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Original Research

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Invitation

The Organising Committee of the 2000 Pre-Olympic Congress invites you to join in a celebration of Sports Science, Medicine, Education and Culture in the new millennium. This multidisciplinary meeting will provide an exciting opportunity to link the latest scientific research with practical applications into Sport Science, Sports Medicine and Physical Education. The Congress will be held in Brisbane, Australia between the 7th - 13th September 2000.

In 2000, the Organising Committee will develop a unique program expanded to include representation from six specialised, sports related disciplines:

- Pedagogy
- Biophysical Science
- Physical Therapies
- Nutrition and Health Promotion
- Sociocultural & Psychology
- Sports Medicine

Specialist Symposia& workshop chair

Dr Graham Costin
Dr Phil Hamdorf
Mr Bill Vicenzino
Mr Ben Desbrow
Dr John Nauright
Dr David Garlick
A. Prof. Andrew Hills

Scientific Program

This International Congress features speakers from all aspect of sports science, sports medicine and physical education. There will be a strong scientific basis as well as applied sessions, focusing on the implementation of these findings into the practical domains of sport and exercise. The program will include presentations by keynote speakers, symposia and trade displays.

Themes running across the program will include:

- The role of the Olympic Games in promoting 'health for all'
- Sports medicine, sports science and physical activity in the new millennium
- Physical education and healthy lifestyles
- The Impact of Elite Sports Medicine on the general community
- Exercise and sport for Special Populations
- Manipulating athletic bodies: Science, Training, Technology, and Drugs in the 21st Century
- Grass Roots Issues: When can I play again?
- Sport as a process for Peace
- Millennium Conundrums: Prevention or Cure? Therapeutic Exercise Approaches?

Official Endorsement

This major international meeting is organised on behalf of the International Council of Sport Science and Physical Education (ICSSPE) and Sports Medicine Australia (SMA). The Congress has been officially endorsed by: H.E. Juan Antonio Samaranch, President of the International Olympic Committee (IOC); the World Health Organisation (WHO); the International Federation of Sports Medicine (FIMS) and the United Nations Education and Science Organisation (UNESCO).

Social Program

An extensive social program is being organised to allow delegates to liaise in many informal settings around Brisbane, providing an opportunity to explore the city, its people and its culture. An exciting program of pre and post Congress outings will provide delegates with the opportunity to experience the spectacular and unique beauty of this diverse country.

Venue

Brisbane is a vibrant, multicultural city on Australia’s East Coast. The Brisbane Convention and Exhibition Centre is the venue for the Congress. This magnificent purpose built conference and exhibition facility provides the latest in audiovisual and telecommunications technology.

Timing

The Congress concludes just two days before the Opening Ceremony for the 2000 Olympic Games in Sydney. For those attending the games, flight times from Brisbane to Sydney is just over one hour.

A Word From The Congress Chair

Professor Tony Parker

It is with great pleasure and enthusiasm that I invite you, on behalf of ICSSPE, SMA and The Congress Organising Committee, to join us at the dawning of the millennium to participate in this unique and historic meeting. Our aim is to provide a program which will involve all groups with interests in the science and education of sport and health. We see the Congress as a great opportunity for facilitating closer understanding of the role and expertise within each group, via the sharing of keynote speakers and with joint scheduling of sessions with topical issues of interest to all groups. The interdisciplinary nature of the Congress ensures interaction and exchange of ideas between the various specialist groups, while at the same time ensuring some autonomy in the groups in the design of their own particular program within the Congress framework. There will be an emphasis on practitioner oriented sessions, including many workshops and topical symposia, examining the issues and controversies in sport and its related disciplines. We have a World class venue, strong international and local support and feel confident that the event will provide an excellent opportunity to present to the world community, the exceptional research and work conducted by our National and International organisations within the sport related disciplines.

To receive further information, please contact

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1998 Outstanding Manuscript Awards

Congratulations to the winners and the runners-up of the 1998 Outstanding Manuscript Awards, as determined by the Editorial Board and the Editors of the Journal of Athletic Training.

1998 Journal of Athletic Training Kenneth L. Knight Award for the Outstanding Research Manuscript
Winner: Worrell TW, Crisp E, LaRosa C. Electromyographic reliability and analysis of selected lower extremity muscles during lateral step-up conditions. 2:156–162.
Second Runner-Up: Moul JL. Differences in selected predictors of anterior cruciate ligament tears between male and female NCAA Division I collegiate basketball players. 2:118–121.

1998 Journal of Athletic Training Clint Thompson Award for the Outstanding Non-Research Manuscript

22nd Annual NATA Student Writing Contest

In an effort to promote scholarship among young athletic trainers, the National Athletic Trainers’ Association, Inc sponsors an annual writing contest.

1. The contest is open to all undergraduate members of the NATA.
2. Papers (eg, original research articles, literature reviews, case reports, or clinical techniques articles) must be on topics germane to the profession of athletic training.
3. Entries must neither have been published by, nor be under consideration for publication by, any journal.
4. The winning entrant will receive a cash award and recognition as the winner of the Annual NATA Student Writing Contest. The winning paper will follow the normal process of submission and review for possible publication in the Journal of Athletic Training. One or more other entries may be given honorable mention.
5. Entries must conform to the Journal’s Authors’ Guide, which provides the most current information on format and style. For advice about writing, we suggest that authors consult Kenneth L. Knight and Christopher D. Ingersoll’s “Structure of a Scholarly Manuscript: 66 Tips for What Goes Where” (J Athl Train. 1996;31:201–206) and “Optimizing Scholarly Communications: 30 Tips for Writing Clearly” (J Athl Train. 1996;31:209–213).
6. Entries must be received by March 1, 2000. The winner will be announced at the Annual Meeting and Clinical Symposia in June.
7. The Writing Contest Committee reserves the right to make no awards if, in its opinion, none of the entries is of sufficient quality to merit recognition.
8. An original and 2 copies of each entry must be received at the following address by March 1, 2000:

NATA Student Writing Contest
Deloss Brubaker, EdD, ATC
Life College
1269 Barclay Circle
Marietta, GA 30060
Anterior Cruciate Ligament Injury in the Female Athlete

David H. Perrin, PhD, ATC
Editor-in-Chief

At the February 1999 annual meeting of the American Academy of Orthopaedic Surgeons, James Garrick and Ralph Requa presented a paper entitled “ACL Injuries in Women: Epidemiology.” They found that, between 1965 and the present, 3514 MEDLINE citations were indexed under “anterior cruciate ligament,” yet only 130 were indexed under prevention, and fewer than 10 focused on prevention of the injury. This special issue of the Journal of Athletic Training has several purposes: to remind readers that the epidemic of ACL injuries in female athletes continues, to identify potential risk factors that can be targeted for preventive interventions, and to recognize important research initiatives in our quest to reduce the incidence of this injury in both female and male athletes.

In 1995, Elizabeth Arendt and Randall Dick published their seminal epidemiologic research in the American Journal of Sports Medicine demonstrating a higher rate of ACL injuries in college female soccer and basketball athletes in comparison with males participating in the same sports. In this issue, you will find a 5-year update of the NCAA epidemiologic research that reaffirms the higher rate of injury in female athletes. You will also find an epidemiologic review that documents a higher rate of ACL injury in physically active females participating at the college, high school, Olympic, and military levels. Both papers emphasize the importance of prevention as the cornerstone to reducing the incidence of ACL injury in the female athlete.

To exemplify this emphasis on prevention, many of the articles in this issue focus on the potential risk factors for ACL injury. Extrinsic factors, which are somewhat controllable, include playing style, preparation and practice, conditioning, skill acquisition, environmental conditions, and equipment such as shoes and playing surface. Intrinsic factors include individual physical and psychosocial factors that are less controllable than the extrinsic factors. A plan for the standardized screening of the clinically measurable intrinsic anatomical risk factors, such as subtalar joint pronation, knee recurvatum, external tibial rotation, and lower extremity muscular strength, is presented. Several of the original research papers in this issue focus on the intrinsic risk factors of joint laxity, postural control, and knee biodynamics in female and male subjects. The general use of electromyography in assessing sex differences is explained, and 3 papers examine the neuromuscular factors related to muscle preactivity, fatigue, and reactive muscle firing during functional activity. Very recent research is presented that documents greater anterior laxity in conjunction with elevations in estrogen and progesterone levels during the menstrual cycle. Fluctuating hormonal levels represent one of the more obvious differences between males and females, yet the relevance of this finding to ACL injury in the female athlete has yet to be elucidated.

Specialized rehabilitation programs for the female athlete who is ACL deficient or who has undergone ACL reconstruction are presented. These programs also have application for preinjury proprioceptive, strength, and neuromuscular control exercises for the prevention of ACL injury. Finally, you will find that the Current Literature and Abstracts sections of this issue are entirely devoted to the anterior cruciate ligament.

Many people deserve recognition for this special issue. The authors and manuscript reviewers completed the process of review and revision in a timely manner so that deadlines for production could be met. The Associate Editors played a critical role in reviewing the papers in this issue, and, as always, the JAT office staff did a stellar job of overseeing and moving the manuscripts into production. I trust you will find the information in this issue useful to your clinical practice, and I hope athletic training researchers are stimulated to continue our efforts to find solutions to the increased risk of anterior cruciate ligament injury in the female athlete.
Anterior Cruciate Ligament Injury Patterns Among Collegiate Men and Women

Elizabeth A. Arendt, MD*; Julie Agel, ATC, MA*; Randall Dick, MS†

* University of Minnesota, Minneapolis, MN; † National Collegiate Athletic Association, Overland Park, KS

Objective: To determine potential patterns that cause males and females to tear the anterior cruciate ligament (ACL) while playing basketball or soccer.

Design and Setting: We reviewed data submitted to the National Collegiate Athletic Association Injury Surveillance System over the last 10 years, as well as profile data collected from collegiate certified athletic trainers.

Subjects: College athletes involved in basketball or soccer.

Measurements: Historical information was collected on those athletes involved in the National Collegiate Athletic Association Injury Surveillance System. Athletes involved in the profiling study underwent physical measurements related to flexibility, as well as a more detailed history relating to the ACL tear.

Results: College-age women involved in basketball or soccer tear their ACLs at significantly higher rates than college-age men involved in the same sports. No distinct physical or historical measurements could be attributed to this different rate of injury.

Conclusions: Although the higher rate at which women compared with men tear their ACLs has persisted over the last 10 years, this increased incidence is not clearly attributable to any physical or historical measurements that were monitored.

