ACL Injuries—The Gender Bias: Introduction

Research Retreat II

April 4-5, 2003
Lexington, KY

Guest Editors
Irene McClay Davis, PT, PhD[1,2]
Mary Lloyd Ireland, MD[3]

This was the second research retreat focused on gender bias in anterior cruciate ligament (ACL) injuries, the first having taken place in Lexington, KY in April 2001. The purpose of this second retreat was to revisit the factors thought to be associated with gender bias in ACL injuries and to update the consensus statement from 2001.[1] The retreat was again cosponsored by Kentucky Sports Medicine and Joyner Sportsmedicine Institute and was attended by both clinicians and scientists with a common interest in the ACL injury gender bias. The 50-plus participants included registrants from across the United States as well as Canada, Australia, and Norway. As with the previous retreat, the group consisted of physicians, physical therapists, athletic trainers, and scientists in the areas of biomechanics, motor control, and neuromuscular function. Thirty percent of the participants in the 2003 retreat were present for the first retreat as well.

A call for abstracts for the retreat was announced in the summer of 2002. All abstracts were then peer reviewed for scientific merit and relevance to the retreat topic. In the end, 19 abstracts were accepted for podium presentations. These were grouped into sessions addressing structural, neuromuscular, biomechanical, and hormonal factors that may influence the gender bias in ACL injury incidence. In addition, a new session on intervention programs was included.

The format of the meeting included 1 keynote presentation per day along with 20-minute podium presentations made by some of the participants. The keynote presenters were chosen for their scientific contribution to the understanding of factors associated with the gender bias seen in the incidence of ACL injuries. Bruce D. Beynnon, PhD, from the University of Vermont gave the first keynote titled "Risk Factors for Knee Ligament Trauma." The second keynote presenter was Braden C. Fleming, PhD, also from the University of Vermont, whose talk was titled "Biomechanics of the Anterior Cruciate Ligament."

In the following pages, you will find a consensus statement, a listing of the presentations and authors, and an abstract on each of the 19 presentations made at the conference, organized by the topics listed above.

REFERENCE

1. McClay Davis I, Ireland ML. The gender bias in ACL injuries: a research retreat. *Clin Biomech (Bristol, Avon).* 2001;16:937–939.

---

[1] *Joyner Sportsmedicine Institute, Mechanicsburg, PA.*
[2] *University of Delaware, Newark, DE.*
[3] *Kentucky Sports Medicine Center, Lexington, KY.*

ACL Injuries—The Gender Bias

Guest Editors
Irene McClay Davis, PT, PhD[1,2]
Mary Lloyd Ireland, MD[3]

The development of the consensus statement was formed in the following manner. After all of the papers for a given factor (structural, neuromuscular, biomechanical, and hormonal) as well as intervention programs were presented, an initial consensus was drafted based on the input of all of the participants as a group. As with the first retreat, this consensus was formed through discussion of what we know, which was grounded in the recent literature, along with what was presented at the current retreat. The group then identified what is still unknown (what we don't know) about each factor's contribution to the gender bias. This led to the final part of the consensus in which suggestions for future research directions were made. Once all papers were presented, the participants formed 5 self-selected groups, based on each of the areas discussed. A participant with expertise in that particular area chaired each group. During this time, the groups refined their part of the consensus statement. They were charged with providing a finalized consensus supported with references, to be submitted at a designated time following the meeting.

During the development of the consensus, the "what we know" portion generated the most discussion. It was difficult at times to agree on what constituted the facts. Participants were less willing to state confidently what was known than what was unknown. Stating what we know proved a much easier process during the first retreat due to the paucity of literature available in April 2001. As the body of literature has grown and more is known, however, more controversy results. Therefore, participants agreed that the consensus should be viewed as the present state of thought about ACL injuries, based upon current knowledge, with the realization that what we know will likely evolve by the time of the next retreat in 2 years.

Participants also agreed that, while the focus of this retreat was the gender bias in ACL injuries, some of the identified factors (structural, neuromuscular, and biomechanical) may not be purely gender specific. For example, genu valgus alignment may be a factor associated with increased ACL strain and may be more prevalent in females. However, there may be males who also exhibit this alignment and so may be at greater risk for ACL injury. Further, there was much discussion regarding whether females need to move more like men to reduce their risk for ACL injury or whether there is an optimal pattern for women that differs from the pattern for men.

Following are the sections of the consensus statement for each of the factors thought to be associated with the ACL injury gender bias, as well as for the section on intervention programs. We would like to thank Lori Livingston, Jean McCrory, William Romani, Sandra Shultz, and Susan Sigward for their assistance in coordinating the final draft of each of these sections. We realize that these lists are not all inclusive, however, they do represent the collective opinions of the participants in this retreat. It is our hope that this consensus statement will promote research studies in the suggested areas so that some of these gaps in the literature might be filled by the next research retreat.

I. Structural Factors

A. What We Know

1. Females do not have wider pelvises than their male counterparts,[1,15] as is often assumed. However, females have been shown to have wider pelvis-to-femoral-length ratios,[7,10] which may contribute to a greater tendency for genu valgum.
2. Females do have larger Q angles than males.[11,12] However, Q angle and the frontal plane tibiofemoral valgus angles are independent measures and cannot be interchanged.[8,9,17] In addition, tibiofemoral valgum in a single leg squat is not related to Q angle.[14]

---

[1] Joyner Sportsmedicine Institute, Mechanicsburg, PA.
[2] University of Delaware, Newark, DE.
[3] Kentucky Sports Medicine Center, Lexington, KY.

   3. Both the size and shape of the notch may contribute to stenosis and ACL impingement and injury.[2,4,19,20]
   4. The combination of knee abduction (valgus) and external rotation positions contribute to ACL impingement in vitro,[6] especially in the presence of a narrow notch.[21] These motions have been shown to be greater in females compared to males during athletic activity.[3,5,13]
   5. Females have greater laxity[16] and greater active hip rotation range of motion compared to males.[18]

B. What We Don't Know
   1. What are the relationships between lower-extremity structure, function, and ACL injury and do those relationships differ between genders?
   2. Does joint congruency at the tibial plateau influence ACL strain and is it different between genders?
   3. Does limb dominance or asymmetries in lower limb alignment (eg, as measured using Q angles or tibiofemoral angles) influence ACL strain?
   4. Is a smaller ligament associated with a smaller notch, and are ligament and notch size scaled to body size?
   5. Do the increased genu valgus and femoral internal rotation seen in females predispose them to greater strain to the ACL?
   6. Does greater laxity or greater range of motion lead to increased risk of ACL injury?

C. Where Do We Go From Here?
   1. Continue to develop valid and reliable clinical (including weight-bearing) measures of structure and function that can be used to identify individuals at risk for ACL injury.
   2. Examine structural measures, not as discrete variables, but as factors that contribute to multifactorial models.
   3. Consider the 3-dimensional shape of the intercondylar notch and how it relates to ligament size as well as ligament impingement.
   4. Further explore the relationship between gender differences in pelvic anatomy and resulting knee postures.
   5. Investigate the prospective relationship between lower-extremity structure, function, and ACL injury across gender. Structural variables that do not change with time could be assessed in retrospective studies.

REFERENCES

1. Abitbol MM. The shapes of the female pelvis. Contributing factors. *J Reprod Med.* 1996;41:242-250.
2. Anderson AF, Lipscomb AB, Liudahl KJ, Addlestone RB. Analysis of the intercondylar notch by computed tomography. *Am J Sports Med.* 1987;15:547-552.
3. Chaudhari AM, Camarillo DB, Hearn BK, Leveille L, Andriacchi T. The mechanical consequences of gender differences in single limb alignment during landing. Proceedings of the ACL Research Retreat II: The Gender Bias. *J Orthop Sports Phys Ther.* 2003;33(8):A25.
4. Charlton WPH, St. John TA, Ciccotti MG, Harrison N, Schweitzer M. Differences in the femoral notch anatomy between men and women-a magnetic resonance imaging study. *Am J Sports Med.* 2002;30:329-333.
5. Ferber R, McClay Davis I, Williams, DS. Gender differences in lower extremity mechanics during running. *Clin Biomech (Bristol, Avon).* 2003;18:350-357.
6. Fung D, et al. Mathematical modeling of ACL impingement against the intercondylar notch wall. Proceedings of the ACL Research Retreat II: The Gender Bias. *J Orthop Sports Phys Ther.* 2003;33(8):A18-A19.
7. Horton MG, Hall TL. Quadriceps femoris muscle angle: normal values and relationships with gender and selected skeletal measures. *Phys Ther.* 1989;69:897-901.
8. Igbigbi PS, Msamati BC. Tibiofemoral angles in Malawians. *Clin Anat.* 2002;15:293-296.
9. LeBlanc SE, Livingston LA, Mahar SM. Q angles and tibiofemoral angles in physically active and inactive females. Proceedings of the ACL Research Retreat II: The Gender Bias. *J Orthop Sports Phys Ther.* 2003;33(8):A16.
10. Livingston LA, Gahagan JC. The wider gynaecoid pelvis—larger Q angle—greater predisposition to ACL injury relationship: myth or reality? *Clin Biomech (Bristol, Avon).* 2001;16:951-952.
11. Livingston LA. The quadriceps angle: a review of the literature. *J Orthop Sports Phys Ther.* 1998;28:105-109.
12. Livingston LA, Mandigo JL. Bilateral Q angle asymmetry and anterior knee pain syndrome. *Clin Biomech (Bristol, Avon).* 1999;14:7-13.
13. Malinzak RA, Colby SM, Kirkendall DT, Yu B, Garrett WE. A comparison of knee joint motion patterns between men and women in selected athletic tasks. *Clin Biomech (Bristol, Avon).* 2001;16:438-445.
14. Pantano KJ, White SC, Gilchrist LA, Leddy J. Differences in peak knee valgus angles between individuals with high and low Q angles during a single limb squat. Proceedings of the ACL Research Retreat II: The Gender Bias. *J Orthop Sports Phys Ther.* 2003;33(8):A17.
15. Petersen A. Sexing the body: representations of sex differences in Gray's Anatomy, 1858 to the present. *Body Soc.* 1998;4:1-15.
16. Rozzi SL, Lephart SM, et al. Knee joint laxity and neuromuscular characteristics of male and female soccer and basketball players. *Am J Sports Med.* 1999;27(3):312-319.
17. Schulthies SS, Francis RS, Fisher AG, Van de Graaff KM. Does the Q angle reflect the force on the patella in the frontal plane? *Phys Ther.* 1995;75:24-30.
18. Simoneau GG, Hoenig KJ, Lepley JE, Papanek, PE. Influence of hip position and gender on active hip

internal and external rotation. *J Orthop Sports Phys Ther.* 1998;28:158-164.
19. Tillman MD, Smith KR, Bauer JA, Cauraugh JH, Falsetti AB, Pattishall JL. Differences in three intercondylar notch geometry indices between males and females: a cadaver study. *Knee,* 2002;9(1):41-6.
20. Van Lunen BL, Perrin DH, Arnold BL, et al. Characteristics of anterior cruciate ligament injuries: preliminary findings. Proceedings of the ACL Research Retreat II: The Gender Bias. *J Orthop Sports Phys Ther.* 2003;33(8):A16.
21. Zhang L-Q, Fung D, Lin F, et al. Noncontact ACL injuries: impingement versus direct stretch. Proceedings of the ACL Research Retreat II: The Gender Bias. *J Orthop Sports Phys Ther.* 2003;33(8):A17.

II. Neuromuscular Factors

A. What We Know
  1. Females activate their muscles sooner in anticipation of landing.[1,13]
  2. Variability in neuromuscular control parameters at impact can cause significant increases in external 3-dimensional knee joint loading during movements linked to noncontact ACL injury.[8]
  3. Females tend to rely more on their quadriceps to stabilize the knee compared to males.[5,6,15]
  4. Females demonstrate reduced muscle stiffness compared to males when attempting to control knee motion.[4,16]
  5. Females take longer than males to produce muscular tension in the quadriceps with reflex activation after fatiguing exercise[10] and in the hamstring muscles with isokinetic testing.[5]
  6. Females exhibit lower muscular endurance compared to males.[5] Lower endurance is thought to lead to earlier fatigue, which is also thought to be related to increased risk of injury.[3,11,12]

B. What We Don't Know
  1. While there are a number of neuromuscular strategies that produce the same joint mechanics,[9] should females produce the same strategies as males? Is there an optimal pattern for each gender?
  2. How are neuromuscular strategies affected by maturation within gender?
  3. While there is evidence to suggest that increased knee joint laxity increases hamstring reflex delays[14] and increases lateral hamstring activity[12,14] in weight bearing, what are the gender differences in these responses?
  4. Does earlier preactivation of muscles negatively or positively affect joint stiffness, kinetics, and ground reaction forces produced during landing from a jump or during a plant and cut maneuver?
  5. While it has been shown that simulated increased stiffness of the hip resulted in an increased resistance to knee valgus buckling,[2] what are the influences of hip and trunk (core) stability on knee function? How can we assess these factors experimentally?
  6. While simulated variations in neuromuscular control parameters at impact can cause significant increases in external 3-dimensional knee joint loading during movements linked to ACL injury,[7] do gender differences in these variations exist and are they associated with injury?

C. Where Do We Go From Here?
  1. Determine the underlying factors for the observed gender differences in neuromuscular function.
  2. Determine at what point during the maturational process neuromuscular strategies begin to differ between genders.
  3. Generate studies combining neuromuscular and biomechanical measures to define more precisely the relationship between muscular activity and knee joint forces and moments.
  4. Clarify what recruitment strategies may be beneficial with respect to protection of the ACL during weight-bearing postures.
  5. Delineate the role of proximal muscle influences (hip and trunk) on lower-extremity function and injury.
  6. Develop models that can predict the effects of neuromuscular control on knee joint and resultant ACL loading.

REFERENCES

1. Cowling EJ, Steele JR. Is lower limb muscle synchrony during landing affected by gender? Implications for variation in ACL injury rates. *J Electromyogr Kinesiol.* 2001;11:263-68.
2. Chaudhari AM, Camarillo DB, Hearn BK, Leveille L, Andriacci T. The mechanical consequences of gender differences in single limb alignment during landing. Proceedings of the ACL Research Retreat II: The Gender Bias. *J Orthop Sports Phys Ther.* 2003;33(8):A25.
3. Gabbett TJ. Incidence of injury in amateur rugby league sevens. *Br J Sports Med.* 2002;36(1):23-26.
4. Granata KP, Padua DA, Wilson SE. Gender differences in active musculoskeletal stiffness. Part II. Quantification of leg stiffness during functional hopping tasks. *J Electromyogr Kinesiol.* 2002;12:127-135.
5. Huston LJ, Wojtys EM. Neuromuscular performance characteristics in elite female athletes. *Am J Sports Med.* 1996;24(4):427-436.

6. Malinzak RA, Colby SM, Kirkendall DT, Yu B, Garrett WE. A comparison of knee joint motion patterns between men and women in selected athletic tasks. *Clin Biomech (Bristol, Avon).* 2001;16:438-445.
7. McLean SG, Neal RJ, Myers PT, Walters MR. Knee joint kinematics during the sidestep cutting maneuver: potential for injury in women. *Med Sci Sports Exerc.* 1999;31(7):959-968.
8. McLean SG, van den Bogert AJ, Su A. Effects of neuromuscular control on knee joint loading during sidestepping: Implications for noncontact ACL injury. Proceedings of the ACL Research Retreat II: The Gender Bias. *J Orthop Sports Phys Ther.* 2003;33(8):A24.
9. McNitt-Gray JL, Hester DM, Mathiyakom W, Munkasy BA. Mechanical demand and multijoint control during landing depend on orientation of the body segments relative to the reaction force. *J Biomech.* 2001;34:1471-1482.
10. Moore BD, Drouin JM, Shultz SJ, Gansneder BG. The effect of gender and fatigue on neuromuscular responses following a patellar tendon tap. *J Athl Train.* 2001;36(2):S9.
11. Rahnama N, Reilly T, Lees A. Injury risk associated with playing actions during competitive soccer. *Br J Sports Med.* 2002;36(5):354-359.
12. Rozzi SL, Lephart SM, Gear WS, Fu FH. Knee joint laxity and neuromuscular characteristics of male and female soccer and basketball players. *Am J Sports Med.* 1999;27(3):312-319.
13. Schmitz RJ, Thompson TT. Gender differences in hip and knee kinematics during single leg landings. *J Athl Train.* 2002;37:S20.
14. Shultz SJ, Carcia CR, Perrin DH. Knee joint laxity affects muscle activation patterns at the knee. Proceedings of the ACL Research Retreat II: The Gender Bias. *J Orthop Sports Phys Ther.* 2003;33(8):A20.
16. Shultz SJ, Perrin DH, Adams JM, Arnold BL, Gansneder BM, Granata KP. Neuromuscular response characteristics in males and females after knee perturbation in a single leg weight-bearing stance. *J Athl Train.* 2001;36(1):37-43.
17. Wojtys EM, Ashton-Miller JA, Huston LJ. A gender-related difference in contribution of the knee musculature to sagittal-plane shear stiffness in subjects with similar knee laxity. *J Bone Joint Surg Am.* 2002;84A(1):10-16.

III. Biomechanical Factors

A. What We Know

1. The mechanisms for noncontact ACL injuries have been reported to include deceleration with the knee in an extended position, landing from a jump, and sidestep cut maneuvers.[4]
2. Females tend to have more knee valgus than males during sidestep cutting[6,13,16] and a more extended knee than males at initial contact.
3. Compared to running, frontal- and transverse-plane moments are greater during anticipated sidecut maneuvers to 30° and 60° and crossover cutting. In addition, these moments were increased when the tasks where performed under unanticipated conditions.[1]
4. Females demonstrate significantly less knee flexion and increased hip and knee internal rotation than males during single-leg landing and forward-hopping tasks.[12]
5. Females demonstrated greater knee extension and valgus moments during the landing phases of jump stop tasks, which are associated with greater anterior tibial shear forces.[5] In vitro studies demonstrate increases in these types of loads (extensor and valgus) are associated with increased strains of the ACL.[3,8,14]

B. What We Don't Know

1. The isolated motions (and moments) of knee valgus and internal rotation have been shown (both in vitro and in vivo) to increase ACL strain, while external rotation alone decreases its strain.[2,7,10,14,15] What is the effect of combined, in vivo, loading of these motions such as genu valgum and external rotation on ACL strain?
2. How is the ACL ligament loaded, in vivo, during high-risk maneuvers such as cutting, landing, and abrupt decelerations?
3. While we know that a heel contact (compared to a forefoot contact) during landings leads to an increased internal rotation moment and greater internal rotation angles,[9] what are the gender differences in landing contact patterns?
4. Do gender differences noted in mechanics of high-risk movements place women at greater risk for ACL injury?
5. Should females move more like males or is there an optimal movement pattern for each gender?

