
- Robert S. Understanding sex differences in visuo-spatial cognition: a study in human behavior and evolution. *Liberte*. 2000;42(4):38-50.
- Sanders G. Sex differences in motor and cognitive abilities predicted from human evolutionary history with some implications for models of the visual system. *J Sex Res*. 2013;50:353-366.
- Shultz SJ, Perrin DH, Adams MJ, Arnold BL, Gansneder BM, Granata KP. Neuromuscular response characteristics in men and women after knee perturbation in a single-leg, weight-bearing stance. *J Athl Train*. 2001;36:37-43.
- Smith TQ, Mitroff SR. Stroboscopic training enhances anticipatory timing. *Int J Exerc Sci*. 2012;5:344-353.

34. Sugimoto D, Myer GD, Barber Foss KD, Hewett TE. Specific exercise effects of preventive neuromuscular training intervention on anterior cruciate ligament injury risk reduction in young females: meta-analysis and subgroup analysis. *Br J Sports Med.* 2015;49:282-289.
35. Sugimoto D, Myer GD, McKeon JM, Hewett TE. Evaluation of the effectiveness of neuromuscular training to reduce anterior cruciate ligament injury in female athletes: a critical review of relative risk reduction and numbers-needed-to-treat analyses. *Br J Sports Med.* 2012;46:979-988.
36. Swanik CB, Covassin T, Stearne DJ, Schatz P. The relationship between neurocognitive function and noncontact anterior cruciate ligament injuries. *Am J Sports Med.* 2007;35:943-948.
37. Swanik CB, Lephart SM, Giraldo JL, DeMont RG, Fu FH. Reactive muscle firing of anterior cruciate ligament-injured females during functional activities. *J Athl Train.* 1999;34:121-129.
38. Uttal DH, Meadow NG, Tipton E, et al. The malleability of spatial skills: a meta-analysis of training studies. *Psychol Bull.* 2013;139:352-402.
39. Vogel JJ, Bowers CA, Vogel DS. Cerebral lateralization of spatial abilities: a meta-analysis. *Brain Cogn.* 2003;52:197-204.
40. Voyer D, Voyer S, Bryden MP. Magnitude of sex differences in spatial abilities: a meta-analysis and consideration of critical variables. *Psychol Bull.* 1995;117:250-270.
41. Wilkerson GB, Mokha M. Neurocognitive reaction time predicts lower extremity sprains and strains. *Int J Athl Ther Train.* 2012;17(6):4-9.
42. Wojtys EM, Huston IJ. Neuromuscular performance in normal and anterior cruciate ligament-deficient lower extremities. *Am J Sport Med.* 1994;22:89-104.
43. Wynn TG, Tierson FD, Palmer CT. Evolution of sex differences in spatial cognition. *Yearb Phys Anthropol.* 1996;39:11-42.

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