Key Words: epidemiology, knee, basketball, soccer

Women and girls began participating in sports in increasing levels and numbers in the 1970s. This increase paralleled the passage of Title IX, which mandated equal sports participation for girls and women in secondary- and college-level education systems. The passage of Title IX paralleled a universal women’s movement, which led to increased recognition for, and acceptance of, the talents and skill levels of women both inside and outside the athletic arena.

The increase in athletic participation also increased awareness of the health and medical issues of the female athlete. It is widely accepted that musculoskeletal injuries are largely sport specific and not sex specific. However, the differences being seen in the total number of injuries and the incidence of serious knee injuries among men and women athletes who participate in jumping and pivoting sports have come under recent review. In particular, the differences in anterior cruciate ligament (ACL) injury rates among men and women have come under special scrutiny.

There are 2 primary limitations to current sports injury epidemiology data. The first is that there is no common definition of injury, measure of severity, or evaluation of exposure in athletic injury literature. This makes it difficult to compare studies and pool data. The second limitation is the evaluation of exposure. An athlete exposure is the unit of risk when an athlete is exposed to the possibility of an athletic injury. The most rigid definition of injury exposure would define exposure by the amount of time played. To conform to this most rigid definition of exposure in a team sport such as basketball, one would need to keep track of the number of minutes played by each person on the team. A less rigorous criterion would define exposure as the participation of one athlete in one practice or game where he or she is exposed to the possibility of an athletic injury. This more practical way of measuring exposure still allows for consistency across schools and across time.

Authors EAA and RD previously undertook a study of available collegiate data to evaluate the incidence of ACL injuries in matched men’s and women’s sports across a broad sample and across multiple years. This paper will include a review of this previous study, as well as presentation of new data.

To test the hypothesis that female athletes were more susceptible to ACL injuries, authors EAA and RD originally looked at the National Collegiate Athletic Association (NCAA) database, which has a long history of experience in collecting injury patterns in a consistent method over time. The sports of basketball and soccer were chosen to study since they are sports that are both followed and reported in the NCAA Injury Surveillance System (ISS) and are played using the same rules. Injury data for the sports of men’s and women’s gymnastics are also tracked by the NCAA ISS. However, men and women in this sport share only the floor routine and the vault. Men’s lacrosse and women’s lacrosse are contact and noncontact sports, respectively. At this time, women’s volleyball, and not men’s volleyball, is followed by the NCAA ISS system.
Table 1. Knee Structures Injured in Soccer (1989 to 1993)

<table>
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<th>Injured Structure</th>
<th>Men's Soccer</th>
<th>Women's Soccer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number</td>
<td>Rate*</td>
</tr>
<tr>
<td>Collateral ligament</td>
<td>316</td>
<td>0.51</td>
</tr>
<tr>
<td>Cartilage (meniscus)</td>
<td>119</td>
<td>0.19</td>
</tr>
<tr>
<td>Patella or patellar tendon</td>
<td>130</td>
<td>0.21</td>
</tr>
<tr>
<td>ACL</td>
<td>81</td>
<td>0.13</td>
</tr>
<tr>
<td>Posterior cruciate ligament</td>
<td>22</td>
<td>0.04</td>
</tr>
</tbody>
</table>

* Rate based on injuries per 1000 athlete exposures. Athlete exposures: men’s, 626,223; women’s, 308,748.
† Probability based on χ² tests.
Reprinted with the permission of the American Journal of Sports Medicine.

METHODS

Data were collected using the NCAA ISS. The ISS was developed in 1982 to provide current and reliable data on injury trends in intercollegiate athletics. Injury data is collected yearly from a representative sample of NCAA member institutions.

To gain more insight into knee injuries, a new question was added to the ISS in 1989. Specific knee injuries were itemized to include injuries to the collateral, anterior cruciate, and posterior cruciate ligaments; cartilage (including the meniscus); and the patella or patellar tendon. Any or all of these structures could be included in a particular injury report. Specifically, since 1989, the enhanced NCAA ISS data on knee injuries have allowed the identification of ACL injury.

Sampling

Participation in the NCAA ISS system is voluntary and limited to the 931 member institutions (as of July 1998). ISS participants are selected from the population of institutions sponsoring a given sport. Selections are random within the constraints of having a minimum of 10% representation by each NCAA division (I, II, and III) and region (East, South, Midwest, and West). It is important to emphasize that this system does not identify every injury that occurs in each NCAA institution in a particular sport. Rather, it collects a sampling that is representative of a national cross-section of NCAA institutions.

Injuries

A reportable injury in the ISS is defined as one that “occurs as a result of participation in an organized intercollegiate practice or game, requires medical attention by a team athletic trainer or physician, and results in restriction of the student’s athletic participation for one or more days beyond the day of the injury.” Each reportable injury was detailed in a variety of subcategories by a single response that best described the injuries. These categories include injury mechanism (no apparent contact, contact with another player, contact with the floor) and an injury time (practice or game).

Exposures

An athlete exposure, the unit of risk in the ISS system, is defined as the participation of one athlete in one practice or game where he or she is exposed to the possibility of athletic injury.

Injury Rate

Injury rate is determined by comparing the number of injuries in a specific category with the number of athletes at risk in that category. The resulting value is expressed as injuries per 1000 athlete exposures.

RESULTS

First 5 Years, 1989 to 1993

Our initial study evaluated sex-specific knee injuries during a 5-year period from 1989 to 1993 in the sports of soccer and basketball.

Figure 1. NCAA ACL injury rate in soccer players, 1989–1993.
Soccer. Data were collected in the sport of soccer in 461 men’s teams (average, 92 per year) and 278 women’s teams (average, 56 per year) during this 5-year period. Participation reflected 15% of the NCAA institutions sponsoring that particular sport. The higher number of men’s teams reflects the greater absolute number of NCAA schools sponsoring the sport of soccer during those years and resulted in a higher number of athlete exposures. The male athlete’s exposure was approximately twice that of the female athlete’s exposure. Therefore, we cannot compare the absolute number of ACL injuries but must compare them over the denominator of athletic exposure, computing a rate.

Knee structures injured are shown in Table 1. The ACL injury rate in women’s soccer (0.31) was more than double that of the men’s rate (0.13). The difference in the ACL injury rate between the sexes was consistent in both practices and games. The mechanism of ACL injury between the sport of soccer was different in the men’s and women’s games. In the women’s games, no apparent contact was the primary mechanism of injury (63%), followed by player contact (37%). Player contact (52%), followed by no apparent contact (48%), was the primary injury mechanism in the men’s games. Women soccer players were 2 times more likely than their male counterparts to have an ACL injury as the result of player contact and 3 times more likely to obtain such an injury through noncontact mechanisms. For soccer, the ACL injury rate differences between men and women during the initial 5-year sample period are shown in Figure 1. The difference in injury rate between men and women was present in each of the years sampled and stayed consistent over the initial 5-year samples.

Basketball. Data were collected for 531 men’s teams (average, 107 per year) and 576 women’s teams (average, 115 per year) from 1989 to 1993. Participation values reflect 16% of the NCAA institutions that sponsored men’s basketball and 17% of the institutions that sponsored women’s basketball. This relatively equivalent number of teams participating in each sport reflects similar sponsorship in both sports and similar numbers of athlete exposures between men and women.

Knee structures injured in the sport of basketball are shown in Table 2. The ACL injury rate in women’s basketball (0.29) was more than 4 times that of the men’s (0.07). The difference in the ACL injury rate between the men and women remained consistent in both practices and games. In the women’s basketball data, no apparent contact (80%) was a primary injury mechanism, followed by player contact (20%). The same pattern was evident in the men’s data. For basketball, the ACL injury rate between men and women during the initial 5-year sample is shown in Figure 2. The difference in this variable was present across each of the years sampled.

Second 5 Years, 1994 to 1998

One theory concerning the disparity in injury rates suggests that a difference in the skill levels of male and female athletes when they enter college sports is responsible for the higher injury rate in women. Presumably, women come into the sports of soccer and basketball with a reduced skill level compared with men and perhaps with fewer years of training. It was felt that, as the years progressed from the early 1990s to the late 1990s, this lack of skill would be less apparent, since more women were entering their sports at earlier ages. Certainly this is reflected in the current data of the number of women playing high school basketball and soccer, as well as the general increase in participation in these sports nationally, both in community and secondary education systems.

**Figure 2. NCAA ACL injury rate in basketball players, 1989–1993.**

*A-E = athlete exposures. Reprinted with the permission of the American Journal of Sports Medicine.**
With this in mind, we recently revisited more modern data for the sports of men’s and women's soccer and basketball. We again used the NCAA ISS data.

**Soccer.** Reviewing the data from the 5-year period of 1994 to 1998, we noted that, in comparison with men, women continued to have a higher incidence of ACL injury in soccer. This holds true for both practice time and game time (Table 3). The athletic exposures for women are approaching those for men, reflecting increasing participation of women in the sport of soccer within NCAA institutions. The ACL injury rates for men and women during the second 5-year sample are shown in Figure 3. The difference in this variable was present across each of the years sampled.

**Basketball.** In basketball during the 5-year period of 1994 through 1998, we again saw a consistently high pattern of injury rate in women as compared with men (Table 4). The injury rate for the ACL in women’s basketball was nearly triple that of men in both practices and games. The athletic exposure for women was comparable with men, reflecting comparable participation for men and women in the sport of basketball within NCAA institutions. The ACL injury rate between men and women during the second 5-year sample is shown in Figure 4. The difference in the variable was present across each of the years sampled. Although the overall exposure in game time was significantly less than practice time for men and women, the injury rate in games was greater than the injury rate in practice among both men and women in both basketball and soccer.

**Women’s volleyball.** We were also interested in looking at women’s injury rates in volleyball, giving us another women’s sport that might have similar mechanisms of injury, ie, jumping, planting, and pivoting with sudden position changes. Looking at women’s volleyball in the years 1997 and 1998, we noted that women have both game and practice ACL injury rates that are substantially less than the injury rates in women’s soccer and basketball (Table 5). Reflecting on these 3 sports, we found it curious that basketball and soccer share a high ACL injury rate for women when they are played very differently, one being a sport that involves a cleated shoe on grass with significant planting and pivoting, the other involving a court shoe on a wood surface that requires planting, pivoting, and jumping. Comparing basketball with volleyball, both are played on a wooden court with a shoe and involve jumping, with perhaps less sudden changes in planting and pivoting. However, women’s volleyball has a significantly lower ACL injury rate than women’s basketball.