C. Where Do We Go From Here?

1. Examine the relationship between in vitro and in vivo data on ACL loading, especially as it relates to high risk athletic activities such as cutting and landing.
2. Further investigate (both in vitro and in vivo) the influence of combined loading patterns associated with mechanisms of injury.
3. Determine if there are gender differences in the ACL strain response.
4. Investigate whether the at risk patterns are task specific (ie, different for cutting than landing).
5. Determine whether there are gender differences in foot contact patterns during high-risk maneuvers such as landing and cutting.
6. Examine whether the gender differences

noted in biomechanical patterns during athletic activities translate into higher risk for ACL injury for females.

7. Explore the effects of experience, age, and maturation on gender differences in mechanics.
8. Develop forward dynamic 3-dimensional models to be able to simulate more accurately real life situations that are not possible in a laboratory setting.[17] In addition, further develop software that can accurately reconstruct 3-dimensional data from markerless video sequences of game situations[11] in which ACL injuries occur.

REFERENCES

1. Besier TF, Lloyd DG, Cochrane JL, Ackland TR. External loading of the knee joint during running and cutting maneuvers. *Med Sci Sports Exerc.* 2001;33:1168-1175.
2. Beynnon BD, Fleming BC. Anterior cruciate ligament strain in vivo: a review of previous work. *J Biomech.* 1998;31:519-525.
3. Beynnon BD, Fleming BC, Johnson RJ, et al. Anterior cruciate ligament strain behavior during rehabilitation exercises in vivo. *Am J Sports Med.* 1995;23:24-34.
4. Boden BP, Dean GS, Feagin JA, Garrett WE. Mechanisms of anterior cruciate ligament injury. *Orthopedics.* 2000;23(6):573-578.
5. 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(2):261-267.
6. Chaudhari AM, Camarillo DB, Hearn, BK, Leveille L, Andriacci T. The mechanical consequences of gender differences in single limb alignment during landing. Proceedings of the ACL Research Retreat II: The Gender Bias. *J Orthop Sports Phys Ther.* 2003;33(8):A25.
7. Fleming BC, Renstrom PA, Beynnon BD, et al. The effect of weightbearing and external loading on anterior cruciate ligament strain. *J Biomech.* 2001;34:163-170.
8. Fleming BC, Renstrom PA, Ohlen G, et al. The gastrocnemius muscle is an antagonist of the anterior cruciate ligament. *J Orthop Res.* 2001;19:1178-1184.
9. Houck JR, Hanford S. Foot landing strategies affect knee biomechanics during sidestep cut tasks. Proceedings of the ACL Research Retreat II: The Gender Bias. *J Orthop Sports Phys Ther.* 2003;33(8):A23.
10. Kanamori A, Woo SL-Y, Ma CB, et al. The forces in the anterior cruciate ligament and knee kinematics during a simulated pivot shift test. *Arthroscopy.* 2002;16:633-639.
11. Krosshaug T, Bahr RA. Model-based image-matching technique for 3-dimensional motion reconstruction from uncalibrated video sequences—application to ACL injury situations. Proceedings of the ACL Research Retreat II: The Gender Bias. *J Orthop Sports Phys Ther.* 2003;33(8):A21.
12. Lephart SM, Ferris CM, Riemann BL, Myers JB, Fu FH. Gender differences in strength and lower extremity kinematics during landing. *Clin Orthop.* 2002;401:162-169.
13. Malinzak RA, Colby SM, Kirkendall DT, Yu B, Garrett WE. A comparison of knee joint motion patterns between men and women in selected athletic tasks. *Clin Biomech (Bristol, Avon).* 2001;16:438-445.
14. Markolf KL, Burchfield DM, Shapiro MM, Shepard MF, Finerman GA, Slauterbeck JL. Combined knee loading states that generate high anterior cruciate ligament forces. *J Orthop Res.* 1995;13:930-935.
15. Markolf KL, Gorek JF, Kabo JM, Shapiro MS. Direct measurement of resultant forces in the anterior cruciate ligament. An in vitro study performed with a new experimental technique. *J Bone Joint Surg Am.* 1990;72:557-567.
16. McLean SG, Neal RJ, Myers PT, Walters MR. Knee joint kinematics during the sidestep cutting maneuver: potential for injury in women. *Med Sci Sports Exerc.* 1999;31:959-968.
17. McLean SG, van den Bogert AJ, Su A. Effects of neuromuscular control on knee joint loading during sidestepping: Implications for noncontact ACL injury. Proceedings of the ACL Research Retreat II: The Gender Bias. *J Orthop Sports Phys Ther.* 2003;33(8):A24.

IV. Hormonal Factors

A. What We Know
  1. Subject self-report of menstrual phase is not accurate and may lead to unreliable findings.[5,7]
  2. There is no change in ultimate failure load of the ACL throughout the estrous cycle in rats.[2]
  3. There may be hormone-dependent changes throughout the menstrual cycle that influence physical performance.[8]
  4. Supraphysiologic levels of estradiol decrease the load-to-failure in ovariectomized rabbits.[5]
  5. There is an association between individual variations in sex hormone concentration and changes in the low load viscoelastic properties of the tibiofemoral joint.[1,4]
  6. There are significant differences in knee joint laxity between genders both pre-exercise and postexercise. However, both genders exhibit a similar increase in knee joint laxity following exercise.[3]

B. What We Don't Know
  1. What is the relationship between animal and human models?
  2. What is the relationship between sex hormone fluctuation, menstrual cycle, and injury pattern?
  3. What is the relationship between joint laxity and ACL laxity?
  4. What is the relationship between ACL laxity and injury risk?

C. Where Do We Go From Here?
   1. Develop consistent definitions of biomechanical properties: stiffness, laxity, load-to-failure properties.
   2. Conduct assay analyses of saliva, urine, or serum to identify more accurately the phase of the menstrual cycle at the time of injury.
   3. Determine the temporal influence of hormones on the low-load viscoelastic properties of the ACL in static and dynamic conditions.
   4. Include specialists in physiology, endocrinology, and reproductive medicine to characterize the menstrual cycle and the hormonal influences on the biomechanical properties of the ACL.
   5. Design multicenter studies that evaluate the relationship between sex hormone concentrations, phase of menstrual cycle, and knee ligament injury patterns as they relate to specific sports.
   6. Examine the influence of sex hormones on the ligament and activated mechanisms of collagen remodeling in ACL tissue.

REFERENCES

1. Deie M, Sakamaki Y, Sumen Y, Urabe Y, Ikuta Y. Anterior knee laxity in young women varies with their menstrual cycle. *Intl Orthop.* 2002;26(3):154-56.
2. Otto D, Raso J, Bagnall K, Amirfazli A, Thorton G. Variation in the mechanical behavior of rat ACL during the estrous cycle. Proceedings of the ACL Research Retreat II: The Gender Bias. *J Orthop Sports Phys Ther.* 2003;33(8):A26.
3. Pollard C, Braun B, Hamill J. Influences of gender and exercise on ACL laxity. Proceedings of the ACL Research Retreat II: The Gender Bias. *J Orthop Sports Phys Ther.* 2003;33(8):A27.
4. Romani WA, Patrie J, Curl LA, Flaws JA. The correlations between estradiol, estrone, estriol, progesterone, and sex hormone binding globulin and anterior cruciate ligament stiffness in healthy, active females. *J Womens Health Gend Based Med.* 2003;12(3):287-298.
5. Slauterbeck J, Clevenger C, Lundberg W, Burchfield D. Estrogen level alters the failure load of the rabbit anterior cruciate ligament. *J Orthop Res.* 1999;17:405-408.
6. Slauterbeck J, Fuzie S, Smith M, et al. The menstrual cycle, sex hormones and anterior cruciate ligament injury. *J Athl Train.* 2002;37(3):275-278.
7. Wojtys E, Huston L, Boynton M, Spindler K, Lindenfeld T. The effect of menstrual cycle on anterior cruciate ligament injuries in women as determined by hormonal levels. *Am J Sports Med.* 2002;30(2):182-188.
8. Yack HJ, Chandran R, Rao S, Wilken J. How normal fluctuations in women influence the biomechanics of stepping and cutting. Proceedings of the ACL Research Retreat II: The Gender Bias. *J Orthop Sports Phys Ther.* 2003;33(8):A28.

V. Interventions

A. What We Know
   1. Therapeutic exercise has been shown to significantly reduce ACL and lower extremity injury rates.[1,3,4,8,13]
   2. Biomechanical analyses have shown that body movement patterns can be modified, and ground reaction forces reduced through an intervention program.[2,5,6,7,10,14]
   3. Perturbation training resulted in neuromuscular adaptations, but strength training did not.[6,7]
   4. A plyometric training protocol resulted in increased quadriceps strength, but no changes in hamstring or hip abductor strength were noted.[6,7]
   5. Education interventions may affect injury rate, as demonstrated in the alpine skiing literature.[11,12]
   6. Feedback has provided a successful reinforcement of movement strategies.[9] Subjects respond better to instructions of body position rather than muscle activations.[2]

B. What We Don't Know
   1. What biomechanical patterns place a person at risk for ACL injury?
   2. What are the ideal movement strategies? Are these strategies different for males and females?
   3. Why have the intervention programs worked? Is success due to better movement patterns or improved neuromuscular characteristics, such as improved joint stiffness or the ability to react to a perturbation? Is the mechanism of success related to the mechanism of injury?
   4. How long does it take to alter programming? How long is the carryover after completion of an intervention program? If it is a preseason program, how much carryover does the athlete have into the season?
   5. Do these interventions need to be different based on age and maturation levels?

C. Where Do We Go From Here?
   1. Determine the risk factors for ACL injury.
   2. Focus intervention programs on these risk factors.
   3. Determine the common denominator of success within the current intervention programs.
   4. Determine the optimal approach for intervention exercises and for the timing of the intervention with respect to the competitive season.
   5. Design well defined prospective, randomized,

double-blind studies with stratification by activity level, sport, playing surface, coaching, etc.
6. Examine whether the biomechanical changes elicited by the intervention programs carry over onto game fields and courts.
7. Investigate the utility of external interventions (such as braces, playing surfaces, etc).

REFERENCES

1. Caraffa A, Cerulli G, Projetti M, Aisa G, Rizzo A. Prevention of anterior cruciate ligament injuries in soccer: a prospective controlled study of proprioception training. *Knee Surg Sports Traumatol Arthrosc.* 1996;4:19-21.
2. Cowling EJ, Steele JR, McNair PJ. Can lower limb muscles be retrained during landing as a means of anterior cruciate ligament injury prevention? Proceedings of the ACL Research Retreat II: The Gender Bias. *J Orthop Sports Phys Ther.* 2003;33(8):A29.
3. Heidt RS Jr, Sweeterman LM, Carlonas RL, Traub JA, Tekulve FX. Avoidance of soccer injuries with preseason conditioning. *Am J Sports Med.* 2000;28(5):659-662.
4. 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.
5. Hewett TE, Stroupe AL, Nance TA, Noyes FR. Plyometric training in female athletes: decreased impact forces and increased hamstring torques. *Am J Sports Med.* 1996;24(6):765-773.
6. Lephart SM, Ferris CM, Sell T, Abt J, Irrgang JJ, Fu F. Neuromuscular and biomechanical adaptations to an intervention program for the prevention of female ACL injuries. *Proceedings of the Orthopaedic Research Society Meeting.* New Orleans, LA: Orthopaedic Research Society; 2003.
7. McCrory JL, Lephart SM, Ferris CM, et al. Adaptations to an intervention program for the prevention of female ACL injuries. Proceedings of the ACL Research Retreat II: The Gender Bias. *J Orthop Sports Phys Ther.* 2003;33(8):A29.
8. Myklebust G, Engebretsen L, Braekken IH, Skjolberg A, Olsen O-E, Barh R. Prevention of anterior cruciate ligament injuries in female team handball players: a prospective intervention study over three seasons. *Clin Sport Med.* 2003;13:71-78.
9. Onate JA, Guskiewicz KM, Sullivan RJ. Augmented feedback reduces jump landing forces. *J Orthop Sports Phys Ther.* 2000;31(9):511-517.
10. Prapavessis H, McNair PJ, Anderson K, Hohepa M. Decreasing landing forces in children: the effect of instructions. *J Orthop Sports Phys Ther.* 2003;33:204-207.
11. Ryder SH, Johnson RJ, Beynnon BD, Ettlinger CF. Prevention of ACL injuries. *J Sport Rehab.* 1997;6:80-96.
12. Skolnick AA. Experts try education to preserve skiers' knees. *JAMA.* 1996;275(7):506-507.
13. Soderman K, Werner S, Pietila T, Engstrom B, Alfredson H. Balance board training: prevention of traumatic injuries of the lower extremities in female soccer players? A prospective randomized intervention study. *Knee Surg Sports Traumatol Arthrosc.* 2000;8(6):356-363.
14. Wojtys EM, Huston LJ, Aston-Miller JA. Changes in lower extremity joint kinematics after completing a jump-training program. *Proceedings of the American Orthopaedic Society for Sports Medicine.* Orlando, FL: American Orthopaedic Society for Sports Medicine; 2002.

ACL Supplement Section: List of Keynotes and Abstracts

ACL Injuries—The Gender Bias

April 4-5, 2003
Lexington, KY

Keynote Address I
Risk Factors for Knee Ligament Trauma
Bruce D. Beynnon, PhD
Burlington, VT

Keynote Address II
Biomechanics of the Anterior Cruciate Ligament
Braden C. Fleming, PhD
Burlington, VT

I. Structural Factors

Characteristics of ACL Injuries: Preliminary Findings
Bonnie L. Van Lunen, PhD, ATC
Old Dominion University
Richmond, VA

Q Angles and Tibiofemoral Angles in Physically Active and Inactive Females
Lori A. Livingston, PhD
School of Health and Human Performance, Dalhousie University
Halifax, Nova Scotia, Canada

Differences in Peak Knee Valgus Angles Between Individuals With High and Low Q Angles During a Single Limb Squat
Kathleen J. Pantano, PT, PhD
Biomechanics Laboratory/Sports Medicine Institute, University at Buffalo
Buffalo, NY

Noncontact ACL Injuries: Impingement Versus Direct Stretch
Li-Qun Zhang, PhD
Rehabilitation Institute of Chicago and the Departments of Physical Medicine & Rehabilitation and Orthopaedic Surgery, Northwestern University
Chicago, IL

Mathematical Modeling of ACL Impingement Against the Intercondylar Notch Wall
David Fung, MS
Sensory-Motor Performance Program, Rehabilitation Institute of Chicago, Department of Biomedical Engineering, Northwestern University
Chicago, IL

II. Neuromuscular Factors

Knee Joint Laxity Affects Muscle Activation Patterns at the Knee Prior to and Following a Weight-Bearing Perturbation
Sandra J. Schultz, PhD, ATC
University of North Carolina at Greensboro
Greensboro, NC

Gender Differences in Hip and Knee Kinematics and Muscle Preactivation During Single Leg Landings
Randy J. Schmitz, PhD, ATC
Applied Neuromechanics Research Laboratory, University of North Carolina at Greensboro
Greensboro, NC

Is Lower Limb Muscle Synchrony During Landing Affected by Gender? Implications for Variations in ACL Injury Rates
Elizabeth J. Cowling, PhD
Biomechanics Research Laboratory, University of Wollongong
New South Wales, Australia

III. Biomechanical Factors

A Model-Based Image-Matching Technique for 3-Dimensional Motion Reconstruction from Uncalibrated Video Sequences—Application to ACL Injury Situations
Tron Krosshaug, MSc, PhD Candidate
Oslo Sports Trauma Research Center
Oslo, Norway

Foot Landing Strategies Affect Knee Biomechanics During Sidestep Cut Tasks
Jeff R. Houck, PT, PhD
Ithaca College
Rochester, NY

Effects of Neuromuscular Control on Knee Joint Loading During Sidestepping: Implications for Noncontact ACL Injury
Scott G. McLean, PhD
Department of Biomedical Engineering, The Cleveland Clinic Foundation
Cleveland, OH

The Mechanical Consequences of Gender Differences in Single Limb Alignment During Landing
Ajit M. Chaudhari, PhD
Stanford Biomotion Laboratory, Stanford University
Stanford, CA

IV. Hormonal Factors

Fluctuations in Estradiol and Progesterone Are Related to Changes in ACL Stiffness in Healthy, Active Females
William A. Romani, PT, PhD, ATC, SCS
University of Maryland School of Medicine
Baltimore, MD

Variation in the Mechanical Behavior of Rat ACL During the Estrous Cycle
V. James Raso, MASc
Glenrose Rehabilitation
Edmonton, Canada

Influences of Gender and Exercise on ACL Laxity
Christine D. Pollard, PhD Candidate
Biomechanics Laboratory, University of Massachusetts
Amherst, MA

How Normal Hormonal Fluctuations in Women Influence the Biomechanics of Stepping and Cutting
H. John Yack, PT, PhD
Orthopaedic Gait Analysis Laboratory, Graduate Program in Physical Therapy and Rehabilitation Science, The University of Iowa
Iowa City, IA

V. Interventions

Can Lower Limb Muscles be Retrained During Landing as a Means of ACL Injury Prevention?
Elizabeth J. Cowling, PhD
Biomechanics Research Laboratory, University of Wollongong
New South Wales, Australia

Adaptations to an Intervention Program for the Prevention of Female ACL Injuries
Jean L. McCrory, PhD
Neuromuscular Research Laboratory, Department of Sports Medicine and Nutrition, University of Pittsburgh
Pittsburgh, PA

Prevention of ACL Injuries in Female Team Handball Players—A Prospective Intervention Study Over 3 Seasons
Grethe Myklebust, PT, Specialist in Sports Physiotherapy, PhD Candidate
Oslo Sports Trauma Research Center
Oslo, Norway

KEYNOTE ADDRESS I

Risk Factors for Knee Ligament Trauma

Bruce D. Beynnon, PhD[1]

INTRODUCTION

The anterior cruciate ligament (ACL) is the most frequently totally disrupted ligament in the knee, and although this injury is relatively uncommon in the general population, it occurs frequently in athletics, particularly among female athletes.[1,2] Many studies have focused on the prevalence of ACL injuries associated with high-risk sports; however, only a limited number have calculated incidence rates based on time-at-risk and compared males and females competing in similar activities. These studies indicate that the rates of ACL tears for female athletes range from 2.4 to 9.7 times higher than these of male athletes.[1,3,4,5,6] Our research at the University of Vermont has focused on competitive alpine ski racing, a sport that imparts tremendous forces on the knee, and has revealed that 1 in 5 female alpine racers suffer an ACL disruption. These female athletes were 3.1 times more likely to sustain an ACL injury in comparison to their male counterparts.[7] Even more disturbing was the finding that 27% of the women who underwent reconstruction suffered reinjury to the graft and underwent a second reconstruction procedure—a rate twice that seen for the men.[7]

Our recent review of the literature[9] revealed 4 prospective studies of ACL injury risk factors,[10,11,12,13] 2 of which only focused on male athletes.[10,12] In a study of high school athletes, Souryal and Freeman reported that athletes with a small intercondylar notch width index (the ratio of the width of the anterior outlet of the intercondylar femoral notch divided by the total condylar width at the level of the popliteal groove) were at significantly increased risk for sustaining an ACL injury.[13] LaPrade and Burnett studied collegiate athletes and reported similar findings.[11] In a study of American football, Lambson et al found that athletes with a greater number of cleats, and an associated higher torsional resistance at the foot-turf interface, were at increased risk for suffering an ACL tear.[10] Orchard and colleagues studied athletes participating in Australian football and found that a history of ACL reconstruction and weather conditions that were characterized by high evaporation and low rainfall before matches were risk factors for repeated ACL injury.[12] Currently, there is very little information regarding the risk factors for ACL injury that have been derived from well-designed prospective studies, and only 2 studies have included females (the group that appears to be at increased risk for this injury) and no study has investigated multiple factors.