### DISCUSSION

Trying to further analyze the causative factors with regard to noncontact ACL (NCACL) injuries has been a difficult task. Athletic injuries result from a complex interaction of risk factors. Risk factors can be classified into 2 categories. The first category, extrinsic factors, comprises those factors related to the type of sports activity, the manner in which the sport is practiced, environmental conditions, and the equipment used to play a sport. The second category, intrinsic factors, comprises those factors that are individual, physical, and psychosocial. Using this scheme, positive causation factors for an increase in ACL injuries among women are frequently divided into extrinsic factors (body movement, muscular strength, shoe-surface interface, and skill level) and intrinsic factors (joint laxity, limb alignment, intercondylar notch dimensions, ligament size, and hormonal influences). The current thought is that the increased risk of ACL injuries among women is likely multifactorial, with no single structural, anatomical, or biomechanical feature solely responsible for this increased rate.

**Table 3. Total ACL Injuries for Women’s and Men’s Soccer (1994 to 1998)**

<table>
<thead>
<tr>
<th>Year</th>
<th>Women's Soccer</th>
<th>Men's Soccer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total Injuries</td>
<td>Total exposure</td>
</tr>
<tr>
<td>1998</td>
<td>38</td>
<td>111336</td>
</tr>
<tr>
<td>1997</td>
<td>42</td>
<td>111887</td>
</tr>
<tr>
<td>1996</td>
<td>29</td>
<td>102836</td>
</tr>
<tr>
<td>1995</td>
<td>27</td>
<td>90377</td>
</tr>
<tr>
<td>1994</td>
<td>22</td>
<td>61840</td>
</tr>
<tr>
<td>Total</td>
<td>158</td>
<td>478276</td>
</tr>
</tbody>
</table>
Table 4. Total ACL Injuries for Women's and Men's Basketball (1994 to 1998)

<table>
<thead>
<tr>
<th>Year</th>
<th>Women's Basketball</th>
<th></th>
<th>Men's Basketball</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total injuries</td>
<td>Total exposure</td>
<td>Rate</td>
<td>Total injuries</td>
</tr>
<tr>
<td>1998</td>
<td>33</td>
<td>133,773</td>
<td>0.247</td>
<td>10</td>
</tr>
<tr>
<td>1997</td>
<td>37</td>
<td>156,252</td>
<td>0.237</td>
<td>18</td>
</tr>
<tr>
<td>1996</td>
<td>39</td>
<td>129,395</td>
<td>0.301</td>
<td>16</td>
</tr>
<tr>
<td>1995</td>
<td>47</td>
<td>142,843</td>
<td>0.329</td>
<td>19</td>
</tr>
<tr>
<td>1994</td>
<td>38</td>
<td>109,125</td>
<td>0.348</td>
<td>12</td>
</tr>
<tr>
<td>Total</td>
<td>194</td>
<td>671,388</td>
<td>0.289</td>
<td>75</td>
</tr>
</tbody>
</table>

BASKETBALL
ACL Injury Rate, 1994-1998

Figure 4. NCAA ACL injury rate in basketball players, 1994-1998.
*A-E = athlete exposures.

The etiology of the increased risk of ACL injuries in women, particularly women who play jumping and pivoting sports, remains speculative. However, skill level continues to be implicated, especially in the early years after the enactment of Title IX. Although years of participation and experience do not equate with skill level, typically there is a positive relationship between the number of years playing a sport and one’s skill level. With this in mind, we hoped that, as the years progressed into the mid 1990s, we might see a drop in the ACL injury rate in the collegiate athlete. This does not appear to be the case based on data collected by a similar method (NCAA ISS) and compared over 2 separate 5-year periods (1989 to 1993 and 1994 to 1998). This finding suggests that neither lack of skill nor lack of years of experience playing a sport is the primary causative factor for injury or that skill level has to be measured in a more rigorous method than by years exposed to an organized athletic experience.

PROFILE OF THE ACL-INJURED ATHLETE: A PILOT STUDY

In an effort to further unravel the ACL problem, the NCAA, along with a group of interested physicians and college certified athletic trainers, launched a pilot study. The goal of this pilot project was to develop a profile of variables that would be consistently present in the injured athlete. The communication network that was used was the same network of communication used in the NCAA ISS system. The variables looked at were those physical examination features, or historical features, of the athlete that could be examined or gathered by a history and physical examination. The variables were based on popular theories as to the causative factors of ACL injuries. They included physical examination features of hip range of motion, especially internal rotation, suggesting an anteverted stance; large Q-angle; hyperextension at the knee; and generalized tissue hyperlaxity. Historical features that could be elicited in this form of survey study included timing of the injury in relation to one’s menstrual cycle (for women only) and the number of years played in one’s sport. Certainly a description of the mechanism of injury and features such as shoe and floor or playing surface could also be included. The number of variables that needed to be collected was sizable. In order to reach statistical significance with this large number of variables, hundreds of ACL injuries would need to be recorded to produce statistical significance. Therefore, the project earmarked the ACL-injured athlete to record features that could be

Table 5. Injury Rate Comparison for Women (1998 and 1997)

<table>
<thead>
<tr>
<th>Sport</th>
<th>Practice</th>
<th>Game</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Year</td>
<td>Injury</td>
</tr>
<tr>
<td>Volleyball</td>
<td>1998</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>1997</td>
<td>8</td>
</tr>
<tr>
<td>Basketball</td>
<td>1998</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>1997</td>
<td>16</td>
</tr>
<tr>
<td>Soccer</td>
<td>1998</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>1997</td>
<td>11</td>
</tr>
</tbody>
</table>
reviewed after the athlete was injured. The goal was to see whether there was any commonality among the injured athletes. This would produce a profile, or snapshot, of the injured athlete that could lay the foundation for which factors would be most important to study in a more rigorously controlled fashion.

Data Collection

Data were gathered from the 1996 to 1998 academic years. Two forms were used for this project. The first involved an interview-type questionnaire that reviewed medical and sports participation history; a second form included physical examination features based on the contralateral limb. All reporting from the colleges and universities was voluntary.

The data were collected by certified athletic trainers. Pictures accompanied the data collection forms to ensure that the data were collected in a consistent manner. At the beginning of the pilot project, we conducted a telephone conference call that included one certified athletic trainer from each participating athletic conference.

Population

There were 104 NCACL injuries reported (43 male, 61 females). Ninety-seven of these athletes were felt to be eligible for further analysis. The diagnosis of an NCACL was confirmed by arthroscopy in 19 cases and by MRI in an additional 48. Of the remaining 30 NCACL tears, 26 were confirmed by an orthopaedic surgeon's manual examination. Forty-nine (50%) of the athletes in this study sustained their injuries in the sports of basketball and soccer.

Mechanism of Injury

The most common reported mechanism of injury, according to the athlete, was planting and pivoting (n = 28) (Table 6). Twenty-one of the NCACL tears occurred in practice and 26 occurred in a game. Two did not report whether their injury occurred in a practice or in a game. Twelve were listed as preseason events, 29 as in-season, and 1 as postseason. Seven did not report the sport season in which their injury occurred.

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Frequency</th>
<th>Percentage</th>
<th>Cumulative Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landing from a jump</td>
<td>6</td>
<td>12.2</td>
<td>12.2</td>
</tr>
<tr>
<td>Planting/pivoting</td>
<td>28</td>
<td>57.1</td>
<td>69.4</td>
</tr>
<tr>
<td>Deceleration</td>
<td>6</td>
<td>12.2</td>
<td>81.6</td>
</tr>
<tr>
<td>Going up for a jump</td>
<td>2</td>
<td>4.1</td>
<td>85.7</td>
</tr>
<tr>
<td>Hyperextension</td>
<td>6</td>
<td>12.2</td>
<td>98.0</td>
</tr>
<tr>
<td>Unsure</td>
<td>1</td>
<td>2.0</td>
<td>100.0</td>
</tr>
<tr>
<td>Total</td>
<td>49</td>
<td>100.0</td>
<td></td>
</tr>
</tbody>
</table>

CONCLUSIONS

In the profile of the injured soccer and basketball athlete, the mechanism of NCACL injury was pivoting or landing from a jump. There was no evidence of comorbidity in injury or illness. These athletes were experienced, with several years of sports participation before and during high school. There was no significant difference between the sexes. The mean age at which the athletes first began playing their sport was 8.7 years, with no difference between the sexes (males = 8.73 ± 3.26, females = 8.58 ± 3.48).

Physical Examination Results

Thirty-six of the injured athletes submitted physical examination data. These athletes had no evidence of a hyperlaxity syndrome. Their hip flexors had normal range of motion. Twelve (33%) of the athletes had hamstring muscle tightness. Q-angles were not excessive, with males averaging 7° and females averaging 12°. Foot-thigh progression angles were also not excessive, with 92% recording a foot-thigh progression angle of less than 20°. Most athletes (90%) had measured heel height to table that was greater than 15 mm, reflecting some degree of knee hyperextension.
no consistent abnormal physical examination feature, except for knee hyperextension. Females were more likely to be injured just before or just after their menses and not midcycle.

We hope that this report stimulates research to examine the multiple variables that may contribute to this difference in rate of injury. Results of such research can contribute to a safer athletic experience for all participants. We feel that this profile of the injured athlete helps us to further refine the variables upon which future studies should be performed.

REFERENCES

Anterior Tibial Translation in Collegiate Athletes with Normal Anterior Cruciate Ligament Integrity

John M. Rosene, DPE, ATC*; Tracey D. Fogarty, DPE†
*University of Southern Maine, Gorham, ME; †Castleton State College, Castleton, VT

Objective: To examine differences in anterior tibial translation (ATT) among sports, sex, and leg dominance in collegiate athletes with normal anterior cruciate ligament integrity.

Design and Setting: Subjects from various athletic teams were measured for ATT in right and left knees.

Subjects: Sixty subjects were measured for ATT with a KT-1000 knee arthrometer.

Measurements: Statistical analyses were computed for each sex and included a $2 \times 3 \times 4$ mixed-factorial analysis of variance (ANOVA) for anterior cruciate ligament displacement, right and left sides, and force and sport. A $2 \times 2 \times 3$ mixed-factorial ANOVA was computed to compare means for sex and force. A $2 \times 3$ mixed-factorial ANOVA was computed to compare sex differences across 3 forces.

Results: For males and females, no significant interactions were found among leg, force, and sport for mean ATT, for leg and sport or leg and force, or for translation values between dominant and nondominant legs. Males had a significant interaction for force and sport, and a significant difference was found for side of body, since the right side had less translation than the left side. Females had greater ATT than males at all forces.

Conclusions: Sex differences exist for ATT, and differences in ATT exist among sports for both sexes. Differences between the right and left sides of the body should be expected when making comparisons of ligamentous laxity.