Recently, our group has focused on studying the risk factors for knee and ankle ligament trauma among precollegiate and collegiate athletes, and 2 recent investigations will be highlighted. The aim of the first investigation was to measure serum levels of estradiol and progesterone, and knee and ankle joint laxity (indirect measures of the biomechanical behavior of ligaments) during the menstrual cycle. The corresponding hypothesis was that knee and ankle joint laxity values increase during the menstrual cycle as serum concentrations of estradiol and progesterone become elevated. The aim of the second study was to examine potential knee injury risk factors among competitive alpine skiers. This was used to test the hypotheses that one or a combination of risk factors can be used to identify an athlete at risk for anterior cruciate ligament trauma.

METHODS

The effect of Serum Estradiol and Progesterone Levels on Knee and Ankle Joint Laxity

Female and male (control) athletes were approached and informed consent was obtained. There

---

[1] *McClure Musculoskeletal Research Center, Department of Orthopaedics and Rehabilitation, College of Medicine, University of Vermont, Burlington, VT.*

were 10 women with normal menstrual cycles (mean age, 20.7; range, 18-23) and 5 males (mean age, 21; range, 19-23). Knee and ankle laxity and blood concentrations of estradiol and progesterone were measured for females at 4 consecutive visits throughout the menstrual cycle, and for males at equivalent time intervals. For the females with a 28-day cycle length, the visits were as follows: visit 1 (early follicular phase, days 1-3), visit 2 (late follicular phase, days 11-13), visit 3 (mid-luteal phase, days 20-22) and visit 4 (late luteal phase, days 27-28). Subjects with different cycle lengths were evaluated at proportional time intervals. Baseline concentrations of estradiol and progesterone were obtained among the women during the early follicular phase of the following cycle (visit 5) to validate that a normal cycle was completed. Serum concentrations of estradiol and progesterone were determined using radioimmunoassay.

Knee and ankle joint laxity were measured at each visit. Knee laxity was measured with the KT-1000 Knee Arthrometer (MedMetrics Corp., San Diego, CA). Anterior-posterior (A-P) laxity was defined as the total A-P translation between the shear loads of –90 N (posterior) and 130 N (anterior). Ankle laxity was measured with the anterior drawer and talar tilt tests by standard stress radiography. The Telos device (Telos Corp., Greisheim, Germany) was used to apply 150-N forces to the ankle joint. All radiographs were obtained by the same individual and numbered to blind the measurement procedure. At each visit, anterior drawer (neutral and anterior load) and talar tilt views (inversion and eversion loads) were obtained.

A paired *t* test for means was used to compare joint laxity values between visit 1 (the early follicular phase when estradiol is low) and visit 2; (the late follicular phase when estradiol is high). Similarly, a paired *t* test for means was used to compare laxity values between visit 1 (early follicular phase when progesterone is low) and visit 3 (the mid luteal phase when progesterone is high). The *P* value was adjusted for multiple comparisons.

A Prospective Study of Knee Injury Risk Factors in Competitive Alpine Ski Racers

Data were collected over 3 ski seasons (1995, 1996, and 1997). Athletes were recruited from 6 competitive alpine ski programs located throughout the northeastern United States. The athletes ranged in age from 13 to 22 years. Prior to the start of each ski season, intrinsic and extrinsic risk factor data were collected. The intrinsic factors included demographic information, generalized joint laxity, flexibility of the hamstrings, quadriceps and heel cord, anatomical alignment of the knee, laxity of the knee, and isokinetic thigh muscle strength. Each athlete was followed throughout the ski season, exposure (the number of days skied) data were documented daily, and injury information were recorded. The sample size was 224 subjects. For all analyses, data from 1 leg were used, the injured leg for subjects who sustained knee trauma, and a randomly selected leg for those who were not injured.

RESULTS

The Effect of Serum Estradiol and Progesterone Levels on Knee and Ankle Joint Laxity

Anterior-posterior knee laxity did not change for the females between visits 1 and 2 ($P = .45$) and did not change between visits 1 and 3 ($P = .27$) (Figure 1). Likewise, there were no changes for the males.

Ankle laxity, as measured by the anterior drawer test, did not change for the females between visits 1 and 2 ($P = .48$) and did not change between visits 1 and 3 ($P = .41$) (Figure 2). Similarly, the anterior drawer did not change for males. Ankle laxity, as

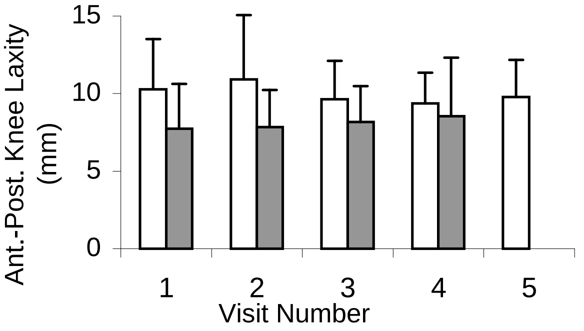


Figure 1. Mean laxity values for the left knee measured with the KT-1000 (males in gray and females in white).

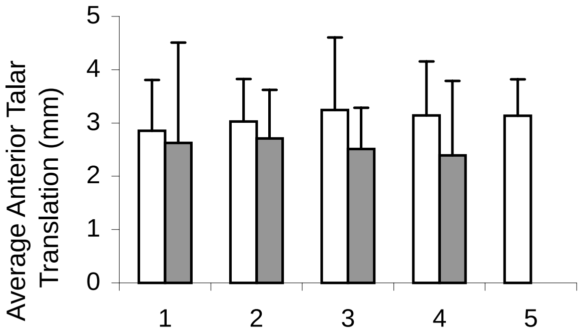


Figure 2. Mean anterior talar translation for the right ankle (males in gray and females in white).

measured by total talar tilt, for females did not change between visits 1 and 2 ($P = .31$) and did not change between visits 1 and 3 ($P = .31$). As well, there were no changes in talar tilt for males.

A Prospective Study of Knee Injury Risk Factors in Competitive Alpine Ski Racers

ACL injuries (16 total) occurred at a rate of 0.78 per 1000 skier days, which translates into 1 ACL tear for every 1275 skier days. Nine out of 87 (10.3%) females and 7 out of 137 (5.1%) males suffered complete ACL disruptions. The difference in time to injury between males and females was significant, with females 2 times more likely to be injured earlier in comparison to their male counterparts. Athletes with increased hyperextension of the knee were found to be significantly more likely to be injured. Skiers were more likely to be injured if they had a longer measurement from the medial malleolus to the anterior superior iliac spine, while also having a shorter measurement from the medial malleolus to the medial joint line.

DISCUSSION

The Effect of Serum Estradiol and Progesterone Levels on Knee and Ankle Joint Laxity

Our investigation confirmed previous reports that knee and ankle laxity values are greater among females compared to males; however, our investigation does not support the previous research that has documented a positive correlation between knee laxity and serum levels of estradiol.[14,15] The concentrations of serum estradiol may not be high enough in our sample of subjects to produce the fluctuations in knee laxity seen in other reports. The mean concentrations of estradiol during follicular phase in our group of athletes was 171.4 pg/ml, compared to 778 pg/ml in the work by Heitz.[14] These differences may help explain why our findings are different.

A Prospective Study of Knee Injury Risk Factors in Competitive Alpine Ski Racers

Our finding that leg length is a risk factor for ACL injury in alpine ski racers suggest that both anatomic and biomechanical factors may predispose alpine ski racers to ACL trauma. The anatomic condition where the thigh is of greater length is meaningful when one considers that the most powerful muscles in the body (the quadriceps and hamstrings) span the longest lever arm in the body (the thigh). Contraction of these muscles produces substantial forces that the articular structures and ligaments must resist. During activity, an increased length of the thigh would act to increase the shear forces transmitted across the knee, thereby exposing the ACL to higher strain magnitudes. This is important when considered in combination with our earlier studies that have documented substantial increases in ACL strain values when the knee is moved into extension by contraction of the dominant quadriceps muscles.[16] This study is intriguing because it suggests that increased hyperextension of the knee and increased thigh length may be some of the risk factors associated with ACL injury among alpine skiers.

CONCLUSIONS

While many have attempted to retrospectively identify potential factors for ACL injury, with specific focus on explaining the higher rate of ACL injuries among female athletes, researchers have failed to demonstrate conclusively the relationship of any one variable to ACL injury risk. Review of the literature leaves one with the impression that gender differences in neuromuscular, biomechanical, anatomical, and hormonal function are the most compelling factors to explain the increased ACL injury rates among females. However, while many studies have identified gender differences in neuromuscular and biomechanical function, they fail to relate these differences to injury risk. Further, the extent to which anatomical and hormonal factors may explain the gender differences noted in neuromuscular and biomechanical function or dependently contribute to ACL injury risk remains unknown. It may be that multiple risk factors act in combination to increase an athlete's risk of suffering knee ligament trauma. This certainly appears to be the case for ankle ligament trauma.[17] At this point in time, our group is conducting a large-scale risk factor study of ankle and knee ligament injuries in precollegiate and collegiate athletes who participate in different sports, and an update on this work will be presented.

REFERENCES

1. Arendt E, Dick R. *Am J Sports Med.* 1995;23:694-701.
2. Arendt EA, Agel J et al. *J Athl Train.* 1999;34(2):86-92.
3. Lindenfeld TN, Schmitt DJ, Hendy MP, Mangine RE, Noyes FR. *Am J Sports Med.* 1994;22:364-371.
4. Myklebust G, Maehlum S, Holm I, Bahr R. *Scan J Med Sci Sports.* 1998;8:149-153.
5. Messina DF, Farney WC, DeLee JC. *Am J Sports Med.* 1999;27(3):294-299.
6. Gwinn DE, Wilkens JH, McDevitt ER, Ross G, Kao T-C. *Am J Sports Med.* 2000;28(1):98-102.

7. Stevenson H, Webster J, Johnson RJ, Beynnon BD. *Iowa Ortho J.* 1998;18:64-66.
8. Daniel DM, Stone ML, Dobson BE, et al. *Am J Sports Med.* 1994;22(5), 632-644.
9. Murphy DF, Connolly DAJ, Beynnon BD. *British J Sports Med.* 2003;37:13-29.
10. Lambson RB, Barnhill BS, Higgins RW. *Am J Sport Med.* 1996;24(2):155-159.
11. LaPrade RF, Burnett QM. *Am J Sports Med.* 1994;22(2):198-203.
12. Orchard J, Seward H, McGivern J, Hood S. *Am J Sports Med.* 2001;29(2):196-200.
13. Souryal TO, Freeman TR. *Am J Sports Med.* 1993;21(4), 535-539.
14. Heitz NA. *J Athl Train.* 1999;343(2):144-149.
15. Deie M, Sakamaki Y, Sumen Y, Urabe Y, Ikuta Y. *Intl Orthop.* 2002;26(3)154-156.
16. Beynnon BD, Fleming BC. *J Biomech.* 1998;31:519-525.
17. Beynnon BD, Renstrom PA, Alosa DM, et al. *J Orthop Res.* 2001;19(2):213-220.

KEYNOTE ADDRESS II

Biomechanics of the Anterior Cruciate Ligament

Braden C. Fleming, PhD[1]

INTRODUCTION

Many factors have been associated with the destruction of knee joint articular cartilage; however, only trauma such as that associated with disruption of the anterior cruciate ligament (ACL) has been shown to initiate osteoarthritis (OA). The optimal treatment of an ACL injury remains an enigma, and there is evidence indicating that the current treatment options (ie, ACL reconstruction) will not slow the progression of OA that occurs following injury. Thus, there is a need to understand how we can prevent these injuries. ACL research has typically focused on the treatment and diagnosis of these injuries but not on prevention. To understand how to prevent ACL injuries it is necessary to understand the biomechanics of the ACL. We can then utilize this information to understand better how the ACL can be injured and how the injuries can be prevented. The goal of this presentation is to provide baseline information about the biomechanical function of the ACL.

METHODS

Over the last decade, we have developed a technique to measure ACL strain in human subjects.[1] Study participants have been volunteers with normal ACLs who were undergoing diagnostic arthroscopy under local anesthesia, permitting all subjects to retain full control of their muscles. After the routine surgical procedure was complete, a differential variable reluctance transducer (DVRT) was implanted on the ACL to measure its displacement response under various controlled loadings. These displacement data were used to determine the strain response of the ligament using the engineering strain formulation. The focus of this lecture is to review the studies evaluating the ACL strain response under various loading conditions: external loading with no muscle activation,[1,4] muscle loading (ie, quadriceps, hamstrings, and gastrocnemius),[1,5] weight bearing,[4] and rehabilitation exercises.[1]

RESULTS

ACL strain was measured during various passive loading conditions: passive flexion-extension motion

---

[1] *McClure Musculoskeletal Research Center, Department of Orthopaedics and Rehabilitation, College of Medicine, University of Vermont, Burlington, VT.*

of the knee (PFE), and under anterior-posterior-directed shear loads, internal-external torques, and varus-valgus moments applied externally to the tibia relative to the femur.[1,4] It has been argued that the ACL is a restraint to all of these loading conditions. Our findings suggest that the ACL remains unstrained during PFE as the knee is extended from 90° to 10° (thigh horizontal). This result was expected because the gravity vector contains a posteriorly directed component throughout most of this range of knee motion. PFE from 10° to full extension strained the ACL. Anterior-directed shear loads produced strain values that were greater when the knee was at 30° as compared to 90°. These data verify that the ACL is a primary restraint to anterior tibial translation and explain the increased sensitivity of the Lachman test compared to the drawer test in detecting ACL injuries. We also determined that significant ACL strains were produced with the application of internal torques. However, the ACL was not strained with the application of external torques, varus or valgus moments up to 10 Nm.

The muscles spanning the knee apply forces and moments to the knee. As the knee joint position is changed, the moment arms of the different muscles and joint contact position change. Thus, joint position and the magnitude of muscle contraction affect ACL strain biomechanics. For isometric quadriceps contractions, ACL strain values were dependent on the knee flexion angle.[1] At 30 Nm of extension torque, ACL strain values produced at 15° of knee flexion were significantly greater than those produced at 30°, while no strain was produced at 60° and 90°. For isometric hamstrings contractions, the ACL strain values were not dependent on knee flexion angle. Hamstrings contractions did not strain the ACL at any knee angle tested. The ACL strain values produced by simultaneous maximum contraction of the quadriceps and hamstrings muscles were also dependent on the knee flexion angle. The strain values produced at 15° and 30° were less than those produced during isolated isometric quadriceps contractions but greater than those produced during isolated isometric hamstrings contractions. The influence of the gastrocnemius is controversial. Because the proximal tendon of the gastrocnemius wraps around the posterior aspect of the tibial plateau, contraction of the muscle could potentially strain the ACL by pushing the tibia anterior when the knee is near extension. We found that both knee flexion angle and gastrocnemius force affected ACL strains.[5] With the knee at 5° and 15° of flexion, contraction of the gastrocnemius increased ACL strain relative to the relaxed state. At the higher knee flexion angles (30° and 45°), the ACL was not strained.

Application of body weight requires the activation of the leg musculature to maintain equilibrium. Previous investigations reported that weight bearing provides a protective mechanism to the ACL, or ACL graft, because the articulating condyles are forced together and muscle cocontraction is utilized to increase contact resistance and joint stiffness.[2,8] However, we found a significant increase in ACL strain with the application of the compressive load produced by body weight as compared to the nonweighted condition with the knee at 20° of flexion.[4] These findings suggest that the quadriceps muscles are dominant in maintaining equilibrium.

We have also evaluated ACL strains during commonly prescribed rehabilitation activities.[1] These exercises included quadriceps-dominated and hamstrings-dominated activities and those that involve cocontraction of these muscle groups. Exercises that produced low strain values were those that were dominated by the hamstrings muscle group, incorporated contraction of the quadriceps muscles with the knee flexed at 50° or more, or involved simultaneous quadriceps and hamstrings contraction. Quadriceps dominated activities with the knee between 50° and full extension produced higher strains. Furthermore, we recently determined that the maximum ACL strain values produced during squatting, a closed-kinetic-chain exercise thought to be protective of the ACL, were similar to those produced during active extension of the knee, an open-kinetic-chain exercise. The similarity of the strain responses during these 2 common rehabilitation exercises calls into question whether we should consider exercises to be either safe, or unsafe, based on the commonly used closed- and open-kinetic-chain terminology.

DISCUSSION

Seventy percent of ACL injuries are noncontact and the mechanisms remain unknown. The injuries typically occur when a subject is decelerating, pivoting, landing or responding to a perturbation. Thus, they occur in response to different combinations of loads that are both internally and externally applied. Considering that the knee is located between the 2 longest lever arms of the body, it is not surprising that ACL injuries are common and that small perturbations could produce high loads at the knee, hence the ACL. Obviously it is not appropriate to use the in vivo measurement technique to directly assess injury mechanisms due to patient safety issues. However, it allows us to evaluate the strain response due to subfailure loadings that can possibly be extrapolated. The strain measurement technique could then be used to determine if these injuries can be prevented using specific techniques (ie, bracing, training). Future work will be directed at looking at subfailure combinations of loads and the response of the ACL to perturbations.