Key Words: knee, displacement, arthrometry

Much has been written on the surgical intervention and rehabilitation of anterior cruciate ligament (ACL) injuries. In the past, interest has been minimal in gaining a full understanding of the mechanism of injury and determining whether any specific conditions exist that may predispose an athlete to ACL damage. There has been speculation that ACL injuries may result from loose or tight joints, and they appear to be prevalent in sports requiring jumping and pivoting. In cases where abnormally loose or tight joints are identified, exercises for increasing strength and flexibility are indicated to try to decrease the incidence of ligament and muscle damage.

Clinicians have noted that, during knee-extension exercises, shear forces resulting in greater ACL tension are evident at the end range of extension, and they appear to be greatest between 0° and 45° of knee flexion. However, these shear forces during knee extension may be compensated for by ACL and hamstring coactivation. In athletic competition, particularly in those sports that require pivoting and jumping, ACL and hamstring coactivation may be of primary importance in reducing shear forces at the knee. Since the ACL provides approximately 86% of primary restraint of anterior tibial translation (ATT), any damage to the ACL may have lasting adverse effects on knee stability.

Researchers have examined a variety of factors that may affect the incidence of ACL injury or the mechanics of the ACL under varied conditions. One factor that may influence damage to theACL is sex, with females displaying a higher incidence of ACL injury than males. Researchers have speculated that this sex difference is primarily related to the physiologic differences between males and females. Arendt and Dick categorized contributing factors for ACL damage into extrinsic and intrinsic factors. Extrins

Much of the literature has addressed the damaged ACL in operative and nonoperative procedures or its rehabilitation. Our review of the literature revealed limited data regarding the effects of normal daily sport activities on the uninjured ACL. Do these activities affect the amount of laxity in the normal ACL, thereby creating a loose joint scenario? Although this may not identify susceptibility to ACL injury, the effects of such activities may assist therapists in designing proper rehabilitation programs after injury to the ACL. Therefore, the purpose of our study was to examine...
differences in ATT among sport, sex, and leg dominance in collegiate athletes with normal ACL integrity.

METHODS

Subjects

The subjects tested were 60 (22 male, 38 female) collegiate athletes with a mean ± SD age of 19 ± 1.3 years, mean height of 172.97 ± 10.73 cm, mean weight of 71.07 ± 11.72 kg, and mean body fat percentage of 17.95% ± 9.02%. Each subject was active with an intercollegiate varsity athletic team and volunteered for the study. The sports represented were men's volleyball (n = 12), women's volleyball (n = 6), men's soccer (n = 9), women's soccer (n = 5), women's basketball (n = 7), and women's softball (n = 21). Subjects were disqualified if they had any documented history of knee ligament or meniscal damage. All procedures were approved by the Human Subjects Research Review Committee at William Woods University.

Measurements

To measure ATT, the KT-1000 knee arthrometer (MEDmetric Corporation, San Diego, CA) was used (Figure 1). This arthrometer has been shown to be a reliable instrument to measure both anterior and posterior tibial translation.\(^4\)\(^{31-33}\) The arthrometer is designed to provide quantitative data on the extent of anterior-posterior tibial translation with respect to the femur at known forces.\(^5\)\(^{32}\) To measure ATT, the procedures as described by Daniel and Stone\(^34\) were followed. All measurements were taken bilaterally. Three trials were performed on each limb, and the mean of the 3 trials at each load was used as the reading. Leg dominance was determined by which leg the subject would use to kick a ball.\(^35\)

Statistical Analysis

Analyses were performed for sport, force, leg dominance, and side of body for each sex. A 2 × 3 × 4 mixed-factorial analysis of variance (ANOVA) was computed to compare the ATT means for females. The 3 independent variables included 2 within-subjects factors, leg (dominant and nondominant) and force (67 N, 89 N, and 134 N), and a between-subjects factor, sport (volleyball, soccer, softball, or basketball). For males, a 2 × 2 × 3 mixed-factorial ANOVA was computed with 2 within-subjects factors, leg and force. The between-subjects factor of sport included only volleyball and soccer. A 2 × 3 × 4 mixed-factorial ANOVA was computed to determine differences in ATT between right and left sides, force, and sport for females. For males, a 2 × 2 × 3 mixed-factorial ANOVA was computed for differences in ATT between right and left sides, force, and sport. Sex differences were examined across the 3 forces using a 2 × 3 mixed-factorial ANOVA. The generalized least-squares procedure from the Statistical Package for Social Sciences (version 8.0, SPSS, Inc, Chicago, IL) for Windows\(^36\) was used to calculate the statistics. For all analyses, the α level was set at \(P < .05\).

RESULTS

The descriptive statistics for dominant and nondominant legs across forces and sport are presented in Table 1 for females and Table 2 for males. Descriptive statistics depicting right and left legs for forces and sport are presented in Table 3 for females and Table 4 for males. To test for basic assumptions, we computed the Mauchly’s test of sphericity for the within-subjects factors of force values and leg dominance in the first analysis and force values and side of body in the second analysis. The test analyzed the similarity of the treatment differences across 3 force conditions for all subjects. For females, force and both leg conditions (dominance and side of body) were significantly different \(P < .05\) (Mauchly’s \(W_{\text{force}} = 0.191\), Mauchly’s \(W_{\text{leg} \times \text{force}} = 0.268\), Mauchly’s \(W_{\text{side} \times \text{force}} = 0.232\)). In addition, for males, force and both leg conditions were significantly different \(P < .05\) (Mauchly’s
Table 2. Anterior Tibial Translation of Dominant and Nondominant Legs for Sport and Force for Males (mm)

<table>
<thead>
<tr>
<th>Sport</th>
<th>Force (N)</th>
<th>Dominant (mean ± SD)</th>
<th>Nondominant (mean ± SD)</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volleyball</td>
<td>67</td>
<td>3.35 ± 1.28</td>
<td>3.50 ± 1.41</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>89</td>
<td>3.89 ± 1.44</td>
<td>4.15 ± 1.57</td>
<td></td>
</tr>
<tr>
<td></td>
<td>134</td>
<td>4.74 ± 1.75</td>
<td>4.84 ± 1.75</td>
<td></td>
</tr>
<tr>
<td>Soccer</td>
<td>67</td>
<td>5.26 ± 1.53</td>
<td>5.61 ± 1.93</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>89</td>
<td>6.17 ± 1.68</td>
<td>6.72 ± 1.82</td>
<td></td>
</tr>
<tr>
<td></td>
<td>134</td>
<td>7.02 ± 1.86</td>
<td>7.89 ± 1.65</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Anterior Tibial Translation of the Right and Left Legs for Sport and Force for Females (mm)

<table>
<thead>
<tr>
<th>Sport</th>
<th>Force (N)</th>
<th>Right (mean ± SD)</th>
<th>Left (mean ± SD)</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volleyball</td>
<td>67</td>
<td>4.62 ± 1.90</td>
<td>3.50 ± 1.10</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>89</td>
<td>5.82 ± 2.25</td>
<td>4.25 ± 1.17</td>
<td></td>
</tr>
<tr>
<td></td>
<td>134</td>
<td>6.80 ± 2.51</td>
<td>5.47 ± 1.03</td>
<td></td>
</tr>
<tr>
<td>Softball</td>
<td>67</td>
<td>5.32 ± 1.63</td>
<td>6.25 ± 2.03</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>89</td>
<td>6.79 ± 1.97</td>
<td>7.55 ± 2.26</td>
<td></td>
</tr>
<tr>
<td></td>
<td>134</td>
<td>8.47 ± 2.75</td>
<td>9.11 ± 2.48</td>
<td></td>
</tr>
<tr>
<td>Soccer</td>
<td>67</td>
<td>3.80 ± 1.79</td>
<td>4.68 ± 1.65</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>89</td>
<td>4.50 ± 2.03</td>
<td>5.56 ± 1.79</td>
<td></td>
</tr>
<tr>
<td></td>
<td>134</td>
<td>4.66 ± 1.65</td>
<td>6.30 ± 1.72</td>
<td></td>
</tr>
<tr>
<td>Basketball</td>
<td>67</td>
<td>5.25 ± 1.24</td>
<td>5.21 ± 1.50</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>89</td>
<td>6.35 ± 1.65</td>
<td>6.14 ± 1.49</td>
<td></td>
</tr>
<tr>
<td></td>
<td>134</td>
<td>8.47 ± 2.27</td>
<td>7.29 ± 1.63</td>
<td></td>
</tr>
</tbody>
</table>

Table 4. Anterior Tibial Translation of the Right and Left Legs for Sport and Force for Males (mm)

<table>
<thead>
<tr>
<th>Sport</th>
<th>Force (N)</th>
<th>Right (mean ± SD)</th>
<th>Left (mean ± SD)</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volleyball</td>
<td>67</td>
<td>2.60 ± 1.25</td>
<td>4.25 ± 0.78</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>89</td>
<td>2.99 ± 1.25</td>
<td>5.05 ± 0.84</td>
<td></td>
</tr>
<tr>
<td></td>
<td>134</td>
<td>3.64 ± 1.44</td>
<td>5.94 ± 1.08</td>
<td></td>
</tr>
<tr>
<td>Soccer</td>
<td>67</td>
<td>5.09 ± 1.58</td>
<td>5.78 ± 1.84</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>89</td>
<td>6.00 ± 1.71</td>
<td>6.89 ± 1.71</td>
<td></td>
</tr>
<tr>
<td></td>
<td>134</td>
<td>7.02 ± 1.74</td>
<td>7.89 ± 1.78</td>
<td></td>
</tr>
</tbody>
</table>

$W_{\text{forc}} = 0.296$, Mauchly’s $W_{\text{leg} \times \text{force}} = 0.349$, Mauchly’s $W_{\text{side} \times \text{force}} = 0.328$. The Greenhouse-Geiser statistic was used to adjust for the degrees of freedom.

For females, no significant interaction was found among leg, force, and sport for mean ATT ($F_{3,5,40.2} = 0.74$, $P > .05$). In addition, no significant interactions were found between leg and sport ($F_{3,35} = 1.06$, $P > .05$), force and sport ($F_{3,38.7} = 1.63$, $P > .05$), or leg and force. The analysis of the main effects revealed no significant effect in ATT values between dominant and nondominant legs ($F_{1,35} = 0.35$, $P > .05$). However, a significant difference was found among force values for mean ATT ($F_{1,38.7} = 74.37$, $P < .05$). Pairwise comparisons were computed to determine where significance occurred. The mean ATT at 67 N was significantly lower than the mean ATTS at 89 N and 134 N. In addition, the mean ATT at 89 N was significantly lower than the mean ATT at 134 N (Figure 2). Also, a significant difference was found among sports for mean ATT ($F_{3,35} = 4.5$, $P < .05$). Pairwise comparisons revealed that volleyball and soccer had significantly lower mean ATT values than softball did (Figure 3).