CONCLUSIONS

The ACL is a primary restraint to anterior shear rotation and internal rotation of the tibia with respect to the femur. In our studies, external rotation and varus-valgus angulation did not strain the ACL. However, there are cadaver studies which suggest that the ACL is loaded when combinations of these loads are applied.[6,7] Contraction of the quads and gastrocnemius strained the ACL at low knee flexion angles, while contraction of the hamstrings reduced ACL strains. Application of a compressive load across the knee joint strained the ACL. Finally, strains up to 4% were seen during exercises that simulate activities of daily living. These strain values are considerably less than the failure strain of the ACL and within the toe region of the stress-strain curve for the ligament.[3]

ACKNOWLEDGEMENTS

The National Institutes of Health (AR39213; AR40174) and the National Football League Charities supported this work. This work was performed in collaboration with Drs. Bruce Beynnon, Robert Johnson, Per Renstrom, Joseph Abate, Claude Nichols, and Glenn Peura.

REFERENCES

1. Beynnon BD. *J Biomech.* 1998;31:591.
2. Beynnon BD. *J Orthop Res.* 2002;20:332.
3. Butler. *J Biomech.* 1992;25:511.
4. Fleming BC. *J Biomech.* 2001;34:163.
5. Fleming BC. *J Orthop Res.* 2001;19:1178.
6. Kanamori. *Arthroscopy*
7. Markolf. *J Orthop Res.* 1995;13:930.
8. Torzilli. *Am J Sports Med.* 1994;22:105.

ACL Injuries—The Gender Bias: Abstracts

I. STRUCTURAL FACTORS

CHARACTERISTICS OF ANTERIOR CRUCIATE LIGAMENT INJURIES: PRELIMINARY FINDINGS

Van Lunen BL,[1] Perrin DH,[2] Arnold BL,[3] Gieck JH,[4] Saliba EN,[4] Gansneder BM,[4] McCue FC[4]

[1]Old Dominion University; [2]University of North Carolina at Greensboro; [3]Virginia Commonwealth University; [4]University of Virginia.

INTRODUCTION

The purpose of this study was to compare several anatomical reference points and knee laxity assessments for anterior cruciate ligament (ACL) injured males and females. Secondly, this study examined the anatomical and laxity differences between those injured through a noncontact or contact mechanism. Lastly, this study examined the intratester reliability of several of the measures.

METHODS

Thirty subjects with disruption of the ACL who gave informed consent (10 females, 20 males; age, 25.53 ± 9.54 years; height, 176.50 ± 9.39 cm; mass, 83.81 ± 20.70 kg) participated in this study. Subjects were classified as being injured due to contact or noncontact. Tunnel view radiographs of both knees were taken and the notch dimensions of popliteal notch width index and half-height notch width index were determined. The subjects were measured for quadriceps angle, navicular drop, sagittal knee extension, tibial fibular varum, tibiofemoral angle, and KT1000 measures at 15 and 30 pounds of force. If applicable, the subjects were asked to place their feet on a premade foot template. All measures were taken bilaterally. Separate 1-way analyses of variance were performed on each dependent measure. Intraclass correlation coefficients ($ICC_{2,1}$) were used to determine intratester reliability.

RESULTS

Results indicated that quadriceps angle was significantly greater for the males injured through a contact mechanism ($F_{2,29} = 3.987$, $P = .031$) than the males injured by noncontact. The injured popliteal notch width index was significantly greater for the contact males ($F_{2,27} = 6.123$, $P = .007$) than the noncontact males and females. The injured half-height notch width index was significantly greater for the contact males ($F_{2,27} = 3.98$, $P = .32$) than the noncontact males only. All other analyses of variance were not significantly different. Values for intratester reliability ranged from 0.57 to 0.94.

DISCUSSION

The values of popliteal notch width index support past research in classifying those individuals with a notch width index of less than 0.2000 as being susceptible to noncontact injuries. Further research should investigate the structural alignment characteristics in a dynamic mode and the relationship to ACL injury.

CONCLUSIONS

Many of the dependent variables examined may not differ between males and females who are injured through contact or noncontact mechanisms.

Q ANGLES AND TIBIOFEMORAL ANGLES IN PHYSICALLY ACTIVE AND INACTIVE FEMALES

LeBlanc SE,[1] Livingston LA,[1] Mahar SM[1]

[1]School of Health and Human Performance, Dalhousie University, Halifax, Nova Scotia, Canada.

INTRODUCTION

Frontal plane quadriceps (Q) angles and tibiofemoral (TF) angles are often viewed as synonymous measures.[1,2] Both have been implicated as anatomical risk factors for ACL ligament injury in females,[3,4] yet while similar in appearance, they differ in definition. The purpose of this study was to examine the relationship between the magnitudes of these angles in young adult females.

METHODS

Physically active (n = 19) and inactive (n = 18) females with a mean age of 19.9 ± 1.3 years and no previous history of lower limb injury participated in the study. The average height and mass of the sample were 168.3 ± 5.5 cm and 62.6 ± 7.0 kg, respectively. Markers were applied bilaterally to the ASIS, midpoint of the patella, and midpoint of the tibial tubercle to define the Q angle. In contrast, TF angles were defined by markers applied to the greater trochanter, midline of the thigh, midpoint of the tibial tubercle, and the midline of the anterior aspect of the shin. Digital photographic images were taken of participants with their feet in self-selected and Romberg (feet side-by-side) stances. Measures of right and left static Q angles and TF angles were then derived from the photos using a manual goniometer. Dependent t tests were used to examine within-subject differences in Q angles and valgus angles, while differences in the dependent variables by group, stance, and limb were analyzed using univariate repeated-measures ANOVA procedures. Measurement reliabilities ($ICC_{2,1}$)[5] were found to be excellent (ICC > 0.89).[6]

RESULTS

The observed means for Q angles and TF angles are found in Table 1. The dependent t tests showed no significant differences in the magnitudes of these 2 measures for individuals regardless of group membership, stance adopted, or limb. However, the range of values used to calculate the means did markedly differ. This led us to examine the data on an individual basis, an exercise that revealed no clear relationship between the magnitude of the Q angle and that of the TF angle. Within any given individual limb, differences between the 2 angles were as great as 18°, with differences of 10° or more observed in 25 (17%) of the 148 measurement trials. These large differences were more frequently observed for the active group. In addition, the Q angle was significantly greater in the right versus the left limb for the entire sample ($F_{1,35} = 12.35$, $P<.001$), and a small yet significant interaction effect ($F_{1,35} = 3.91$, $P<.05$) of stance by group was observed for the TF angle.

TABLE 1. Mean (SD) and range of Q and TF angles by group and stance.

	Angle	
Group/Stance	**Q**	**TF**
Active (n = 19)		
S-selected	10.0 (6.0), 1-24	11.3 (3.0), 6-18
Romberg	12.7 (6.0), 3-28	12.0 (3.0), 6-17
Inactive (n = 18)		
S-selected	11.9 (5.2), −2-22	12.7 (3.0), 8-19
Romberg	12.9 (5.9), −2-25	12.7 (2.9), 7-18

DISCUSSION

The finding of no statistically significant difference between the 2 measures within individuals should be approached with caution as our data provide a good example of how the act of pooling data may mask important findings. The observation of greater differences in magnitude between the Q and TF angles in the active group would be expected, given that increases in quadriceps strength are known to reduce Q angles.[7] In contrast, the significant reduction seen in the TF angle for the active group when changing from a Romberg to self-selected foot position is small and perhaps clinically insignificant.

CONCLUSIONS

The Q angle provides a reasonable estimate of the line of pull of the extensor mechanism,[8] while by contrast the TF angle describes the functional adequacy of the bony articulation between the femur and tibia.[9] Given the data presented herein, the 2 should not be seen as synonymous or directly related. Future study of these 2 measures, the imbalance between them, and their relationship to ACL injury seems warranted.

REFERENCES

1. Holloway M. *Scientific Am.* 2000;11(3):32–37.
2. Veenema KR. *Physician Sportsmed.* 1999;27(8):62.
3. Griffin L, et al. *J Am Acad Orthop Surg.* 2000;8:141-150.
4. Huston LJ, et al. *Clin Orthop Rel Res.* 2000;372:50-63.
5. Shrout, et al. *Psych Bull.* 1979;86:420-428.
6. Fleiss J. *Reliability of measurement.* New York: Wiley, 1986.
7. Byl N, et al. *J Sport Rehabil.* 2000;9:26-34.
8. Igbigbi PS, et al. *Clin Anat.* 2002;15:293-296.
9. Schulthies SS, et al. *Phys Ther.* 1995;75:24-30.

DIFFERENCES IN PEAK KNEE VALGUS ANGLES BETWEEN INDIVIDUALS WITH HIGH AND LOW Q ANGLES DURING A SINGLE LIMB SQUAT

Pantano KJ, White SC, Gilchrist LA, Leddy J

[1]Biomechanics Laboratory/Sports Medicine Institute, University at Buffalo, Buffalo, NY.

INTRODUCTION

Differences in anatomical alignment between genders, such as a greater quadriceps angle (Q angle), have been suggested as causes of the disparity in anterior cruciate ligament (ACL) injury rates. A larger Q angle may contribute to increased knee valgus during movement and increased stress on the ACL. This study investigated whether significant differences in peak knee valgus angles exist in healthy college-aged subjects with a large Q angle, compared to those with a small Q angle, while performing a single limb squatting motion. The relationship between Q angle and selected skeletal measures was also determined.

METHODS

Twenty subjects, categorized as having a ‘‘high Q angle’’ ($\geq$17°) or a ‘‘low Q angle’’ ($\leq$8°) were videotaped during the performance of a single leg squat. The peak valgus angles for the right knee were calculated. A *t* test was used to determine whether there were differences in peak knee valgus angles between the high and low Q angle groups ($P<.05$).

RESULTS

There were no significant differences in peak knee valgus angles exhibited for the high and low Q-angle groups during the single leg squat ($P = .17$). Q angle was not associated with pelvic width, tibiofemoral angle, or dynamic knee valgus, but was moderately correlated with the pelvic width/femoral length ratio ($r = 0.54$).

DISCUSSION

The degree of knee valgus exhibited during a single leg squat is not a function of Q angle and static measures may not be predictive of knee valgus during dynamic movement.

CONCLUSIONS

Further research into gender differences other than Q angle is needed to explore causes of increased knee valgus during limb loading tasks.

NONCONTACT ACL INJURIES: IMPINGEMENT VERSUS DIRECT STRETCH

Zhang L-Q, Fung D, Lin F, Makhsous M, Koh JL, Hendrix RW, Nuber GW

Rehabilitation Institute of Chicago and Northwestern University, Chicago, IL.

INTRODUCTION

Sudden deceleration, hyperextension, abrupt change in direction, fixed foot, and tibial rotation have been reported as key elements of noncontact ACL injuries.[1,3] However, although tibial internal and external rotations seem to increase and decrease ACL loading, respectively,[4,5] both excessive internal rotation and external rotation of the tibia seem to be associated with noncontact ACL injuries. We hypothesize that tibial external rotation (and abduction) causes ACL impingement against the lateral intercondylar notch wall (especially for knees with a narrow

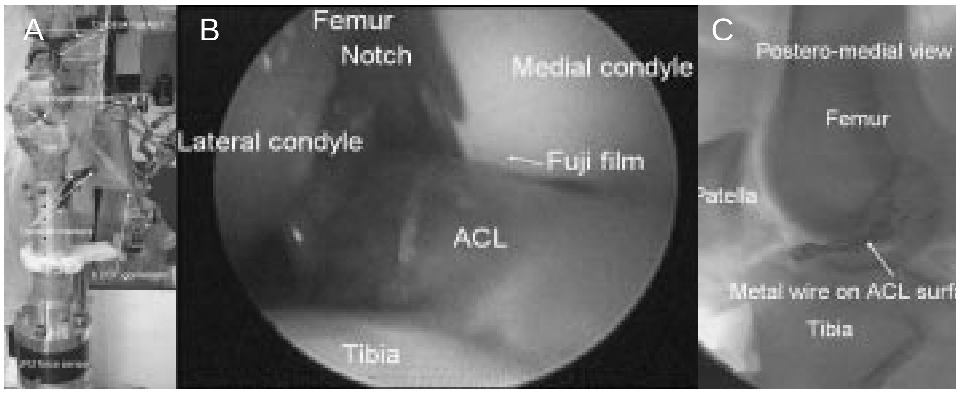


Figure 1. (Zhang et al.) Experiment setup for ACL impingement in a cadaver model: (A) A left female knee in tibial external rotation and abduction with a narrow notch width of 16.4 mm and NWI of 0.22. External load applied to the tibia was measured by a JR3 multi-axis force sensor. ACL impingement force was measured by a paper-thin FSR sensor. An FSR sensor (or Fuji film) was inserted at the potential impingement site to measure the impingement force (or pressure). (B) Arthroscopic image (anterolateral view) of ACL impingement in a right male knee. A piece of Fuji film was inserted at the potential impingement site (anterolateral edge of the medial condyle) to measure the impingement pressure (the medial condyle was partially blocked by the Fuji film in the image). (C) Fluoroscopic image (posteromedial view) of the right knee under extension, adduction, and internal rotation loads. Metal wire tied to the ACL was straightened during the impingement.

intercondylar notch and certain notch shape), which in turn may result in rupture of the ACL. For knees with a regular notch width, ACL may impinge the anterior-lateral edge of the medial condyle during tibial internal rotation and adduction near full knee extension. The purpose of the study was to investigate the different injury mechanisms by measuring impingement directly and using fluoroscopy and arthroscopy.

METHODS

ACL impingement was investigated using 8 cadaver knee specimens (4 female, 4 male). Two of the specimens were fresh frozen, the rest were embalmed. Through an arthroscope or with ACL and intercondylar notch exposed, ACL impingement was inspected during manual manipulation of the knee throughout the ROMs about multiple knee axes. Intercondylar notch width index (NWI) was measured directly from each of the knees.

For the embalmed specimens, the patella was removed. With the femur fixed to a bench, the tibia was moved passively under moderate externally applied loads measured by a multi-axis force sensor (JR3, Inc., Woodland, CA), while the impingement was directly observed through the exposed intercondylar notch and measured by force sensitive resistors (FSR, Tekscan, Inc., Boston, MA, or Fuji film, Fuji Photo Film USA, Inc., Carrollton, TX). Six-DOF knee kinematics were measured with a 6-DOF goniometer (Figure 1A).

For the fresh-frozen specimens, a small parapatellar incision was made on the specimen to expose the ACL and intercondylar notch. A paper-thin FSR sensor (or Fuji film) was inserted at the potential impingement site to record the impingement force (pressure). With the femur fixed to a bench, the knee was moved forcefully throughout its range of motion (ROM) in 3-dimensional space to evaluate possible ACL impingement. An arthroscope was used to inspect the inside of the knee for potential ACL impingement under various loads to the tibia (Figure 1B). A fluoroscope was also used to evaluate possible ACL impingement. Through bilateral parapatellar incisions, a flat copper wire (about 3 mm wide and 20 mm long) was tied to the anterior-superior surface of the ACL using metal surgical suture. After closing the incisions using regular surgical suture, the knee was inspected dynamically under fluoroscope while the knee was moved throughout its 3-dimensional ROMs (Figure 1C).

RESULTS

NWI (mean ± standard deviation) for the 4 male knees was 0.25 ± 0.02, for the 4 female knees, 0.19 ± 0.02, and across all the knees, 0.22 ± 0.04.

There were 2 patterns of ACL impingement among the knee specimens evaluated. First, for knees with a ''narrow'' intercondylar notch, ACL could impinge the lateral wall of the intercondylar notch during tibial external rotation and abduction in flexed knees (Figure 1A with narrow notch [NWI = 0.22]). It was observed that the ACL impinged against the anteromedial edge of the lateral condyle under moderate tibial external rotation and abduction torques in the knee (Figures 1A and 2A). As the knee was abducted, impingement occurred. When the tibia was externally rotated on top of the abduction, the impingement force increased considerably, reaching about 25N (Figure 2A). Similar impingement was observed at other knee flexion angles. Fuji film inserted showed considerable contact pressure (300 psi) at the impingement site during the manual manipulation.

Second, for knees with a regular notch width, the ACL did not impinge against the medial edge of the lateral condyle during various tibiofemoral movements. However, when the knee was at near full extension, the ACL impinged the anterolateral edge of the medial condyle under tibial internal rotation and loads (Figures 1B and 1C and Figure 2B). Fluoroscopy showed that the copper wire attached to the ACL was straightened as the knee was extended to full extension, adducted, and internally rotated (Figure 1C), indicating ACL impingement at the knee positions. Arthroscopic images showed similar impingement (Figure 1B).

DISCUSSION

In addition to being overloaded directly by excessive tibial anterior translation, hyperextension, and/or internal rotation, the ACL can be injured by impingement with the intercondylar notch in noncontact ACL injuries. Different mechanisms may be involved in ACL impingement against the intercondylar notch, depending on the specific 3-dimensional shape of the notch. Notch width may not be enough to analyze impingement, and 3-dimensional characterization of the notch and ACL is needed. Further work on a larger sample is needed to reach more reliable results.

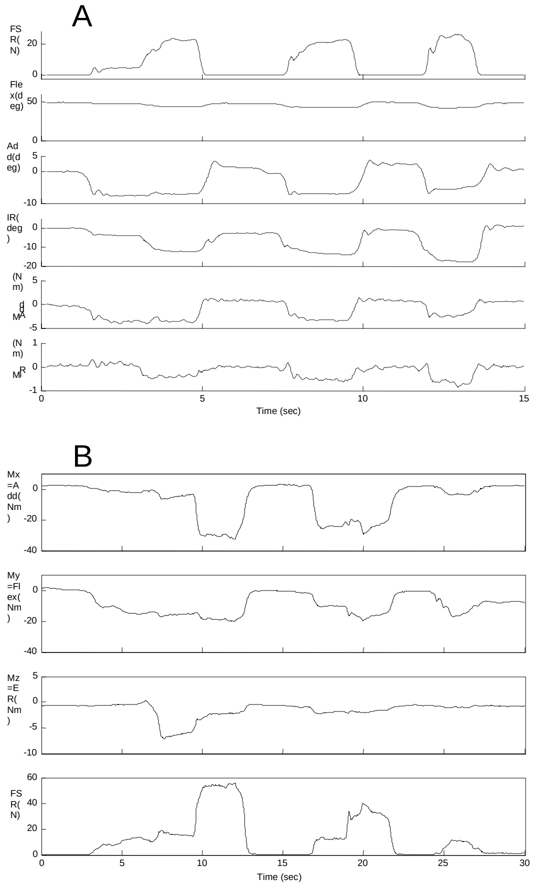


Figure 2. From top to bottom, the 6 subplots correspond to the ACL impingement force against the medial edge of the lateral condyle for knee flexion, adduction, internal rotation, and (externally applied) adduction torque and internal rotation torque in a knee with a ''narrow'' notch (A). ACL impingement against the anterolateral edge of the medial condyle during tibial adduction, extension, and internal rotation of the right knee with a ''regular'' notch width (B).