For males, no significant interaction was found among leg, force, and sport for mean ATT ($F_{1,223} = 1.61$, $P > .05$). Furthermore, no significant interactions were found between leg and sport ($F_{1.19} = 0.21$, $P > .05$) or leg and force ($F_{1,223} = 0.98$, $P > .05$). However, a significant interaction between force and sport was found ($F_{1.22.3} = 6.14$, $P < .05$). A least-significant difference post hoc analysis was performed to provide further information on how the three forces impacted the two sports. For all forces, volleyball players had significantly lower mean ATT values than soccer players did (Figure 4).

In the second analysis, mean ATT for the side of the body (right and left), force, and sport were examined. It should be noted that females were 95% dominant on the right side, while 5% were dominant on the left side. Males were 66.6% dominant on the right side and 33.4% dominant on the left. For both females and males, there was no significant interaction among side of body, force, and sport (females $F_{3,5,40.2} = 48$, $P > .05$, males $F_{1,22.3} = 1.14$, $P > .05$). For females, no significant interactions existed for force and sport ($F_{3,38.7} = 1.63$, $P > .05$), side and sport ($F_{3,35} = 2.33$, $P > .05$), or side and force ($F_{1,40.2} = 0.86$, $P > .05$). Significant differences existed for sport and force (Figures 2 and 3).

For males, no significant interactions existed for side and force ($F_{1,22.2} = 3.75$, $P > .05$) or side and sport ($F_{1,9} = 3.96$, $P > .05$). There was a significant interaction between force and sport (Figure 4). A significant mean difference was found for side of body ($F_{1,19} = 22.28$, $P < .05$). The right side had a lower mean ATT than the left side (Figure 5).

Figure 2. Mean ATT values for the 3 forces for females for dominant and nondominant legs. * Sixty-seven Newtons was associated with less ATT than 89 and 134 N ($P < .05$); ** 89 N was associated with less ATT than 134 N ($P < .05$).
Figure 3. Mean ATT values for the 4 sports for females for dominant and nondominant legs. * Volleyball and soccer players had less ATT than softball players ($P < .05$).

Figure 4. Interaction chart for force and sport for males. * Volleyball players had less ATT than soccer players at 67, 89, and 134 N ($P < .05$).

Figure 5. Mean ATT for side of body for males. * Right side had less ATT than left side ($P < .05$).

**DISCUSSION**

Perhaps the most consistent proposed reason for injury of the ACL is a twisting motion at the knee, such as occurs during a cutting maneuver or with deceleration, both common in most sports. During these actions, the hamstrings and ACL work in concert to restrict ATT, while the quadriceps encourage translation. The athlete who favors the dominant leg during these movements or jumping motions may be increasing ACL stress. In the ACL-deficient knee, the hamstrings assist in decreasing the amount of ATT, and rehabilitation protocols that focus on hamstring strengthening may aid in joint stabilization, especially during cutting maneuvers. As a result of possible strength differences between dominant and nondominant limbs, limb dominance may affect the stabilization at each knee joint. Burnie and Brodie found that preadolescent males did not differ in limb strength between dominant and nondominant limbs. However, they suggested that, as children get older

<table>
<thead>
<tr>
<th>Source</th>
<th>Sums of Squares</th>
<th>Degrees of Freedom</th>
<th>Mean Square</th>
<th>$F$</th>
<th>$P$</th>
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<tr>
<td>Between subjects</td>
<td></td>
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<td>15.42</td>
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<tr>
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<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Leg</td>
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<td>1</td>
<td>2.18</td>
<td>.35</td>
<td>.559</td>
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<td>3</td>
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<tr>
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<td>1.1</td>
<td>142.36</td>
<td>74.37</td>
<td>.000*</td>
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<tr>
<td>Force $\times$ sport</td>
<td>10.36</td>
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<tr>
<td>Error (force)</td>
<td>74.05</td>
<td>38.7</td>
<td>1.91</td>
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<td>Leg $\times$ force</td>
<td>.39</td>
<td>1.3</td>
<td>.34</td>
<td>.29</td>
<td>.628</td>
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<tr>
<td>Leg $\times$ force $\times$ sport</td>
<td>3.02</td>
<td>3.5</td>
<td>.87</td>
<td>.74</td>
<td>.552</td>
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<td>Error (leg $\times$ force)</td>
<td>47.82</td>
<td>40.4</td>
<td>1.18</td>
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<td></td>
</tr>
</tbody>
</table>

* $P < .05$.  

Table 5. Anterior Tibial Translation of Males and Females Across Three Forces (mm)
At each force, females had higher ATT than males transmitted through the patellar tendon. The magnitude of this force influences the amount of ATT. In normal daily activities, forces at the knee joint typically exceed 1 to 2 times body weight. In sports activities, these forces increase to approximately 5 times body weight.

In our investigation, there were no significant differences between dominant and nondominant limbs for ATT. This suggests that the load imposed on the ACL during a forceful quadriceps contraction may be reduced with hamstring activation, since the hamstrings also function to restrain ATT. Hamstring activation is an essential component of knee joint stabilization, since the quadriceps muscle group can impose a load that exceeds the forces required for tensile failure of ligament.

Significant differences between right and left legs were found in males, with the right leg having lower mean ATT values than the left leg. These differences may represent normal side-to-side differences in ligamentous laxity. Sakai et al. reported side-to-side differences of less than 2 mm in ATT in female basketball players with no history of knee trauma. Daniel et al. reported that detection of a 3-mm difference in ATT between right and left knees is highly accurate in diagnosing ACL injury. Clinicians performing subjective comparisons must be aware that differences in laxity may exist in the absence of injury. When objective measures are used, such as the KT-1000 arthrometer, side-to-side differences should be expected. However, as Daniel et al. reported, further testing is warranted with a 3-mm or more difference in ATT between right and left sides and a history of knee injury.

An increase in sports participation has resulted in an increase in sport-related injuries. These injuries, particularly of the musculoskeletal system, appear to be sport specific and not sex specific. However, the role sex may play in the incidence of sports injuries cannot be ignored. For example, basketball has been identified as being a high-risk sport, especially for female athletes, due to a higher incidence of injury in female basketball players than in their male counterparts. Arendt and Dick speculated that males may be more effective at modifying their movements to prevent ACL injury than females are.

In our study, female volleyball and soccer subjects had lower mean ATT values as compared with softball players. For males, volleyball subjects had lower mean ATT values as compared with soccer players. Such readings may be a result of sport-specific adaptation by the ACL and thigh musculature due to the number of jumping and pivoting movements required in each sport. In jumping activities, the knee extensors achieve peak maximum muscle activity 190 milliseconds before leaving the ground. In pivoting or change-of-direction movements, the hamstrings and ACL assist in stabilizing the tibia via the screw-home mechanism. Both movements require proper functioning of the bony and soft tissue structures to achieve movement. The repetitive use of these structures, particularly the soft tissues, may enhance their restraint capabilities for ATT during activity, which may translate to a reduction in ATT when the leg is relaxed.

Sex differences found for ATT were not surprising, since females tend to have greater ATTs. Speculative explanations for these differences have involved hormonal differences, ligament size, state of physical training, muscle strength, anatomical structure, and muscle coordination, among others. These differences may be implicated in a higher incidence of knee injury for females than males.

Recently, hormonal concentrations and their effects on ACL structure and composition have been investigated. Liu et al. examined 17 ACL specimens (13 female, 4 male) obtained surgically and found estrogen and progesterone target cells in the ACL. Liu et al. suggested that the presence of these receptors, in addition to other causes, may be responsible for the increased incidence of ACL injury in females.

The normal activities of sports participation and daily living may not be sufficient to impose a stress on the ACL that would create abnormal laxity. Bilateral comparisons between ACLs may yield differences in laxity, which may result in false-positive tests. Any suspicions of ACL damage should be confirmed with additional diagnostic procedures, such as magnetic resonance imaging.

Further investigation is warranted into the effects of limb dominance, sports participation, and side-to-side differences on the normal ACL. Also, the causes of sex differences in ligamentous laxity should be investigated.

**ACKNOWLEDGMENTS**

We express sincere thanks to Bill Elliott, Orthopaedic Physician Assistant-Certified, of the Columbia Orthopaedic Group, Columbia, MO, for allowing us the use of the KT-1000 knee arthrometer; to Robin Audesse of the University of Southern Maine, Department of Sports Medicine, for her assistance in compiling the data and preparation of the manuscript; and to Dr. Darryn Willoughby of the University of Southern Maine, Department of Sports Medicine, for helping with the preparation of the manuscript.
REFERENCES


Generalized Joint Hypermobility and Its Relationship to Injury Patterns Among NCAA Lacrosse Players

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* HealthSouth/New Hampshire Musculoskeletal Institute, Manchester, NH; † Plymouth State College, Plymouth NH; ‡ University of Vermont, Burlington, VT; § New Hampshire Musculoskeletal Institute, Manchester, NH

**Objective:** To prospectively observe and compare injury patterns between hypermobile and nonhypermobile NCAA athletes.

**Design and Setting:** Athletes were screened for generalized joint hypermobility before the 1995 lacrosse season. Injuries were recorded through the end of the postseason and compared in hypermobile and nonhypermobile athletes.

**Subjects:** A total of 310 male and female volunteers from 17 lacrosse teams participated in the study.

**Measurements:** Hypermobility was evaluated with the technique of Carter and Wilkinson (as modified by Beighton and colleagues), which uses 9 joint measurements to assess global joint mobility. For an athlete to be considered hypermobile, 5/9 of these measurements must have been positive. Next, certified athletic trainers prospectively recorded injuries and hours of practice and game participation on a standard form. After the season, all data forms were returned to us for analysis. Significance was set at \( P = .05 \), and \( \chi^2 \) and independent \( t \) tests were used to compare injuries between groups.

**Results:** Twenty of 147 men (13.6%) and 54 of 163 women (33.1%) were hypermobile, yielding an overall hypermobility prevalence of 23.8%. One hundred athletes sustained 134 injuries. There were no significant differences in overall injury rate among hypermobile (2.29/1000 hours) compared with nonhypermobile (3.54/1000 hours) athletes. Nonhypermobile athletes suffered contact injuries at a higher rate (1.38/1000 hours) than hypermobile athletes (0.52/1000 hours). Hypermobile athletes showed an increased rate of ankle injuries, and nonhypermobile athletes showed a trend toward an increased rate of strains. Multiple approaches to analysis of the data revealed no other significant findings.

**Conclusions:** There was no difference in overall injury rates between hypermobile and nonhypermobile athletes in this sample. This finding is somewhat surprising in light of significant evidence that hypermobility appears to be a factor in joint complaints among nonathletes. Additional research is needed to clearly determine whether a relationship exists between hypermobility and injury rates among athletes.

**Key Words:** athletic injury surveillance, laxity, injury risk, rheumatology

Joint hypermobility is a well-recognized characteristic of collagen disorders such as Marfan syndrome and Ehlers-Danlos syndrome. However, joint hypermobility also exists in the absence of rheumatic disease and is often referred to as “double jointedness” by the lay public. This subject has been the topic of many studies, with research beginning in earnest in the early 1960s. Since that time, relationships have been found among global joint hypermobility and a wide array of physical maladies, including insidious arthralgia, premature osteoarthritis, and fibromyalgia. Based on such research and discussion in the rheumatologic and pediatric literature, current wisdom among rheumatologists and pediatricians suggests that hypermobile individuals should avoid strenuous physical activity because of a possible increased risk of athletic injury.

However, many hypermobile individuals are currently participating in athletic programs and activities. And, while the morbidity of hypermobility appears well supported by studies of nonathletes, studies of athletes are relatively limited. Further, the conclusions of these limited studies are split with regard to whether hypermobile individuals actually run a higher risk of athletic injury. For example, Kujala et al found no relationship between hypermobility and back pain or between hypermobility and injuries, respectively, in athletic populations. Acasuso-Diaz et al and Klemp et al, however, have found a relationship between hypermobility and injuries among soldiers and ballet dancers. Differences in methodology, common in hypermobility studies, also create problems in combining and comparing existing studies.

It is important to recognize and confirm any conditions that might predispose athletes to injury. The purpose of our study was to prospectively observe injury patterns among hypermobile and nonhypermobile athletes over one athletic season.
METHODS

Two members of the research team (RHL and LCD) traveled to all participating schools to screen athletes and to train data collectors.

Hypermobility Assessment

A total of 310 (147 males, age = 20 ± 2 years; 163 females, age = 20 ± 4 years) volunteers from 17 NCAA lacrosse teams were screened for hypermobility using the method developed by Carter and Wilkinson\(^{18}\) and modified by Beighton et al.\(^{6}\) The cohort included all members of the participating teams. This method, validated by Bird et al.\(^{39}\) examines the ability to hyperextend knees and elbows beyond 10°, to passively extend the fingers so they are parallel to the forearm, to passively abduct the thumb so that it touches the forearm, and to forward flex the trunk so that the palms easily touch the floor, and it employs a 0 to 9 scoring scheme (Figure 1). A goniometer was used to measure knee and elbow hyperextension. We also employed an “injury allowance,” whereby athletes who screened positive for only one side of a bilateral test, but had a history of significant injury (eg, anterior cruciate ligament tear or reconstruction) to the contralateral joint, were given an injury allowance point. The same certified athletic trainer (RHL) was involved in screening all the athletes. Athletes who scored 5 or higher were considered hypermobile.

Injury Surveillance

Certified athletic trainers at each participating school were recruited to prospectively record injury data. One researcher (RHL) met individually with each data collector to review data collection forms and procedure. The certified athletic trainers prospectively recorded on a standard form injuries and time lost from participation during the 1995 season, including preseason and postseason play. For this study, only injuries that required the athlete to miss at least one practice or game were considered. Time missed was counted until athletes returned to full participation. Information obtained about all injuries included body part, mechanism of injury, activity at the time of injury, diagnosis, referral to physician, surgical intervention, and practices, games, and classes missed because of the injury. To account for exposure differences, athletic trainers also recorded hours of practice and game participation for their team(s), and injuries were expressed per 1000 hours of exposure.

Statistical Analysis

An independent \(t\) test was used to determine differences in injury rate between hypermobile and nonhypermobile athletes, while \(\chi^2\) analyses were used to assess independence in all other variables. Analyses were performed using SPSS for Windows (version 6.01, SPSS Inc, Chicago, IL).

RESULTS

At the end of the 1995 season, data were forwarded to the research team by all participating schools. Figure 2 shows the injuries reported per team.

Prevalence and Features of Hypermobility

The Table outlines demographic data about our subjects. The injury allowance alone did not cause any athletes to be

![Figure 1. Motion required for positive hypermobility screening tests. Reprinted with permission from Archives of Pediatrics and Adolescent Medicine, (1997;151:989–992). Copyright 1997, American Medical Association.]

![Figure 2. Frequency of injuries by institution. Schools 1–5 had both men's and women's teams participating in the study, schools 6 and 9 had only men participating, and schools 7, 8, and 10–12 had only women participating.]
Description of Sample

<table>
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<th>Sex</th>
<th>Subjects (number)</th>
<th>Mean Age (y)</th>
<th>Mean Height (cm)</th>
<th>Mean Weight (kg)</th>
<th>Hypermobility Prevalence (% of N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>147</td>
<td>20 ± 2*</td>
<td>179.07</td>
<td>81.19</td>
<td>13.6</td>
</tr>
<tr>
<td>Female</td>
<td>163</td>
<td>20 ± 4</td>
<td>166.12</td>
<td>59.87</td>
<td>33.1</td>
</tr>
</tbody>
</table>

* Mean ± standard deviation.

Figure 3. Frequency of hypermobility by sex. Significantly more females ($P < .001$) met the 5/9 criteria to be considered hypermobile.

Injury Surveillance

One hundred athletes sustained 134 injuries. Males suffered injuries at a rate of 4.67 per 1000 player-hours of exposure and females at a rate of 1.76 per 1000 hours ($P < .001$) (Figure 6A). Mechanism of injury was dependent on sex ($P < .05$), with contact injuries more common in males and spontaneous (unknown cause) injuries more common in females. Analysis of the data, with contact injuries excluded, brings these figures significantly closer, with males at 2.13 injuries per 1000 hours and females at 1.67 per 1000 hours ($t_{308} = 1.05$, $P = .293$; 2-tailed for independent samples) (Figure 6B). The knee was the most common site of injury in males at 15.2% (14/92) of injuries, while the thigh was most often injured in females, representing 28.6% (12/42) of injuries. The thigh was also the most common site of injury overall, accounting for 18.7% (25/134) of injuries, primarily strains.
Analysis of the injury data by hypermobility status (Figure 7) showed no significant difference in injury rate between hypermobile (2.29/1000 hours) and nonhypermobile (3.54/1000 hours, \( t_{308} = 1.37, P = 0.18 \); 2-tailed for independent samples) athletes. There was no difference in injury severity as judged by time missed: of the 134 injuries in 100 athletes, 44% (59) resulted in the athlete’s missing a week or more of practices or games (Figure 8). Further, there was no significant finding in activity at the time of injury (89% occurred during sport) or referral to physician (27% of injuries referred). There was also no significant difference in the occurrence of sprains, fractures, bursitis, or cartilage injuries. An exhaustive analysis of the data set from many perspectives revealed only 2 statistically significant findings. Hypermobile athletes showed an increased rate of ankle injuries: 26.1% (6/23), compared with only 9% (10/111) of injuries to nonhypermobile athletes \( (P < .05) \). Nonhypermobile athletes had a higher rate of contact injuries (1.38/1000) than hypermobile athletes (0.52/1000, \( P = .037 \)) (Figure 9). Nonhypermobile athletes showed a trend toward an increased rate of strains: 40.5% (45/111) of injuries to nonhypermobile athletes versus 30.4% (7/23) to hypermobile athletes \( (P = .051) \) (Figure 10).

**DISCUSSION**

**Prevalence and Features of Hypermobility**

A review of the literature reveals that researchers have screened more than 10000 people for hypermobility, including school children, college students, factory workers, rheumatology clinic patients, people of different ethnic backgrounds, and athletes. In general, laxity decreases with age, females are more lax than males (although this is less true in young children), and nonwhites are more lax than whites.

The range of reported prevalence (4% to 38.5%) is quite large, so it is not surprising that our results fall within the range. This large range is likely related, at least in part, to differences in screening methodology. A review of more than 50 articles on hypermobility shows that over 85% have used the Carter and Wilkinson method at least as a starting point. However, cutoffs of both 4 and 5 have been used frequently, demonstrating an apparent lack of agreement on which is appropriate. Interestingly, even in the paper of Beighton et al. which originally used the 0 to 9 scale, no cutoff is suggested. Further, Bird et al performed a validation study.
of the Carter and Wilkinson\textsuperscript{18} method without mentioning the
cutoff studied, although one assumes it was the 3/5 used by
Carter and Wilkinson (3/5 seems to correspond to 5/9, although
with decreased quantifiability). There is little doubt that the
cutoff can make a significant difference in prevalence. For
example, in our study, instead of an overall prevalence of 23%
using 5/9, prevalence would rise to 49% (153/310) using 4/9.

Injury Surveillance

The vast differences in rules between men’s and women’s
lacrosse likely account for the increase in both overall and
contact injury rates among males. Since men’s lacrosse is a
contact game, it seems likely there would be more contact
injuries, and the analysis of the data with contact injuries
excluded confirms this. We can conclude that male lacrosse
players are more likely to be injured than female lacrosse
players; however, it was not a goal of this study to make a sex
comparison. Rather, we were specifically interested in injury
patterns between hypermobile and nonhypermobile athletes. In
particular, because some experts recommend limiting sport
participation for hypermobile athletes, we were looking for an
increased injury rate among hypermobile athletes.

Sutro\textsuperscript{16} was among the first to call attention to the possible
involvement of joint hypermobility in cases of recurrent,
insidious joint effusions. Continued investigation confirmed
the existence of a type of generalized joint laxity that was not
associated with other common connective tissue anomalies,
such as hyperelasticity of the skin, vessel failure, and skeletal
abnormalities.\textsuperscript{1,10,20,25,42} Because of the lack of disease, loose
jointedness in otherwise healthy individuals became known as
“benign” hypermobility. This tag was short-lived, however, as
many researchers began reporting on musculoskeletal complaints
associated with “benign” joint hypermobility.\textsuperscript{1,10,13,19,42}
In 1967, Kirk et al\textsuperscript{10} coined the term “hypermobility syn­
drome” to describe cases in which joint laxity was associated
with unexplained rheumatic complaints, such as recurrent joint
pain and effusion, recurrent dislocations of the patella and
shoulder, and early osteoarthritis. Indictments of joint hyper­
mobility as a factor in joint complaints continue to grow. In
fact, researchers have found such convincing evidence that
hypermobility causes musculoskeletal problems that they fre­
quently conclude their manuscripts with comments like the
following:

“Sports and careers that result in over stretching the joints
are unsuitable for hypermobile children and teenagers and
should be advised against them.”\textsuperscript{8}

“The adolescent boy or girl with joint laxity or joint
hypermobility must be recognized and deterred from partici­
pation in contact sports.”\textsuperscript{1,5}

“...adolescent overindulgence in athleticism may precipi­
tate the hypermobility syndrome.”\textsuperscript{1,4}

“The above results can be exploited to advise relatively lax
individuals to avoid physical exertion at a higher than
normal rhythm.”\textsuperscript{13}

This last quotation followed the description of a study of 675
male soldiers who were screened for hypermobility before a
military boot camp. Injuries were recorded during the 2-month
training period, revealing a significantly higher rate of muscu­
oskeletal lesions, particularly of the knee and ankle, among the
hyperlax individuals. This study was well designed and had the
advantage of being performed on a group of similar subjects
with identical levels of activity during the study period.
Unfortunately, the researchers’ changes in the existing screen­ing
criteria make it difficult to compare their results with other
studies. Further, they did not validate the new screening
criteria. In particular, the criterion for knee hyperextension was
decreased to 5°, and men who had scores of only 2/5 were
included in the lax group. We are concerned, therefore, that
individuals described as lax based on these criteria may not
actually be significantly outside the realm of normal joint
mobility. Methodologic changes such as these are noted
throughout the hypermobility literature, and, as previously
mentioned, the use of different cutoffs is especially common.
Interestingly, however, even using a 4/9 cutoff with our injury
data did not produce a significant difference in injury rates.