REFERENCES

1. Feagin JA, Lambert KL. *Orthop Clin N Am,* 1985;16:41-45.
2. Boden BP, et al. *Orthopedics,* 2000;23:573-578.
3. Kirkendall DT, Garrett WE, Jr. *CORR.* 2000;372:64-68.
4. Markolf KL, et al. *J Orthop Res.* 1995;13:930-935.
5. Kennedy JC, et al. *Clin Orthop Rel Res.* 1977;129:225-229.

MATHEMATICAL MODELING OF ACL IMPINGEMENT AGAINST THE INTERCONDYLAR NOTCH WALL

Fung D,[1] Zhang L-Q[2,3]

[1]Sensory-Motor Performance Program, Rehabilitation Institute of Chicago, Department of Biomedical Engineering, [2]Department of Physical Medicine and Rehabilitation, and [3]Department of Orthopaedic Surgery, Northwestern University, Chicago, IL.

INTRODUCTION

While many ACL injuries may have resulted from direct loading of the ligament, the ACL may also be injured due to its impingement against the intercondylar notch wall. A number of studies have been conducted to evaluate the relationship between the intercondylar notch width and risk of noncontact ACL injury based on notch-view planar X ray,[1] with gender-specific implications. Considering the complex shape of the notch and oblique arrangement of the ACL, it is needed to investigate the impingement accurately in 3-dimensional space. The purpose of this study was to evaluate ACL impingement against the notch through computer modeling based on data from individual cadaver knees in which ACL impingement was measured.

METHODS

In 5 cadaver knee specimens with intact ligaments, ACL impingement against the intercondylar notch was evaluated visually by moving the tibia passively relative to the femur. In 1 representative specimen with low-notch-width index (0.22), impingement was measured with paper-thin FlexiForce force sensors at the ligament-notch wall interface along with the corresponding tibiofemoral kinematics in 6-DOF. ACL origin (O), insertion (I), and a small patch surface representing an area around the site of impingement on the medial edge of the lateral intercondylar notch wall were digitized and used in the modeling (Figure 1).

ACL impingement against the notch was determined as follows. First, the small patch surface was fitted by bicubic splines with continuity up to the second derivative.[2] Positions of the anteromedial, intermediate, and posterolateral bands of the ACL during the impingement were represented by lines connecting their respective origins and insertions. If impingement of any band occurs, its corresponding line would generally intersect with the patch surface at 2 points, an entry point E_1 and an exit point E_2 (Figure 2). Second, based on these 2 points, and point H, the highest point along the path E_1E_2 on the fitted surface, an initial plane P_1 was generated, followed by a family of incremental planes (P_i, i = 2,3,4 . . .) rotating about an axis defined by the line connecting E_1 and E_2. The impinging band of the ACL should wrap around the curved notch surface in the plane that gives the shortest deformed ACL length. Third, the wrapping path on each plane was determined by ‘‘crawling’’ on the surface from E_1 to E_2 in small steps. Starting from E_1, point C advances a small step along the y-axis to obtain a new location on the surface. If C is off the plane, an adjustment along the x-axis will be made until C is in the plane (Figure 3), reaching the next point on the ACL path. C then continues to ‘‘crawl’’ in small steps along the y-axis and shifts along the x-axis accordingly in establishing the subsequent points along the path until its tangent at point C matches the slope of line OT_1. This location marks the tangential point T_1 where the impinging band makes its first contact with the curved surface (Figure 2). From T_1, point C continues to crawl until reaching tangential point T_2 where the path's tangent matches the slope of line T_2I. The impinging band conforms to the curvature of the surface between T_1 and T_2, and connects directly between O and T_1 and between T_2 and I. The deformed length of the ACL in each plane was determined by adding the linear lengths of OT_1 and T_2I and the curved length T_1T_2.

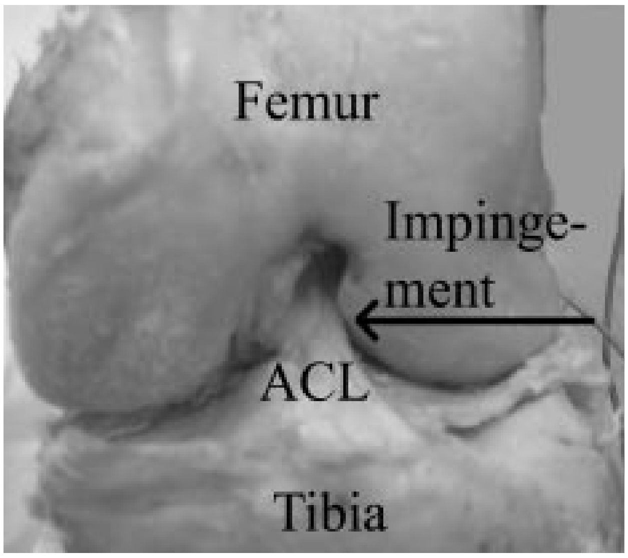


Figure 1. A left cadaver knee in abduction and external rotation used for modeling.

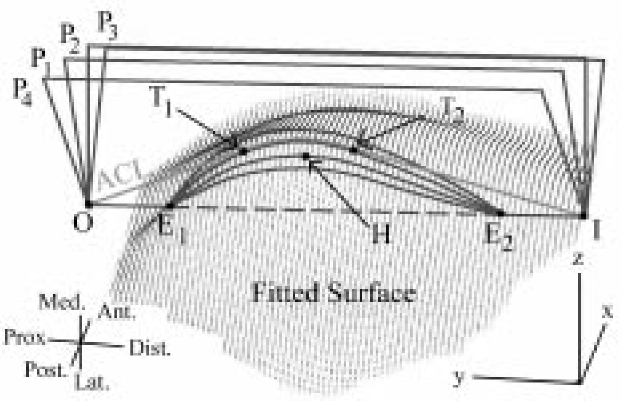


Figure 2. Fitted surface and its incremental planes.

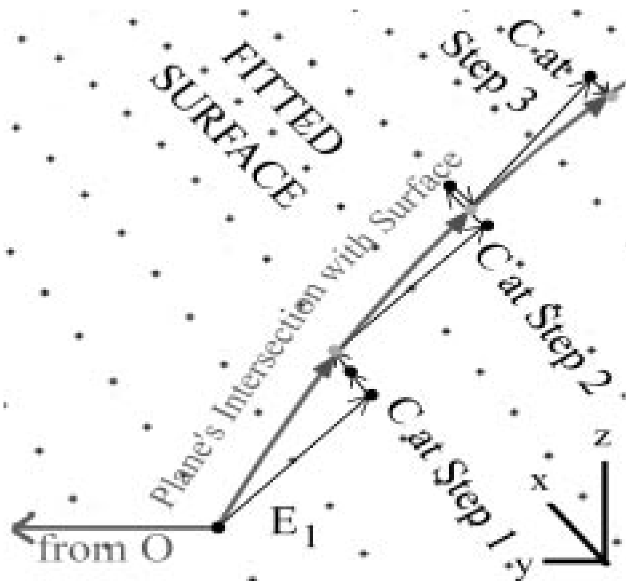


Figure 3. ‘‘Crawling’’ on the surface.

RESULTS AND DISCUSSION

Impingement was observed to occur at the medial side of the lateral notch wall in the representative specimen during adduction and external rotation. At extreme adduction and external rotation, the AM band, whose unimpinged length is 25.5 mm, showed a deformed length of 25.7 mm (OT_1 = 8.0 mm, T_1T_2 = 0.4 mm, T_2I= 17.3 mm), a strain of 0.0078 (Figure 4). Results on the I and PL bands showed less strain than that of the AM band.

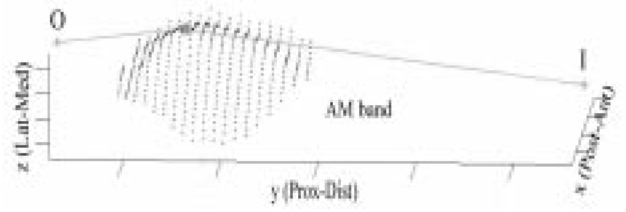


Figure 4. Graphical output of the model showing the impinging AM band.

CONCLUSIONS

The mathematical model provided a useful method to determine ACL impingement in 3-dimensional space, including its deformed shape, length, and strain as the ligament wraps around the notch surface. It was demonstrated that ACL impingement on the intercondylar notch wall loaded the ACL considerably. Further work needs to be done to identify the different areas of the notch wall where impingement is likely to occur in relation to notch width and gender, and to corroborate with the recorded data from the force sensors.

REFERENCES

1. Arendt E. *In Prevent. Noncontact ACL Injuries*. 2001; AAOS, Rosemont, IL.
2. Hayes JG, Halliday J. *J. Inst. Maths Applics*. 1974;14,89-103.

II. NEUROMUSCULAR FACTORS

KNEE JOINT LAXITY AFFECTS MUSCLE ACTIVATION PATTERNS AT THE KNEE PRIOR TO AND FOLLOWING A WEIGHT-BEARING PERTURBATION

Shultz SJ, Carcia CR, Perrin DH

University of North Carolina at Greensboro, Greensboro, NC.

INTRODUCTION

Anterior knee joint laxity is greater in females compared to males and has been implicated as a potential risk factor in ACL injury. While hormonal and structural differences may contribute to increased anterior knee joint laxity in females, the consequence of increased joint laxity on neuromuscular and biomechanical function at the knee has received little attention. This study investigated the effects of anterior knee joint laxity on muscle timing and pre- and postperturbation response amplitudes in the gastrocnemius, hamstring, and quadriceps muscles in response to a lower extremity perturbation.

METHODS

To evoke the reflex response, a lower extremity perturbation device produced a forward and either internal rotation (IR) or external rotation (ER) of the trunk and femur on the weight-bearing tibia. Preperturbation muscle activity level 50 ms prior to the perturbation (Pre_{Amp} = %MVIC), long latency reflex time (RT = ms), and mean reflex amplitude over 150 ms postperturbation (R_{Amp} = %MVIC) were recorded via surface EMG in the medial and lateral gastrocnemius (MG, LG), hamstring (MH, LH), and quadriceps (MQ, LQ) muscles for both ER and IR. Participants consisted of 42 healthy NCAA Division I intercollegiate female athletes, comparing 21 with anterior tibial translation (ATT) <5 mm (KT1 = 19.8 ± 1.3 years; 172.4 ± 7.5 cm; 69.3 ± 7.8 kg; 4.3 ± 0.8 mm ATT) to 21 with ATT > 7 mm (KT2 = 19.2 ± 1.1 years; 171.1 ± 7.3 cm; 69.9 ± 9.3 kg; 9.2 ± 2.0 mm ATT) as measured by a standard knee arthrometer.

RESULTS

A mixed-model repeated-measures ANOVA found groups differed in reflex timing by muscle (P = .013), with the LH demonstrating a 16-millisecond delay in KT2 compared to KT1. While a similar group difference in the onset of the MH was found (KT2 15 milliseconds>KT1), the post hoc comparison was not significant. A separate mixed-model repeated-measures ANOVA found groups also differed in pre- and postperturbation response amplitude by response (Pre_{Amp} versus R_{Amp}) (P = .007), response by muscle (P = .036), and rotation by response by muscle (P= .045). With muscles combined, KT2 demonstrated greater Pre_{Amp} (58%) compared to KT1 (47%), but no difference in R_{Amp} (76% versus 77%). However, the 3-way interaction revealed this effect was muscle specific, with KT2 showing increased Pre_{Amp} in the MG (43% versus 23%), LG (61% versus 45%), and LH (65% versus 37%), but no difference in the MH (48% versus 43%), MQ (67% versus 72%), or LQ (65% versus 59%). While R_{Amp} was significantly greater than Pre_{Amp} for the MG, LG, MH, and LH for both groups, only the LH differed between groups, with KT2 demonstrating 22% greater activation compared to KT1. No differences were found between groups or response type for the MQ and LQ. These responses were similar for ER versus IR, with few exceptions. Subtle increases in Pre_{Amp} and R_{Amp} were found in KT2 compared to KT1 for the LQ on IR (Pre_{Amp} =66% versus 57%, R_{Amp} = 67% versus 60%), but were not found for ER (Pre_{Amp} = 63% versus 61%, R_{Amp} = 63% versus 58%). Further, both groups showed greater R_{Amp} than Pre_{Amp} for the MQ for ER (79% versus 66% KT1, 72% versus 64% KT2), but not IR (80% versus 77% KT1, 78% versus 71% KT2).

DISCUSSION

In summary, participants with increased knee joint laxity demonstrated increased levels of preactivity in the gastrocnemius and LH muscles during static, single-leg weight bearing prior to a lower extremity perturbation, then showed increased reflex delays and reflex amplitude of the LH following the perturbation. These group differences in muscle activation patterns may suggest both a proprioceptive deficit (delayed hamstring reflex) and a learned compensatory strategy (increased Pre_{Amp} and R_{Amp}) may exist with increased knee joint laxity. The implication of these findings on knee joint stabilization and injury risk warrants further research.

ACKNOWLEDGEMENTS

Funded by a grant from the National Athletic Trainers' Association Research and Education Foundation (#999A003). This grant was originally awarded to the University of Virginia, and later transferred to the University of North Carolina at Greensboro.

GENDER DIFFERENCES IN HIP AND KNEE KINEMATICS AND MUSCLE PREACTIVATION DURING SINGLE-LEG LANDINGS

Schmitz RJ, Thompson TJ, Riemann BL, Goldfarb AH

Applied Neuromechanics Research Laboratory; University of North Carolina Greensboro, Greensboro NC.

INTRODUCTION

Lower-extremity joint kinematics and the ability of the lower-extremity muscles to act as dynamic stabilizers during periods of deceleration have been implicated as potential contributing factors in the gender bias seen in ACL injury rates. The purpose of this study was to assess lower extremity kinematic patterns and muscle preactivation timing in males and females during 3 different landing tasks.

METHODS

Thirty recreationally active subjects (15 male [mean ± SD age, 22.0 ± 2.8 years; mean ± SD weight, 78.1 ± 14.2 kg; mean ± SD height, 178.7 ± 8.5 cm]; 15 female [mean ± SD age, 21.3 ± 3.0 years; mean ± SD weight, 57.8 ± 8.0 kg; mean ± SD height, 167.0 ± 7.0 cm]) performed 3 single-leg dynamic jump tasks: forward drop jump, lateral jump from ground level, and medial jump from ground level. Height (20% of the subject's height) and distance (32% of the subject's height) of each jump were individualized. Three-dimensional joint kinematics of the hip and knee were measured by an electromagnetic tracking system during the 5 trials of each task. Initial joint angles were measured at the time of ground contact. Peak displacement was defined as the difference between initial angle and peak angle up to 3 seconds after ground contact. Time to peak displacement was defined as the period between ground contact and peak displacement. Surface EMG signals were obtained from the vastus lateralis, biceps femoris, and gluteus medius muscles during all jumping activities. Muscle preactivation time was defined as when the myoelectric signal reached 2 standard deviations above a quiet bilateral stance baseline up to 200 ms prior to foot contact. Separate 1-between (gender), 1-within (task) repeated-measures ANOVAs were performed for hip and knee time and displacements. A 1-between (gender), 2-within (muscle and task) repeated-measures ANOVA was performed for muscle preactivation time. For all statistical tests, the alpha level was set at $P<.05$.

RESULTS

A significant main effect for gender existed for time ± SD to peak knee flexion ($P = .039$) across the 3 tasks (males, 224.5 ± 46.5 milliseconds; females, 200.3 ± 48.1 milliseconds). Although not statistically significant ($P = .058$), it is noteworthy that the gender main effect for time ± SD to peak hip flexion across the tasks neared significance (males, 213.7 ± 65.6 milliseconds; females, 177.4 ± 80.5 milliseconds). A significant ($P = .007$) main effect for gender revealed females (time ± SD, 189.8 ± 7.7 milliseconds) activated their muscles sooner than males (time ± SD, 185 ± 13.8 milliseconds) prior to foot contact.

DISCUSSION

Although the total joint flexion displacements were similar between genders, average forces and resulting moments may be higher in females because of the lesser time to peak angle. The decreased time to peak angle in conjunction with earlier muscle activation before foot contact found in females would theoretically allow for diminished attenuation of force by dynamic stabilizers (particularly the hamstrings and quadriceps) through increased stiffness of the joints. This process may potentially place a greater load on the noncontractile joint structures. The clinical and/or physiologic significance of a 5-millisecond difference is not known and must be clarified.

CONCLUSIONS

Males and females had similar joint excursions during landing tasks. Additionally, females in this study had a tendency to activate their muscles sooner, which may have contributed to their decreased time to peak hip and knee flexion.

Originally presented at the 2002 National Athletic Trainers' Association Annual Meeting. Reproduced with permission from the *Journal of Athletic Training,* 37:S-20. ©2002 National Athletic Trainers' Association, Inc.

IS LOWER LIMB MUSCLE SYNCHRONY DURING LANDING AFFECTED BY GENDER? IMPLICATIONS FOR VARIATIONS IN ACL INJURY RATES

Cowling EJ, Steele JR

Biomechanics Research Laboratory, University of Wollongong, New South Wales, Australia.

INTRODUCTION

This study examined whether lower-limb muscle synchrony during abrupt landings was affected by gender, thereby predisposing females to a higher incidence of noncontact anterior cruciate ligament (ACL) injuries than males.

METHODS

Seven males and 11 females landed in single-limb stance on a force platform after receiving a chest-height netball pass and decelerating abruptly. Ground reaction force and electromyographic data for rectus femoris, vastus lateralis, vastus medialis, semimembranosus (SM), biceps femoris, and gastrocnemius were sampled (1000 Hz) during landing. Subjects' sagittal plane motion was also filmed (200 Hz). Knee joint reaction forces and sagittal planar net moments of force were estimated using Newtonian equations of motion and inverse dynamics. Tibiofemoral shear forces (Fs) were obtained and muscle bursts temporally analyzed with respect to initial foot-ground contact (IC) and the time of the peak F_s.