Studies that have looked at athletes are few in number and
also have design variations like those noted above. The most
well known of the athlete studies was performed by Nicholas.\textsuperscript{30}
He developed a new screening protocol that was similar to the
Carter and Wilkinson\textsuperscript{18} standard in that it included 5 measure­
ments to test for global joint laxity. He concluded that
loose-jointed professional football players were significantly
more likely to rupture their knee ligaments than tight-jointed
players. The tight-jointed players were more likely to tear
muscles. Kalenak and Morehouse\textsuperscript{31} attempted to reproduce the
Nicholas findings but noted an equal number of knee ligament
injuries in both loose-jointed and tight-jointed college football
players. In 1978, Grana and Moretz\textsuperscript{25} used the Nicholas
method to screen male and female high school basketball
players but found no correlation between joint laxity and the
occurrence or type of injury. Godshall\textsuperscript{32} also was unable to correlate
joint looseness with injuries in high school football­
ballers. Again, these studies are basically well designed,
although no study of the validity or reliability of the Nicholas
method has been undertaken.

Research that has used the Carter and Wilkinson\textsuperscript{18}/
Beighton et al\textsuperscript{9} method to study athletic individuals has also
reached varying conclusions. Kujala et al\textsuperscript{16} reported that
joint hypermobility was not a factor in low back pain among
athletes, although the cutoff used to determine hypermobili­
ity is unclear. Harner et al\textsuperscript{44} determined that hypermobility
was not a factor in bilateral anterior cruciate ligament
rupture, but they used only upper extremity tests. Hopper et
al\textsuperscript{38} also found no difference comparing lower extremity
injuries between hypermobile and nonhypermobile netball
players. In a study of ballet dancers, however, Klemp et al\textsuperscript{33}
found a significantly higher rate of injury among dancers
who scored 4/9 or higher and noted that hypermobility
seems to be a liability for the professional ballet dancer.
Although we found a statistically significant increase in ankle injuries, our data generally seem to support previous research in finding no overall difference in injury rates among hypermobile and nonhypermobile athletes. Our study revealed a relatively small number of injured athletes, which may have affected our statistical analysis.

Appropriate Activity for Hypermobile Athletes

In addition to weighing injury surveillance data, we believe 2 points should be considered before recommending that hypermobile individuals avoid sports activity. First, some proprioception data suggest that athletic activity may actually be protective for hypermobile individuals. While studies by Hall et al\textsuperscript{45} and Mallik et al\textsuperscript{26} have found hypermobile individuals to have decreased proprioceptive ability at the knee and proximal interphalangeal joints, Barrack et al\textsuperscript{46,47} have determined that proprioceptive and joint-stabilizing abilities are trainable. Further, the work of Barrack et al\textsuperscript{46,47} showed athletes to have enhanced proprioceptive abilities when compared with nonathletes. This suggests that athletes might be able to avoid some injuries that nonathletes would sustain. Since other studies show strong evidence of increased joint complaints among hypermobile nonathletes and our study did not show increased joint complaints among hypermobile athletes, it is possible that athletic activity may actually be protective for hypermobile athletes. This could explain why studies of joint complaints among nonathletes strongly support the as-yet unsubstantiated notion that hypermobile athletes will suffer a higher rate of injuries.

The second item to consider when deciding appropriate activities for hypermobile individuals is the finding of Larsson et al\textsuperscript{40,41} that the relationship of hypermobility to injuries depended on the demands placed on the hypermobile body part. Hypermobile joints withstand repetitive activity better than they withstand stabilization tasks. Larsson et al\textsuperscript{40} use the example of a violinist in whom hypermobility of the thumb and wrist might be an asset, but who might have overuse complaints in hypermobile knees or spines secondary to prolonged standing or sitting. While the findings of Larsson et al\textsuperscript{40,41} might keep some hypermobile individuals from certain activities, they leave the door open for many other types of activity.

CONCLUSIONS

The purpose of our study was to compare injury patterns in hypermobile and nonhypermobile athletes. Other research suggested that we might find a higher injury rate among hypermobile subjects. However, we did not find this, and generalized joint hypermobility had no apparent effect on overall injury rates in this study. Given the current information concerning athletes, we feel that more conclusive and persuasive evidence of the impact of hypermobility on athletic injury rates must be found before we could justify depriving hypermobile individuals of the many known benefits of regular, strenuous exercise. Further, if injury risk does prove to be higher, hypermobile individuals may still be better served by an effort to determine a means of protecting them from undue risk while permitting regular physical activity. Areas for future research include a large study of anterior cruciate ligament tears and patellar and shoulder dislocations in athletes to determine whether hypermobility is a factor in specific injuries. Comparing hypermobile athletes with nonhypermobile athletes, members of our study group are currently investigating proprioception.

REFERENCES

21. Gedalia A, Person DA, Brewer EJ Jr, Giannini EH. Hypermobility of the


Effects of Muscular Fatigue on Knee Joint Laxity and Neuromuscular Characteristics of Male and Female Athletes

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Objective: To elucidate the effects of muscular fatigue on knee joint laxity and the neuromuscular characteristics of male and female athletes. We were particularly interested in determining whether such effects would be more pronounced in female athletes than in males participating in the same sport.

Design and Setting: Subjects were assessed on 4 dependent variables during a rested and an isokinetically induced muscular fatigue state. We ensured that posttesting measurements were obtained in the fatigued state by testing only 2 dependent variables after each exercise bout.

Subjects: We recruited male (n = 17) and female (n = 17) subjects from a population of healthy collegiate basketball and soccer players.

Measurements: Measured dependent variables were as follows: anterior tibial translation, kinesthesia determined by assessing the threshold to detection of passive motion moving into knee flexion and extension; lower extremity balance ability quantified through a stability index value; and the electromyography-measured muscle activity of 6 knee-stabilizing muscles.

Results: In response to muscular fatigue, subjects demonstrated an overall decrease in the ability to detect joint motion moving into the direction of extension, an increase in the onset of contraction time for the medial hamstring and lateral gastrocnemius muscles, and an increase in the first contraction area of the vastus medialis and vastus lateralis muscles. Additionally, the increase in area of the vastus lateralis was greater for the males compared with the females.

Conclusions: Our results suggest that both male and female athletes exhibit decrements in proprioceptive ability and alterations in muscular activity subsequent to muscular fatigue.

Key Words: electromyography, anterior cruciate ligament, proprioception

As the number of females participating in high school and collegiate sports has increased, so has the incidence of trauma to the anterior cruciate ligament (ACL). Epidemiologic injury surveillance has demonstrated and continues to show a high and disproportionate number of ACL injuries occurring to female athletes participating in the sports of soccer and basketball, compared with their male counterparts.1-10 While influential factors have been suggested and investigated as the underlying causes of the disproportionate rate of ACL injury,11-20 research has increasingly focused on the impact of excessive joint laxity, joint proprioception, and muscle activation patterns on functional knee joint stabilization.

In healthy athletes, functional joint stabilization is routinely achieved as the body gathers visual information, proprioceptive information from articular and musculotendinous receptors, and vestibular system information from the vestibules and semicircular canals of the ears. Once gathered, this information is processed by the central nervous system and results in the maintenance of posture and balance, the conscious appreciation of joint motion and position sense, and protective spinal-mediated reflexes. In addition to protective reflexive muscular activity, athletes appear to achieve functional joint stabilization by relying on some form of preactivated muscle tension in anticipation of expected joint load, whereby previously experienced muscle activation patterns and joint motions preprogram or “feed-forward” muscle activity.21-26 This combination permits athletes to routinely stabilize the knee joint against potentially damaging joint forces.21-26 However, it has been suggested that female athletes, who injure the ACL at a greater rate than males, may inherently possess alterations in joint proprioception and aberrations in muscle activation that may affect their ability to stabilize the joint and subsequently may predispose them to ACL injury.

Therefore, we initially conducted and published an investigation aimed at elucidating the sex differences in knee joint laxity and neuromuscular characteristics of collegiate-level soccer and basketball players.27 We were particularly interested in determining whether previously uninjured male and female basketball and soccer players achieve functional joint...
stabilization through similar means. Interestingly, our results revealed that, compared with males, females who participate in basketball and soccer inherently possess greater knee joint laxity and demonstrate a longer time to detect knee joint motion moving into extension, rendering the knee less sensitive to potentially damaging forces. Additionally, the results of this investigation revealed that these female athletes exhibit greater electromyography (EMG)-measured peak amplitude and area of the lateral hamstring when landing, suggesting that they may have adopted a compensatory muscle activation pattern to routinely achieve functional joint stabilization. We concluded that female and male athletes, specifically those participating in soccer and basketball, differ in their means of routinely achieving knee joint functional stabilization.27

Since ACL injuries in females often occur during routine noncontact activities, female athletes may be able to routinely rely on compensatory muscle activation patterns to perform potential injury-causing activities without sustaining trauma to the ACL. Theoretically, a female athlete could perform many run-and-stop maneuvers or landings while rebonding a basketball and continually maintain joint stabilization against potentially damaging forces. However, interruption of the compensatory mechanism relied on for dynamic stability may produce a joint unable to sense and respond to imparted joint forces, resulting in ligamentous trauma.