RESULTS

Males displayed significantly delayed SM onset relative to IC (113 ± 46 milliseconds) compared to females (173 ± 54 milliseconds; $P = .03$), and significantly delayed SM peak activity relative to the time of the peak F_s (54 ± 27 milliseconds) compared to females (77 ± 15 milliseconds; $P = .03$).

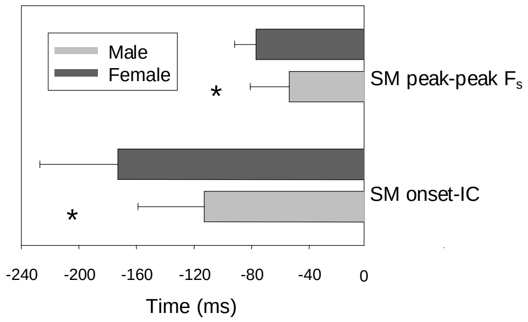


Figure 1. Time from SM peak-to-peak Fs and from SM onset to initial contact for males versus females (*indicates a significant difference).

DISCUSSION

Delayed SM activity during landing was suggested to allow peak muscle activity to coincide better with the high anterior F_s, thereby acting as an ACL synergist via increased joint compression and posterior tibial drawer.

CONCLUSIONS

It was concluded that females displayed muscle synchrony less protective of the ACL than males, possibly increasing their susceptibility to noncontact ACL injuries.

ACKNOWLEDGEMENT

The NSW Sporting Injuries Committee, Australia, funded this study.

III. BIOMECHANICAL FACTORS

A MODEL-BASED IMAGE-MATCHING TECHNIQUE FOR 3-DIMENSIONAL MOTION RECONSTRUCTION FROM UNCALIBRATED VIDEO SEQUENCES—APPLICATION TO ACL INJURY SITUATIONS

Krosshaug T, Bahr R

Oslo Sports Trauma Research Center, Oslo, Norway.

INTRODUCTION

Knowledge about injury mechanisms is essential to prevent injuries. For obvious reasons, injury situations cannot be reconstructed in a lab setting. As video sequences are often the only objective source of information from the injuries, special interest lies in utilizing video material. The purpose of this project is to develop a model-based image-matching technique to reconstruct injury situations for later 3-dimensional biomechanical analyses. The method will be used to describe the injury mechanisms for noncontact ACL injuries in sports.

METHODS

An interactive model-based image-matching method is used for the estimation of 3-dimensional motion from 1 or more (manually synchronized) 2-dimensional video sequences. The 3-dimensional modeling program, Poser, provides the environment for image matching. The matching procedure consists of the following steps:

- Measuring the anthropometry of the subject and building a customized computer-model (eg, by changing segment dimensions of an existing model);
- Measuring landmarks (eg, floor, walls, lines, objects) in the background and building a virtual environment similar to the original;
- Importing the video sequence(s) in Poser as background for the virtual environment and model;

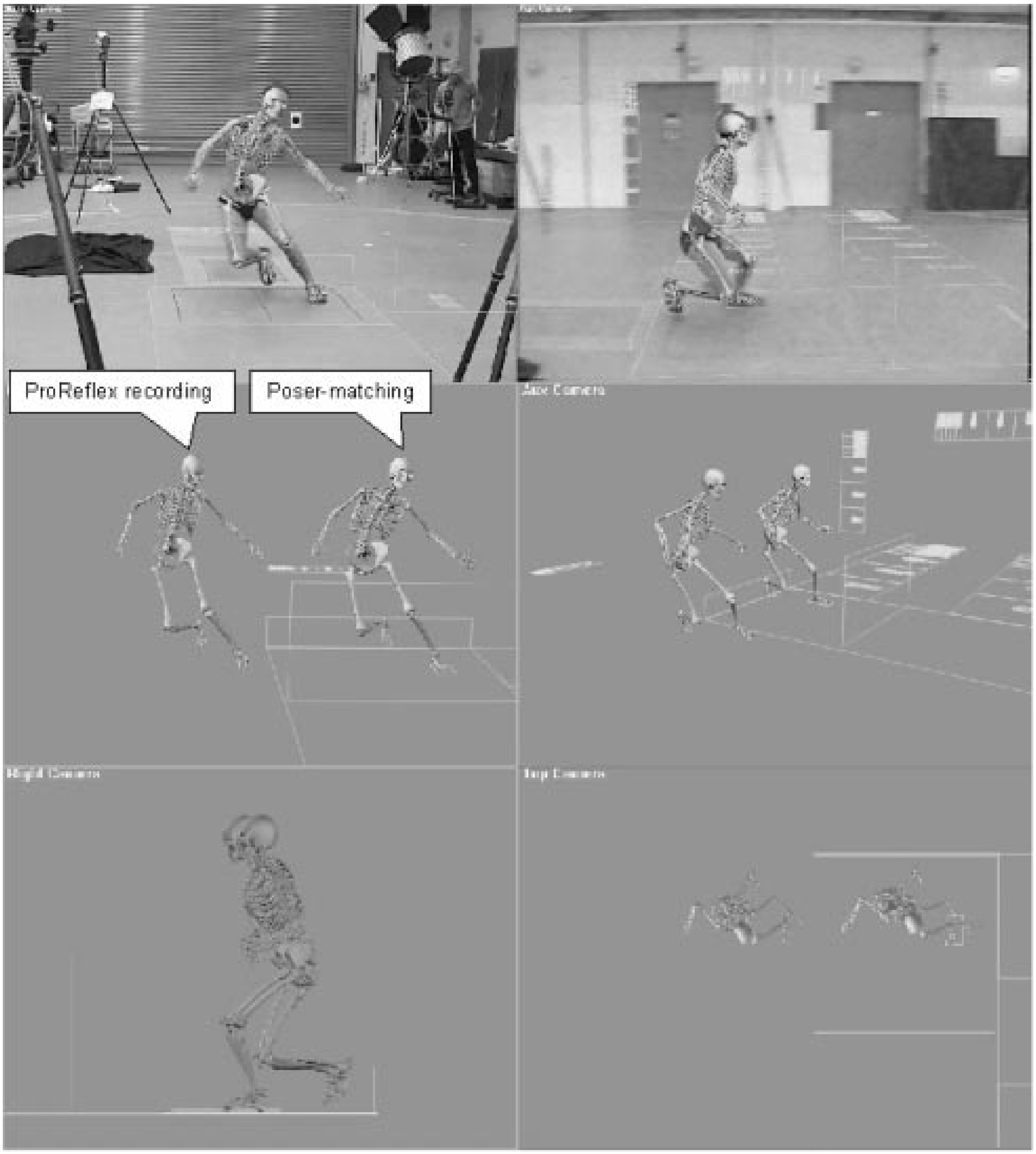


Figure 1. (Krosshaug and Bahr.) A Poser model matching of the video sequences and the comparison with the recorded ProReflex motion.

TABLE 1. Joint angle RMS errors (max errors in parenthesis).

Hip Flexion (degrees)	Hip Adduction (degrees)	Hip Rotation (degrees)	Knee Flexion (degrees)	Knee Varus (degrees)	Knee Rotation (degrees)
3-11 (6-19)	14-16 (19-24)	6-17 (13-26)	5-12 (12-22)	5-7 (8-13)	8-13 (15-19)

TABLE 2. Center of mass (COM) velocity and acceleration RMS errors (max errors in parenthesis).

AP Velocity (m/s)	ML Velocity (m/s)	Vertical Velocity (m/s)	AP Acceleration (m/s^2)	ML Acceleration (m/s^2)	Vert Acceleration (m/s^2)
0.09-0.40 (0.21-0.75)	0.09-0.61 (0.22-1.04)	0.13-0.18 (0.14-0.44)	3.0-9.2 (6.6-18.1)	2.9-12.7 (10.1-21.1)	4.7-5.8 (13.8-23.5)

- ''Calibrating'' the Poser cameras at each time step (eg, adjust the translation, orientation, and focal length parameters to make them similar to the original) by matching the virtual environment to the background reference;
- Matching the model to the background person, starting at the pelvis.

Trials of running and sidestep cutting were recorded by 3 ordinary video cameras. We then used the described matching technique to reconstruct the 3-dimensional motion from respectively 1, 2, and finally, all 3 cameras. A lab validation of the method was done by comparing the results from this method to the results given by a 7-camera, infra-red, 240-Hz, reflective-marker-based system (ProReflex, Qualisys Inc., Gotnenburg, Sweden), and 2 AMTI force platforms.

RESULTS

Preliminary analyses were done for the cutting maneuver. Table 1 gives the range of RMS errors in joint angles for the support leg during the stance (plus 0.04 seconds before and after ground contact) for all the 7 matchings. Table 2 gives velocity and acceleration RMS and max errors for the center of mass (COM).

DISCUSSION

Flexion angles were quite consistent for the triple, double, and single camera matchings. Error analyses for the individual segments showed that the major reason for the inaccuracies originated from erroneous matching of the pelvis. This led to a shift in hip abduction of about 15° for all the matchings. The femur orientation was generally better, while the tibia was best. The velocity estimates were generally good, as long as the movement was not in the depth direction for the camera view. The matchings where 2 perpendicular cameras were available also produced good accelerations. These results indicate that inverse dynamics estimations may be feasible in situations where we have 2 camera views, at least for the knee.

CONCLUSIONS

The proposed method can potentially bring us a step closer to understanding the mechanisms of ACL injuries in a variety of sports by providing kinematic information that can be used for description and classification of injury mechanisms and as input for different biomechanical models.

FOOT LANDING STRATEGIES AFFECT KNEE BIOMECHANICS DURING SIDESTEP CUT TASKS

Houck, JR,[1] Hanford, S[2]

[1]Ithaca College—Rochester Center, [2]University of Pittsburgh

INTRODUCTION

The impact of the foot ground interface on gender-specific ACL injuries has been identified as an area in need of further investigation.[1] Stacoff et al[3] imposed a heel-first (HF) landing strategy on subjects executing sidestep cut tasks, while recognizing that some subjects prefer to use a forefoot-first (FF) strategy. Kovacs et al[2] confirmed that FF and HF landing strategies during a jump land resulted in significantly altered sagittal plane moments. However, this study did not consider cutting tasks or the knee transverse and frontal plane moments. The purpose of this study was to compare the peak ankle and knee angles and moments of sidestep cut tasks using a HF landing strategy to equivalent sidestep cut tasks using a FF landing strategy.

METHODS

Ten healthy female college athletes with an average age (±SD) of 21.3 ± 1.2 years, height (±SD) of 1.68 ± .06 m, and mass of 63.7 ± 6 kg were recruited for this study. Three infrared-emitting diodes (IREDs) were placed on the foot, leg, thigh, pelvis, and trunk and were tracked by the Optotrak Motion Analysis System, generating a 5-segment model. Kinematic data were combined with force plate data to estimate joint moments. Subjects were required to perform a step-down (21-cm curb) and sidestep (SS) cut 45° (Step + SS) at 1.34 m/s using a HF and a FF landing strategy. In addition, subjects performed a running sidestep cut 45° (Run + SS) at 3.0 m/s using a HF and FF landing strategy. Peak ankle and knee angles and moments were compared using a paired t test at selected points of stance.

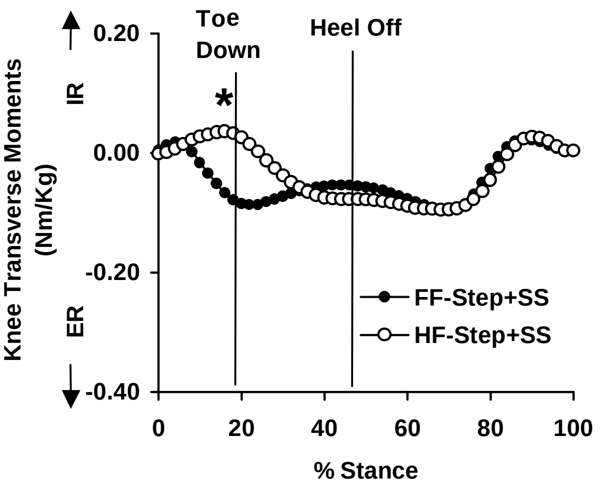


Figure 1. (Houck and Hanford.)

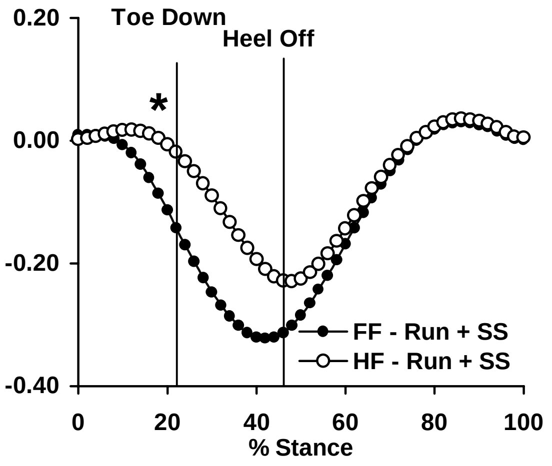


Figure 2. (Houck and Hanford.)

RESULTS

The knee transverse plane moments during early stance were significantly different ($P<.05$) for both the step + SS (Figure 1) and run + SS (Figure 2) conditions. The internal rotation knee moment associated with the HF strategy was also associated with higher knee internal rotation angles ($P<.05$). The patterns of the knee HF and FF transverse plane moments suggest the differences primarily occur during early stance for the Step + SS task (Figure 1) and extend from early stance to heel-off during the Run + SS task (Figure 2).

DISCUSSION

The new findings of this study suggest foot-landing strategies may significantly affect the knee transverse plane moments, which theoretically are associated with ACL injuries. The HF landing strategy led to a period of full foot contact and a knee internal rotation moment not observed during the FF landing strategy. The changes in knee moments were also associated with changes in the knee transverse plane angles, which may affect ACL strain.

CONCLUSIONS

Training and prevention programs may consider the effects of manipulating foot position during sidestep cut activities to influence knee angles and moments.

REFERENCES

1. McClay I, Ireland ML. *Clin Biomech (Bristol, Avon).* 2001;16:937-939.
2. Kovacs I, Tihany J, Devita P et al. *Med Sci Sports Exerc.* 1999;31:708-716.
3. Stacoff A, Steger J, Stussi E, Reinschmidt C. *Med Sci Sports Exerc.* 1996;28:350-358.

ACKNOWLEDGEMENT

Partial support from NSF-REU Grant 0097470.

EFFECTS OF NEUROMUSCULAR CONTROL ON KNEE JOINT LOADING DURING SIDESTEPPING: IMPLICATIONS FOR NONCONTACT ACL INJURY

McLean SG, van den Bogert AG, Su A

Department of Biomedical Engineering, The Cleveland Clinic Foundation, Cleveland, OH.

INTRODUCTION

In a number of sporting scenarios, the knee joint is subjected to complex 3-dimensional loading patterns that offer the potential for anterior cruciate ligament (ACL) injury. It is known that anterior drawer force, varus-valgus (VV), and internal-external rotation (IE) moments, both in isolation and in combination, produce significant increases in ACL loading.[2,4] However, the relationship between in vivo movements and these resultant loads, and more importantly, the effects of neuromuscular control (NMC) as it pertains to gender, remain unclear. The purpose of this study was to establish a methodological approach enabling estimation of knee joint loads and torques during a sidestep cutting maneuver. The method was applied to predict the effects of variability in NMC on these loads to provide insight into means of reducing the risk of noncontact ACL injury.

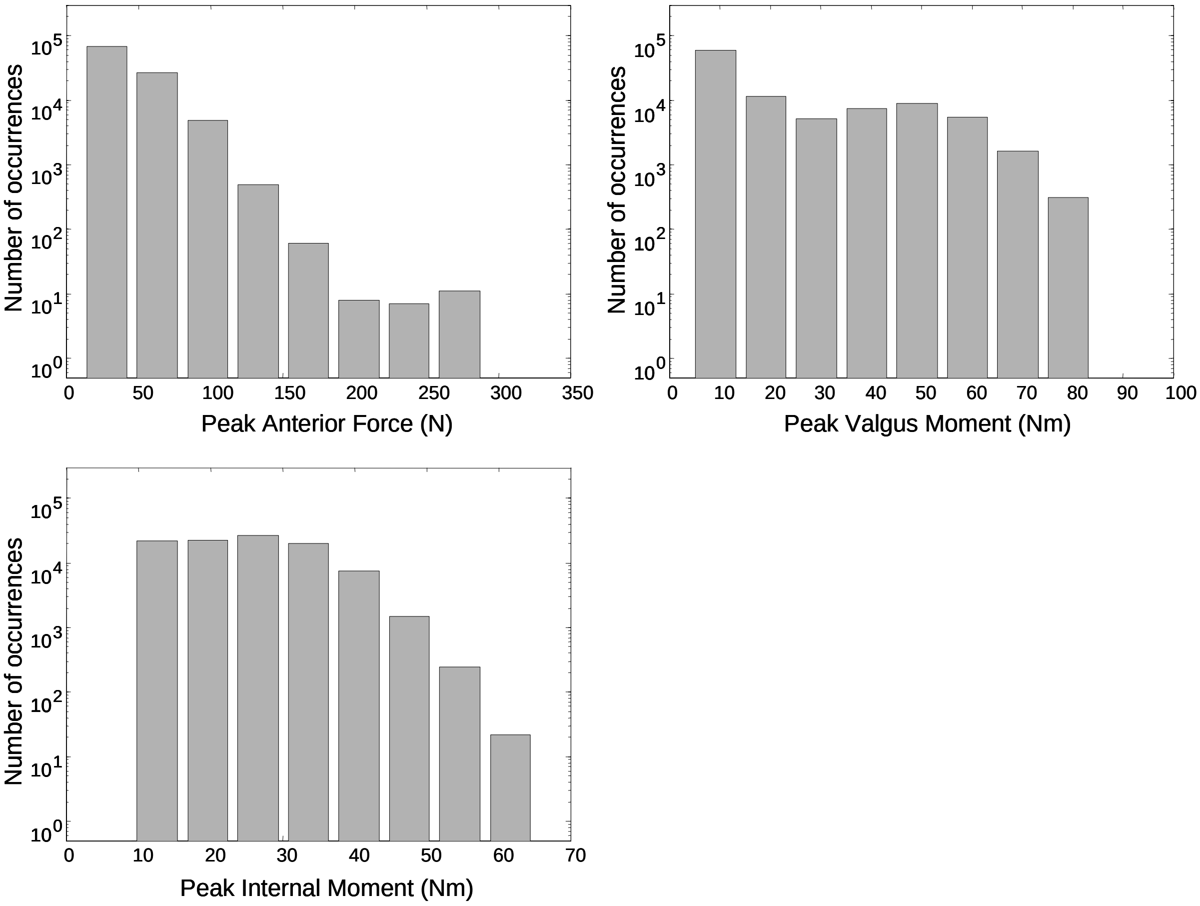


FIGURE 1. (McLean et al.) Effects of variability in neuromuscular control at impact on peak external knee loads during sidestepping.

METHODS

A validated forward dynamic 3-dimensional simulation of a sidestep cutting maneuver was used.[5] Data were obtained from 3-dimensional linear and angular kinematics, and GRF data measured across 10 sidestep trials in a single subject. A simulated annealing algorithm was implemented to find optimal muscle control inputs, by minimizing the difference between simulated and measured kinematic and GRF variables. The resultant anterior-posterior (AP) knee joint force and VV and IE knee moments were obtained at 1-millisecond intervals and peaks were quantified. Monte Carlo simulations ($n = 100000$) were performed on the initial skeletal positions and velocities to determine the effects of NMC variability on the peak magnitudes of these knee joint loads.

RESULTS

For the optimized system, a peak anterior drawer force of 34.6 N was observed, occurring at heel strike. Peak valgus and internal rotation moments of 8.6 Nm and 22.7 Nm were observed, respectively at 24 milliseconds and 75 milliseconds after initial contact. Monte Carlo simulations produced noticeable variations in knee joint loading (Figure 1). Specifically, a peak anterior drawer load, valgus and internal rotation moment of 316.3 N, 89.3 Nm, and 68.6 Nm were observed, respectively.

DISCUSSION

The magnitudes and timing of peak external knee joint loads obtained from the model were similar to those estimated previously via an EMG driven model.[1] Monte Carlo simulations, representing variations in NMC, produced substantial increases in loading (Figure 1). This result is important considering that females display increased movement variability.[3] The predicted anterior drawer force is the resultant of all forces across the knee, including muscle forces. Since the contributions of patellar tendon and hamstrings were known, the AP force on the joint itself could be estimated. The highest value found during the Monte Carlo simulations was still only 874.4 N, which suggests that VV and IE moments are necessary to explain ACL injury during sidestepping. Piziali et al[6] reported that ligament damage occurred in cadaveric knee joints within 125-210 Nm of isolated VV torque or 35-80 Nm of isolated IE torque. The combined loads predicted by our model therefore appear large enough to cause injury. We noticed especially that neuromuscular perturbations often caused large valgus moments (Figure 1, top right).

CONCLUSIONS

The Monte Carlo results identified instances of combined extreme knee loads during sidestepping and the neuromuscular patterns that caused these loads. These results can be used to design specific neuromuscular training regimens that will reduce the likelihood of excessive knee loading and the subsequent risk of noncontact ACL injury. However, this outcome, and the identification of mechanisms of ACL injury specific to sidestepping, requires the direct contributions of these 3 loading variables to ACL force to be clearly identified.

REFERENCES

1. Besier, et al. *Med Sci Sports Exerc.* 2001;33:1168-1175.
2. Kanamori, et al. *Arthroscopy.* 2000;16:633-639.
3. Markolf, et al. *J Orthop Res.* 1995;13:930-935.
4. McLean, et al. *J Biomech. Eng.* 2002; Submitted.
5. McLean, et al. *Med Sci Sports Exerc.* 1999;31:959-968.
6. Piziali, et al. *J Biomech Eng.* 1980;102:277-283.

THE MECHANICAL CONSEQUENCES OF GENDER DIFFERENCES IN SINGLE LIMB ALIGNMENT DURING LANDING

Chaudhari AM, Camarillo DB, Hearn BK, Leveille L, Andriacchi TP

Stanford Biomotion Laboratory, Stanford University, Stanford, CA.

INTRODUCTION

Noncontact injuries are reported most frequently during the deceleration phase of landing after a jump or in preparation for a cutting maneuver. Moreover, the knee is in a position near full extension and there is typically a valgus collapse of the knee associated with landing or deceleration. These observations suggest a potential mechanism for the noncontact ACL injury that can be associated with the limb buckling in a valgus or varus mode in a manner analogous to an articulated column. The buckling analogy would suggest that the risk of the noncontact ACL injury is increased when the limb is malaligned at landing. Limb alignment at landing could be one of the factors associated with the gender differences in the incidence of noncontact ACL injury.

FIGURE 1. Differences in limb alignment during landing.

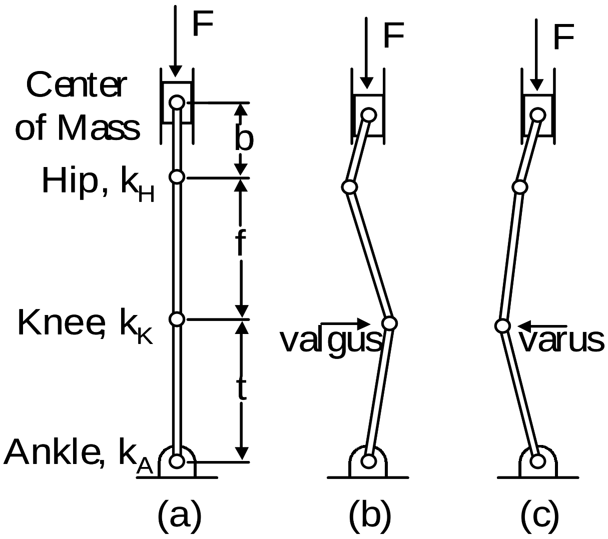


FIGURE 2. An illustration of the limb-buckling model.

The purpose of this study was to test the hypothesis that the dynamic alignment of the lower extremity differs between men and women and to evaluate the mechanical consequences of differences in dynamic limb alignment during landing.

METHODS

Ten subjects (4 males and 6 females), all varsity athletes, were recorded in the frontal plane using a digital video camera while performing a 90° sidestep cutting maneuver. Each subject was classified based on the angle between shank and thigh during weight acceptance as valgus, varus, or neutral. A planar 3-link model with torsional springs at all joints was used to evaluate the mechanical implications of applying the buckling analogy to the

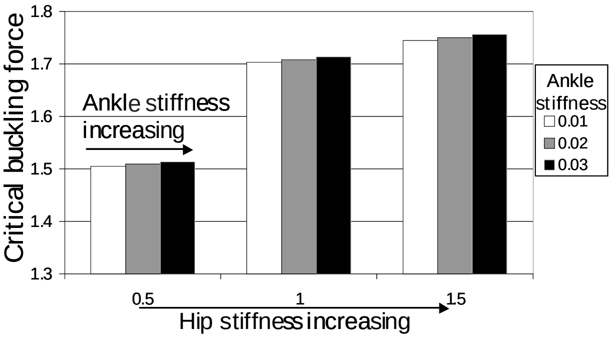


Figure 3. Change in critical force with changes in ankle and hip stiffness. All values are normalized with respect to the knee stiffness. The values for hip stiffness and ankle stiffness represent a reasonable physiologic range.

noncontact injury problem (Figure 2). The limb buckles in the frontal plane when the force exceeds a critical value.

The equations describing this effect were calculated from conservation of energy principles. These equations were solved for the critical force that would cause buckling of the system, F_{CR}, as a function of 2 free parameters: k_H, the hip stiffness, and k_A, the ankle stiffness. In the frontal plane, hip and ankle stiffnesses may be highly dependent upon strength as opposed to knee stiffness, which is largely passive. Therefore, knee stiffness was held constant and all other values were normalized with respect to it. A parametric variation analysis was performed to determine what combinations of parameters lead to a more stable system, indicated by a higher critical force. Average values for knee stiffness were found in the literature. Hip stiffness and ankle stiffness ranges were estimated based on in vivo laboratory tests from previous studies.

RESULTS

Four women of the 6 tested were valgus during the landing phase (Figure 1), while none of the 4 men landed in a valgus alignment. Two of the 4 men were varus, while none of the females landed in varus. The other 2 men and 2 women were neutral.

The buckling model produces limb configurations that closely resemble the limb alignments observed at the instant of injury. The model demonstrated that stabilizing the hip (simulated by increased stiffness) had a greater effect on increasing the limb's ability to resist buckling at the knee than increasing ankle stiffness.

DISCUSSION

The female athletes in this study had a larger tendency toward valgus alignment than male athletes. The buckling analogy demonstrates that limb alignment during landing can influence the critical buckling force. The buckling analogy demonstrated a large sensitivity of buckling to hip stiffness. Dynamic hip stiffness can be controlled by muscle contraction.

This buckling analogy for the mechanism of noncontact ACL injury through valgus collapse provides valuable insights into the effects of different limb alignment and muscle strength, which are particularly relevant due to the gender differences observed in these 2 areas. These insights illuminate directions for further research to confirm the importance of dynamic alignment and muscle strength and design efficient and effective strategies for the prevention of ACL injuries in the future.

IV. HORMONAL FACTORS

FLUCTUATIONS IN ESTRADIOL AND PROGESTERONE ARE RELATED TO CHANGES IN ANTERIOR CRUCIATE LIGAMENT STIFFNESS IN HEALTHY, ACTIVE FEMALES

Romani W, Patrie J, Curl LA, Flaws JA

University of Maryland School of Medicine, Baltimore, MD.

INTRODUCTION

Women injure their anterior cruciate ligament 2 to 10 times more frequently than men. Female sex hormones are thought to influence the remodeling of the type 1 collagen that provides the tensile strength of the ligament. The mechanism by which sex hormones interact to influence the tensile strength of the ACL and its susceptibility to injury is not well understood. The purpose of this study was to determine the relationship between changes in estradiol (E2) and progesterone concentrations with changes in anterior cruciate ligament (ACL) stiffness between 3 phases of the menstrual cycle in 20 healthy, active females. In addition, we examined the relationship between the estradiol to progesterone concentration ratio (E/P ratio) and ACL stiffness during the same 3 phases.

METHODS

Subjects had blood drawn and ACL stiffness measured with the KT-2000 knee arthrometer at the onset of menses, near ovulation, and in the luteal phase of a single menstrual cycle.

RESULTS

Changes in E2 concentration between the onset of menses and near ovulation were negatively correlated with changes in ACL stiffness during the same interval ($r_s = -0.51$, 95% CI [−0.66,−0.23], $P = .021$). Changes in progesterone concentration were positively correlated with changes in ACL stiffness between the onset of menses and near ovulation ($r_s = 0.41$, 95% CI [−0.02,0.73], $P = .070$). E/P ratio near ovulation was negatively correlated with ACL stiffness near ovulation ($r_s = -0.64$, 95% CI [−0.87, −0.15], $P = .003$), and in the luteal phase ($r_s = -0.56$, 95% CI [−0.81,−0.38], $P = .011$).

DISCUSSION

These findings suggest that changes in ACL stiffness may be influenced by fluctuations in E2 and progesterone between the onset of menses and near ovulation, and that higher E/P ratios near ovulation could result in lower ACL stiffness that reduces the ligament's ability to withstand the tensile loads placed upon it during athletic and military activity.

VARIATION IN THE MECHANICAL BEHAVIOR OF RAT ACL DURING THE ESTROUS CYCLE

Otto D[1], Raso VJ[2], Bagnall K[1], Amirfazli A[1], Thorton G[1]

[1]University of Alberta,[2] Glenrose Rehabilitation, Edmonton, Canada.

INTRODUCTION

We hypothesized that increased estrogen levels weaken ligaments by reducing collagen and elastin levels. This contributes to the higher incidence of ACL injuries in women. The objective of this study was to determine if the variation in estrogen levels that occur during the estrous cycle affected the mechanical response of the rat ACL.

METHODS

Once the estrous cycle of 60 female white rats was established, they were separated into 4 groups: diestrus, metaestrus, proestrus, and estrous. The right knee was harvested, cleaned of all soft tissues except for the ACL, clamped into a custom made materials testing machine, and loaded at 3 mm per minute. Elongation and failure tests were performed on each knee specimen. In the load relaxation tests, 15 specimens were loaded to approximately 10 N, unloaded, reloaded to 10 N, and the reduction of force in the following minute noted. Each ACL was then loaded to failure; the peak load and ligament stiffness were determined. The results were compared using an unpaired Student's *t* test.

RESULTS

Mean (±SD) failure loads and ligament stiffness for the 4 cycles were diestrus (26.91 ± 7.8 N and 41.2 ± 6.7 N/mm, respectively), metaestrus (30.7 ± 9.6 N and 41.7 ± 7.6 N/mm, respectively), proestrus (28.0 ± 7.0 N and 42.3 ± 4.21 N/mm, respectively), and estrus (25.1 ± 6.2 N and 42.8 ± 5.1 N/mm, respectively). In the load relaxation tests, the drop in load varied from 2.1 to 2.4 N. There were no significant differences found for any of the tests results.

DISCUSSION

It was hypothesized that the heightened estrogen levels experienced just before ovulation would weaken the ACL. In the rat's estrus cycle, estrogen levels are highest during the proestrus phase. The ligaments tested from this phase were not found to have any mechanical properties that were significantly different from the other phases. The menstrual cycle is not likely to contribute significantly to the ACL injuries in women.

CONCLUSIONS

Variation in estrogen level does not significantly affect the load elongation or failure loads of the rat's ACL.

Previously presented at the Canadian Orthopaedic Association 57th Annual Meeting, June 2002.

INFLUENCES OF GENDER AND EXERCISE ON ACL LAXITY

Pollard C, Braun B, Hamill J

Biomechanics Laboratory, University of Massachusetts, Amherst, MA.

INTRODUCTION

Women have been reported to experience 4 to 8 times the number of anterior cruciate ligament (ACL) injuries that men do. Researchers have investigated a variety of factors that may affect this disproportionate incidence rate. Recent work has focused on potential hormonal influences on injury due to the difference in estrogen levels between genders. More specifically, investigators have focused on the influences of high estrogen levels during specific times of the menstrual cycle. These authors have suggested that changes in circulating estrogen levels across the menstrual cycle phases may contribute to this higher incidence of injury.[1] This potential factor has stemmed from recent in vitro work, which has reported that physiologic levels of estrogen may significantly reduce ACL fibroblast proliferation and rate of collagen synthesis.[2] This reduction may be associated with changes in ligament laxity. Investigators have also suggested an increase in ACL laxity following exercise.[3] The purpose of this study was to determine if there were changes in ACL laxity associated with serum estrogen changes across the menstrual cycle phases in active females. In addition, the effect of exercise on ACL laxity between genders and across the menstrual cycle phases were investigated.

METHODS

Subjects consisted of 10 females with a history of a normal menstrual cycle lasting 28 to 32 days and 10 males. All subjects had intact knee ligaments bilaterally and exercised on average at least 5 times a week for 30 minutes. Female subjects were assigned to start data collection at either the onset of menses or the onset of ovulation, depending on which event came first after signing the informed consent to participate. Ovulation was determined by a positive test on an ovulation kit. Serum estrogen levels of the female subjects were measured via radioimmunoassay procedures.

Knee laxity was measured with a KT1000 Knee Arthrometer at 20° of knee flexion with a displacement force of 89 N. Estrogen levels and ACL laxity were measured for the female subjects at specific times to represent the 3 menstrual cycle phases. These times were at onset menses (menstrual phase), days 10 and 12 postonset menses (follicular phase), and days 7 and 9 postovulation (luteal phase). ACL laxity of the male subjects was measured on 3 different days, with 10 to 12 days between each measurement. For each data collection session, ACL laxity was measured just prior and immediately following an exercise protocol. The exercise protocol consisted of 15 minutes of treadmill running, 2 minutes of weaving, 2 minutes of cutting, and 25 jump-downs from a 14-inch surface. An ANOVA and repeated-measures ANOVA were used to test for significant differences in ACL laxity between females and males and across the different menstrual cycle phases, respectively ($P \leq .05$).

RESULTS

There were significant differences in ACL laxity between genders both pre- and postexercise (Figure 1). However, there were no significant differences in the effect of exercise on ACL laxity between males and females (Figure 1). In addition, the effect of exercise did not differ across the menstrual cycle phases (Figure 2). There were no significant differences in ACL laxity between the menstrual cycle phases both pre- and postexercise (Figure 2). However, there was a significant increase in estrogen between the menstrual and the follicular phase (Figure 3).

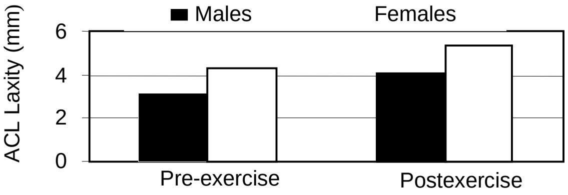


Figure 1. Effects of exercise between genders.

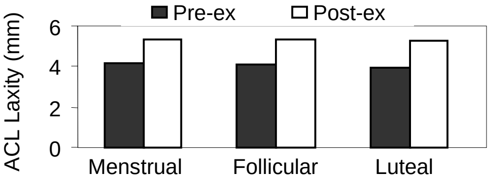


Figure 2. Effects of exercise across the phases.

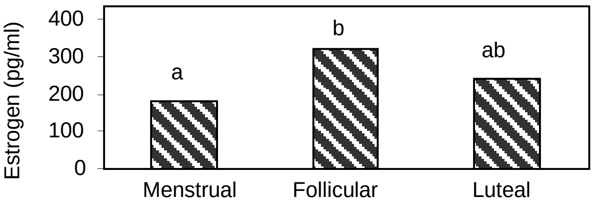


Figure 3. Serum Estrogen Levels

DISCUSSION

These results suggest that ACL laxity is increased in both genders following exercise. This increase in laxity due to exercise does not appear to differ in females across the menstrual cycle phases. Although the females did not exhibit changes in ACL laxity consistent with changes in circulating estrogen levels, they did demonstrate greater ACL laxity than did males both pre- and postexercise.

CONCLUSIONS

Although in vitro investigations have suggested that the ACL may be at greater risk of injury when exposed to higher levels of circulating estrogen, there does not appear to be a clinically significant association between ACL laxity and acute changes in serum estrogen. However, because the females did consistently demonstrate greater laxity than did the males both pre- and postexercise, future studies are necessary to investigate the relationship of this greater laxity with the female's chronic exposure to higher levels of estrogen. In addition, future studies are necessary to investigate the effects of circulating hormones on lower extremity dynamics.

REFERENCES

1. Heitz, et al. *J Athl Train*. 1999.
2. Liu, et al. *Am J Sports Med*. 1997.
3. Steiner, et al. *Am J Sports Med*. 1986.

HOW NORMAL HORMONAL FLUCTUATIONS IN WOMEN INFLUENCE THE BIOMECHANICS OF STEPPING AND CUTTING

Yack HJ, Chandran R, Rao S, Wilken J

Orthopaedic Gait Analysis Laboratory, Graduate Program in Physical Therapy and Rehabilitation Science, The University of Iowa, Iowa City, IA.

INTRODUCTION

Normal hormonal fluctuations that are associated with the menstrual cycle are one factor that has been used to help explain the 2 to 8 times higher rate of knee injuries in female athletes. Results from prospective studies that have tried to establish the link between injury and the menstrual cycle are inconsistent.[2] Few well-controlled studies have attempted to examine how performance might be affected by hormonal changes in the uninjured population. The purpose of this study was to identify biomechanical changes in performance that could be associated with hormonal variations during the normal menstrual cycle.

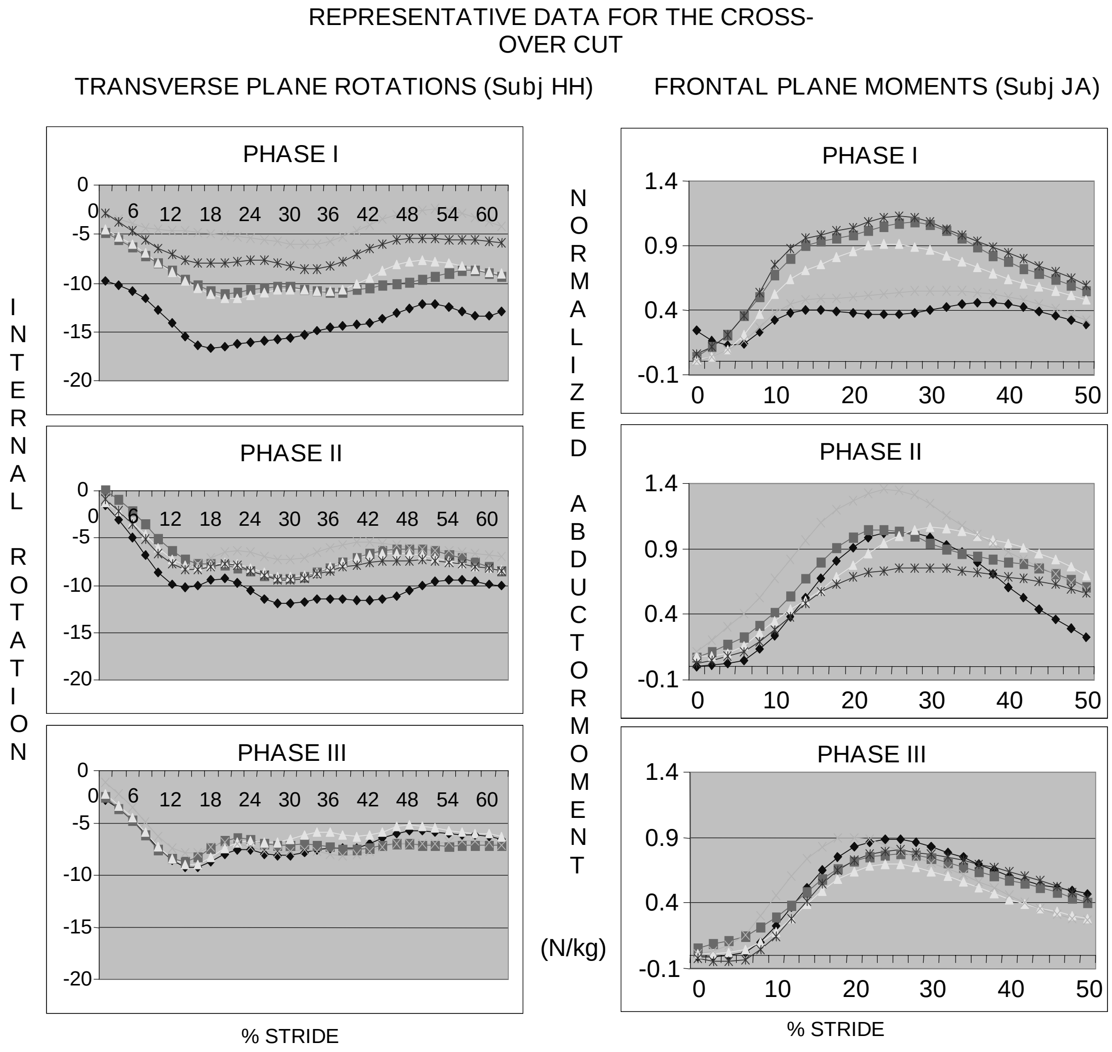
METHODS

Seven female recreational athletes participated in the study. The month prior to data collection, subjects monitored their menstrual cycles and the timing of the luteal surge was identified. During the following month testing was started in a randomized manner to capture the 3 phases of the menstrual cycle: follicular (days 2-4), ovulatory (LH surge, within 1 day), and luteal (6-8 days before the end of the cycle). On the day of testing, serum samples were collected. Subjects warmed up by running on a treadmill for 20 minutes. Markers were placed on each subject to capture the 3-dimensional motion of the right lower limb, pelvis, and trunk. Subjects stepped off a raised (20 cm) walkway while walking at 1.8 m per second, with their right foot landing on a force platform. A directional light, triggered by the subject, randomly determined if they should continue straight ahead or cut at a 45° angle to the left or right. Five trials of each direction were collected.

Marker positions were captured in 3 dimensions (Optotrak, NDI, Waterloo, Ontario, Canada) at 60 Hz and force plate data were captured at 300 Hz. Data were filtered at 6 Hz and processed to obtain kinematic and kinetic measures using KinGait3 software. Variability in performance during each phase was judged by the mean standard deviation for 5 trials over specific intervals.

RESULTS

The results demonstrate overall greater variability in knee transverse plane rotations and frontal plane (abductor) moments during the initial part of weight acceptance when subjects were in


REPRESENTATIVE DATA FOR THE CROSS-OVER CUT

TRANSVERSE PLANE ROTATIONS (Subj HH)

FRONTAL PLANE MOMENTS (Subj JA)

Figure 1. (Yack et al.) Representative data for transverse plane rotations and frontal plane moments showing 5 individual trials for 2 subjects performing the crossover cut during 3 phases (follicular, ovulatory, and luteal) of the menstrual cycle. Significant main effects for phase were found for transverse rotations and frontal plane moments.

the follicular phase. This initial period of weight acceptance has been identified as being important in helping to control the knee and may be associated with give-way episodes in ACL deficient patients.[1]

CONCLUSIONS

- Women demonstrated greater variability in biomechanical measures of performance during the follicular phase compared to the other 2 phases of the menstrual cycle.
- The increased variability found in the current study is consistent with previous findings comparing men and women[3] and points to the need to control for hormonal levels when making such comparisons.
- Increased variability in these measures means that there may be trials when the ACL experiences greater stress and is therefore more susceptible to injury.

REFERENCES

1. Houck J, Yack HJ. *J Orthop Sports Phys Ther.* 2001;31:481–489.
2. Huston LJ, Wojtys EM. Prevention of noncontact ACL injuries. *Am Acad Ortho Surg.* 2001.
3. McLean SG, van den Bogert AG, *Clin Biomech (Bristol, Avon).* 2001;16:954–955.

V. INTERVENTIONS

CAN LOWER LIMB MUSCLES BE RETRAINED DURING LANDING AS A MEANS OF ANTERIOR CRUCIATE LIGAMENT INJURY PREVENTION?

Cowling EJ,[1] Steele JR,[1] McNair PJ[2]

[1]Biomechanics Research Laboratory, University of Wollongong, NSW, Australia. [2]Auckland University of Technology, Auckland, New Zealand.

INTRODUCTION

This study examined whether surface electromyographic (EMG) biofeedback could be used as a means of retraining lower-limb muscle activation patterns during abrupt landing, so as to better protect the knee from anterior cruciate ligament (ACL) rupture.

METHODS

Twenty-eight female netball players (control subjects, $n = 14$; experimental subjects, $n = 14$) landed in single-limb stance on a force platform after receiving a chest height pass and decelerating abruptly on 2 test occasions: before and after a 6-week interval. During this 6-week interval, although the control subjects completed no additional training, the experimental subjects completed 3 x 30 minute sessions per week of progressive hamstring muscle biofeedback training. The aim of this training was to elicit earlier hamstring muscle recruitment with respect to initial contact (IC) with the ground at landing, which has been suggested to be more protective to the ACL. Ground reaction force and electromyographic data for rectus femoris (RF), vastus lateralis, semimembranosus, and biceps femoris (BF) were sampled (1000 Hz) during each landing and subjects' sagittal plane motion was captured at 200 Hz.

RESULTS

Although there was a trend for the experimental subjects to recruit their hamstring muscles earlier with respect to IC following training (eg, BF pretraining [mean ± SD] −189 ± 48 milliseconds; BF posttraining [mean ± SD], −205 ± 67 milliseconds) compared to the controls (BF pretraining [mean ± SD], −187 ± 64 milliseconds; BF postraining [mean ± SD], −193 ± 58 milliseconds), there was no significant main effect of either training or test group on the hamstring muscle recruitment data. However, following the hamstring training program, there was a significant training *x* test group interaction whereby although the control subjects increased the time between IC and the peak RF activity, the experimental subjects displayed significantly less time between these 2 events.

DISCUSSION

Although producing the desired trends in achieving earlier hamstring muscle onset, the hamstring training program was not successful in significantly altering the timing of this muscle activity relative to IC. Instead, subjects inadvertently altered their quadriceps muscle activity such that the muscle training produced a shorter time interval between the onset of the hamstring muscles with respect to the onset of the quadriceps muscles for the experimental subjects. Therefore, the training program elicited muscle patterning that may be less protective to the ACL.

CONCLUSIONS

It was concluded that the training was ineffective in producing the desired significant changes in hamstring muscle activity during landing. However, further research is recommended to determine whether more intensive and comprehensive training that monitors both quadriceps and hamstring muscle activity during training may be effective in altering muscle synchrony to protect the ACL better from rupture during landing.

ACKNOWLEDGEMENT

The NSW Sporting Injuries Committee, Australia, funded this study.

ADAPTATIONS TO AN INTERVENTION PROGRAM FOR THE PREVENTION OF FEMALE ACL INJURIES

McCrory, JL, Lephart SM, Ferris CM, Sell T C, Abt JP, Irrgang JJ, Fu FH

Neuromuscular Research Laboratory, Department of Sports Medicine and Nutrition, University of Pittsburgh, Pittsburgh, PA.

INTRODUCTION

Many biomechanical factors have been proposed to explain the increased incidence of ACL injury in females.[1-7] Few studies have investigated the influence of preventative training programs on this greater risk of ACL injury in females.[8,9] The purpose of this study was to compare the effects of 2 lower-extremity training programs on these biomechanical factors in female athletes during 2 functional tasks.

METHODS

Twenty-seven female athletes participated in an 8-week neuromuscular training program. Subjects were randomly assigned to either an advanced training group (n = 13; mean age ± SD, 14.5 ± 1.31 years; mean height ± SD, 1.65 ± 0.06 m; mean mass ± SD, 55.07 ± 8.02 kg) or a basic training group (n = 14; mean age ± SD, 14.29 ± 1.38 years; mean height ± SD, 1.66 ± 0.08 m; mean mass ± SD, 58.29 ± 10.81 kg). Each exercise program was divided into 2 4-week phases. Both groups performed lower-extremity stretching, strengthening, and balance exercises. In the second 4 weeks, the advanced group also received neuromuscular control exercises consisting of plyometric and agility type exercises.

A pre- and posttraining biomechanical analysis was performed for both a cutting task and a jump landing. Three-dimensional kinematic and kinetic data were collected with 6 120-Hz cameras interfaced with a force plate (Peak Performance, Inc., Englewood, CO; Bertec Corporation, Worthington, OH). The cutting task included a 10-m run followed by a 45° open-medial cut. The jump-landing task consisted of a double-legged takeoff and landing. Isometric hip abduction and isokinetic knee flexion and extension strength were assessed with an isokinetic dynamometer (Biodex, Inc., Shirley, NY). Four trials of each functional task were averaged for statistical analysis. Multiple 2-way (group x session) repeated-measures ANOVA ($a = .05$) assessed differences in dependent variables.

RESULTS

All subjects demonstrated significantly less plantar flexion (pretraining mean ± SD, 20.1° ± 14.6°; posttraining mean ± SD, 12.6° ± 9.4°) and greater hip internal rotation (pretraining mean ± SD, 22.4° ± 12.7°; posttraining mean ± SD, 28.0° ± 14.2°) and abduction (pretraining mean ± SD, -1.3° ± 9.1°; posttraining mean ± SD, 2.3° ± 8.5°) at initial contact in the 45° cut. Additionally, all subjects demonstrated significantly greater ankle dorsiflexion (pretraining mean ± SD, 1.5° ± 9.3°; posttraining mean ± SD, 6.6° ± 9.1°), hip internal rotation (pretraining mean ± SD, 20.9° ± 13.1°; posttraining mean ± SD, 16.0° ± 13.8°), and hip abduction (pretraining mean ± SD, 29.7° ± 6.9°; posttraining mean ± SD, 24.9° ± 7.1°) from initial contact to peak vertical ground reaction force (vGRF). All subjects significantly increased hip flexion at contact (pretraining mean ± SD, 2.9° ± 6.9°; posttraining mean ± SD, 7.6° ± 8.3°) and at peak vGRF (pretraining mean ± SD, 2.8° ± 6.9°; posttraining mean ± SD, 7.5° ± 8.4°) in the jump landing. Peak knee flexion (pretraining mean ± SD, 62.6° ± 14.4°; posttraining mean ± SD, 78.2° ± 28.7°) and time to peak knee flexion (pretraining mean ± SD, 163.3 ± 52.8 milliseconds; posttraining mean ± SD, 203.4 ± 84.2 milliseconds) significantly increased during the jump landing. All subjects demonstrated significantly greater quadriceps strength normalized to bodyweight at 60°/sec(pretraining mean ± SD, 199.2 ± 41.5; posttraining mean ± SD, 217.3 ± 30.6), and 180°/sec (pretraining mean ± SD, 141.3 ± 27.3; posttraining mean ± SD, 154.8 ± 19.3). Although both groups saw biomechanical adaptations to training, no differences were noted between the 2 training protocols.

DISCUSSION

Both training programs resulted in adaptations that established a basis of neuromuscular control required for efficient biomechanical movement patterns such that the center of gravity was closer to the base of support or column of stability as the position of the ankle and hip at impact permitted a more vertical body alignment. Additionally, increased dorsiflexion, hip abduction, and hip internal rotation throughout the stance phase demonstrated enhanced motor control strategies. The lack of group differences in kinematic and kinetic variables suggests that a strength and balance training program would provide adequate neuromuscular control needed to perform these tasks in a less vulnerable position.

CONCLUSIONS

The results suggest that biomechanical characteristics of the lower extremity in female athletes can be improved with training, potentially reducing the risk of ACL injuries.

REFERENCES

1. Arendt EA, Agel J, Dick R. *J Athl Train*. 1999;34(2):86–92.
2. Caraffa A, Cerulli G, Projetti M, Aisa G, Rizzo A. *Knee Surg Sports Traumatol Arthrosc*. 1996;4(1):19–21.
3. Chappell JD, Yu B, Kirkendall DT, Garrett WE. *Am J Sports Med*. 2002;30(2):261–267.
4. Colby S, Francisco A, Yu B, Kirkendall D, Finch M, Garrett WE. *Am J Sports Med*. 2000;28(2):234–240.
5. Hewett TE, Stroupe AL, Nance TA, Noyes FR. *Am J Sports Med*. 1996;24(6):765–773.
6. Lephart SM, Ferris CM, Riemann BL, Myers JB, Fu FH. *Clin Orthops*. 2002;401: 162–169.
7. Malinzak RA, Colby SM, Kirkendall DT, Yu B, Garrett WE. *Clin Biomech (Bristol, Avon)*. 2001;16(5): 438–445.
8. Rozzi SL, Lephart SM, Fu FH. *J Athl Train*. 1999;34(2):106–114.
9. Rozzi SL, Lephart SM, Gear WS, Fu FH. *Am J Sports Med*. 1999;27(3):312–319.

PREVENTION OF ACL INJURIES IN FEMALE TEAM HANDBALL PLAYERS—A PROSPECTIVE INTERVENTION STUDY OVER 3 SEASONS

Myklebust G,[1] Engebretsen L,[1,2] Braekken IH,[1] Skjolberg A,[1] Olsen OE,[1] Bahr R[1]

[1]Oslo Sports Trauma Research Center, Norwegian University of Sport and Physical Education, [2]Oslo Orthopedic University Clinic, Oslo, Norway.

INTRODUCTION

The aim of the study was to assess the effect of a special balance and coordination training program on the incidence of ACL injuries in female team handball players.

METHODS

The incidence of ACL injuries was evaluated in 58 female teams (940 players) in the 3 upper divisions from August 15 to May 31 during the 1998 to 1999 seasons (control period), the 1999 to 2000 seasons (intervention period I), and the 2000 to 2001 seasons (intervention period II). A program with 3 different balance exercises focusing on neuromuscular control and planting and landing skills was developed and introduced to the players in the autumn of 1999, and a revised program in the autumn of 2000, making the exercises more handball-specific and functional. The teams were instructed to use the program 3 times weekly, 15 minutes each time, during a 5-week training period, and then once a week during the season. The teams were visited in the preparation period and were supplied with instructional video, posters, 6 balance mats, and 6 wobble boards. Additionally, a physical therapist was attached to each team to follow up the intervention program from autumn 2000.

RESULTS

There were 29 ACL injuries during the control season, 23 injuries during the first intervention season (odds ratio [OR], 0.87 [0.50–1.52]; $P = .62$), and 17 injuries during the second intervention season (OR, 0.64 [0.35–1.18]; $P = .15$). In the elite division there were 13 injuries during the control season, 6 injuries during the first intervention season (OR, 0.51 [0.19-1.35]; $P = .17$), and 5 injuries in the second intervention season (OR, 0.37 [0.13-1.05]; $P = .06$). For the entire cohort, there was no difference in injury rates during the second intervention season between compliers and noncompliers (OR, 0.52 [0.15-1.82], $P = .31$). In the elite division the risk of injury was reduced among those who completed the ACL injury prevention program (OR, 0.06 [0.01-0.54], $P = .01$) compared with those who did not.

DISCUSSION

The study shows that ACL injuries among female team handball players can be prevented with specific balance training, and it seems to be a further potential for reduction of ACL injuries through better compliance with the training program.

ACKNOWLEDGEMENTS

The Oslo Sports Trauma Research Center has been established at the Norwegian University of Sport and Physical Education through generous grants from the Royal Norwegian Ministry of Culture, the Norwegian Olympic Committee and Confederation of Sport, Norsk Tipping AS, and Pfizer AS.