Muscular fatigue is considered a viable culprit to interrupt the compensatory stabilizing mechanism, as research has demonstrated its deleterious effects on knee joint laxity,28-31 as well as both the afferent and efferent neuromuscular pathways.29,32-36 In response to various exercise protocols designed to induce muscular fatigue, increases in knee joint laxity have been documented in male and female athletes.28-31,37 Even though researchers have studied the sexes in the investigation of muscular fatigue’s effects on joint laxity, exercise protocols between the sexes have varied, making comparisons by sex virtually impossible. Knee joint proprioception, determined by examining joint kinesthesia (the ability to sense joint motion) and joint position sense (the perception of joint position), appears to be both directly and indirectly affected by muscular fatigue. Directly, muscular fatigue appears to worsen or impair expected learning improvements in joint position sense,29,34 while having no apparent effect on joint kinesthesia.29,36 Indirectly, muscular fatigue affects proprioception in that alterations in kinesthesia and joint position sense have been demonstrated secondary to increased knee joint laxity.38-40 The efferent pathway, assessed by measuring balance or by examining muscle activity with EMG, appears to also be affected by muscular fatigue. After an isokinetic exercise program designed to induce muscular fatigue, healthy individuals have demonstrated decreased balance ability, suggesting that fatigue results in motor control deficits.33 EMG studies suggest that, in addition to balance, muscular fatigue affects muscle activity by extending the latency of muscle firing35 and by resulting in less efficient muscular processes.32

For female basketball and soccer players, the effects of muscular fatigue may be more deleterious than those occurring to their male counterparts and, therefore, may lead to a greater risk for ACL injury. These female athletes may be affected to a greater extent since they are inherently different from their male counterparts. As our previous study27 suggests, female basketball and soccer players inherently possess greater knee joint laxity and diminished joint kinesthesia and rely on an apparently adopted pattern of increased muscle activation to achieve functional joint stabilization. Therefore, even if muscular fatigue affects the joint laxity and neuromuscular characteristics of male and female athletes to a similar degree, the females’ ability to achieve functional joint stabilization may be affected to a greater extent.

Understanding the impact of muscular fatigue on knee joint laxity, as well as its impact on joint proprioception and muscle activity, we conducted a study to elucidate the effects of muscular fatigue on knee joint laxity and the neuromuscular characteristics of male and female athletes. We were particularly interested in determining whether such effects would be more pronounced in female athletes than in males participating in the same sport. Therefore, the purpose of our study was to examine and compare, by sex, the effects of muscular fatigue on the knee joint laxity, joint proprioception, balance, and EMG-assessed muscle activity of male and female athletes.

**METHODS**

**Subjects**

This study recruited male (n = 17; age = 20.4 ± 1.7 years, height = 181.5 ± 7.2 cm, weight = 80.3 ± 10.3 kg) and female (n = 17; age = 18.9 ± 0.9 years, height = 168.5 ± 4.9 cm, weight = 65.6 ± 8.3 kg) subjects from a population of male and female collegiate basketball players and soccer players at the University of Pittsburgh and surrounding colleges and universities. Subjects were healthy, had no history of knee joint ligamentous trauma to either lower extremity, and possessed a self-proclaimed functionally stable test limb ankle. Additionally, no subject reported suffering from any systemic or vestibular disorders known to impair cutaneous sensation or balance. All subjects gave written consent to participate in this study, which was approved by the University of Pittsburgh Investigatory Review Board for Biomedical Research. For all subjects, the dominant lower extremity limb served as the exclusive data collection limb. For this investigation, dominance was established by ascertaining which lower extremity the subject would prefer to land on when dropping from a 25.4-cm high step.

**Instrumentation**

**Anterior tibial translation.** To quantify knee joint laxity we utilized the KT-1000 (MEDmetric, San Diego, CA) instrumented knee arthrometer to measure anterior tibial translation.
during the application of a 133-N (30-lb) anterior displacement force. Subjects were tested in the supine position with the knee joint in 20° of flexion, as confirmed by a goniometric reading. We employed the manufacturer’s specifications for placement of the KT-100 onto the test limb as well as for all data collection. Three trials were performed, with the millimeters of anterior tibial translation recorded for each. From the 3 test trials, a mean test score was calculated and used for data analysis.

Although questioned, the reliability of the KT-1000 has been established, even though it appears to be dependent upon the knee joint test angle. Conducted at 20° of knee flexion, interexaminer and intraexaminer reliability studies have reported Pearson product-moment correlation coefficients of \( r = 0.85 \) and \( r = 0.83 \), respectively. McLaughlin and Perrin, investigating the intraexaminer reliability at 20° of knee joint flexion, reported an intraclass correlation coefficient of \( r = 0.92 \). We enhanced the reliability of this test device by ensuring that data collection was performed by a single researcher.

**Knee joint proprioception.** The assessment of the perception of knee joint proprioception was conducted by measuring knee joint kinesthesia, the ability to sense joint motion. We determined kinesthesia clinically by establishing the threshold to detection of passive motion (TTDP), an assessment of the ability to detect relatively slow passive joint motion. For this investigation, TTDP was established by using a proprioception testing device, which moves the knee joint into flexion or extension, while a rotational transducer interfaced with a digital microprocessor counter provides angular displacement values. We gathered TTDP data, moving into both knee flexion and extension, by following a well-established research protocol. Six random trials, 3 moving into flexion and 3 moving into extension, were performed, and the degrees of angular motion were recorded for each. A mean test score for each direction (into flexion and into extension) was calculated from the 3 test trials and used for data analysis. Reliability of the proprioception testing device has previously been established, with correlation coefficients of \( r = 0.92 \).

**Single-leg balance assessment.** To assess lower extremity balance, we used a commercially available balance device, the Biodex Stability System (Biodex Inc, Shirley, NY). The Biodex Stability System consists of a movable platform that is interfaced with computer software (Biodex, version 3.1), which enables the device to perform as an objective assessment of balance. Reliability of the Biodex Stability System has been established with an interclass correlation coefficient ranging from 0.6 to 0.95. For all data collection, the platform was set and remained at stability level 2, indicating a degree of platform instability that ranges from 1 to 6, with 1 representing the greatest amount of instability.

For all single-leg balance data collection, we employed an established laboratory protocol whereby subjects were asked to single-leg stand on the balance platform with both arms folded across the chest and maintain the unsupported limb in a position of 0° of hip flexion and 90° of knee flexion while slightly abducting, so as not to contact the test limb. For 20 seconds, subjects attempted to maintain this unstable platform in a level position. For each test of balance the software program generated a stability index value, which was calculated by assessing the time and degree the platform was out of level. Three practice and 3 test trials were performed. From the 3 test trials, a mean stability index score was calculated and used for data analysis.

**Muscle activity in response to landing.** We collected muscle activity data in response to a landing task with the use of surface EMG, which is the study of the motor unit action potential. Muscle activity of the test limb was measured simultaneously in 6 knee joint muscles, as subjects, using only the test limb, dropped from a 25.4-cm high step and landed on the floor. The task of dropping and landing was selected based on epidemiologic injury data, which suggests that the primary mechanism of ACL injury in basketball and soccer players is a noncontact-type mechanism, such as landing from a jump.

Before data collection, the electrodes were affixed to the skin in accordance with a previously established protocol. To prepare the skin, the area of electrode placement was abraded with a pumice stone and cleaned with isopropyl alcohol, which ensured adequate surface contact for the electrodes. Ten-millimeter self-adhesive silver/silver electrodes (Multi Bio Sensors, Inc, El Paso, TX) were placed in pairs, 5 mm apart, over the muscle bellies of the following muscles: vastus medialis, vastus lateralis, medial hamstrings, lateral hamstring, gastrocnemius (medial head), and gastrocnemius (lateral head). Additionally, a ground electrode was mounted on the patella.

Before determining the EMG activity during the single-leg landing task, we assessed the EMG activity of each of the 6 test muscles during a maximal isometric voluntary contraction (MVC). The MVC of the quadriceps and hamstring muscles was established using the Biodex Isokinetic Dynamometer (Biodex, Inc, Shirley, NY). After the application of the surface electrodes, the subject was seated in the Biodex testing chair with the distal lower limb secured to the test arm of the dynamometer. The knee was locked in 60° of flexion when the hamstring muscle data were collected. With the lever arm speed set at 0°/s, we instructed the subject to maximally push against the distal lower leg pad for a 5-second data-collection period. The MVC of the gastrocnemius muscle was obtained as the subject performed 1 5-second-long, manually resisted maximal isometric contraction in the direction of ankle plantar flexion.

Once MVC data were collected, the subject was asked to perform the single-leg landing test. The landing test required the subjects to use the test limb to single-leg stand atop a 25.4-cm high bench and drop from the bench to the floor, landing on the test limb. To synchronize muscle activity with landing, a footswitch, which was connected to an EMG channel, was secured to the floor within the landing.
area. Landing on the footswitch signified contact with the floor. Testing required the subject to begin the landing task assessment single-leg standing and motionless on the bench, in order to establish the baseline EMG activity; the subject then dropped from the bench and landed on the floor footswitch. EMG activity was sampled from the time the subject single-leg stood on the bench until approximately 5 seconds after floor contact. Each subject performed 2 practice trials and 3 test trials. A trial was not considered for data collection if the subject landed on the contralateral limb, failed to land on the footswitch, or was unable to maintain balance upon landing.

**EMG data management.** For each landing task test trial, the muscle signal activity was collected by the surface electrodes and passed to a battery-operated FM transmitter worn by the subject. From the transmitter, the signal was passed to the computer, where the raw EMG data were sampled with a frequency of 2500 Hz. For each test trial, we employed Myoresearch software (Noraxon USA, Inc, Scottsdale, AZ) to calculate the onset time, amplitude, and area of the first contraction subsequent to landing, for each of the 6 muscles. From the 3 test trials, a mean score was calculated and used for data analysis. For this investigation, onset time was defined as the time in milliseconds from landing, indicated by contact with the footswitch, until the first muscle contraction. A muscle signal was considered a contraction if it exceeded the set trigger level of 10% of the MVC.

### Induction of Muscular Fatigue

Using the Biodex Isokinetic Dynamometer, the test leg knee joint flexor and extensor musculature performed maximal effort concentric contractions until fatigue of the extensor musculature was quantified. However, before the initial induction of muscular fatigue, concentric peak torque of the knee joint extensors was determined. Securely fastened into the test chair of the Biodex with the knee joint of the test limb aligned with the axis of rotation of the dynamometer and the distal lower limb secured to the dynamometer’s test arm, subjects initially completed 5 maximal repetitions of knee joint extension and flexion at a constant angular velocity of 180°/s. After the subject’s extension peak torque was established, we conducted the first treatment intervention. This treatment consisted of 3 bouts of knee joint flexion and extension exercises with a 40-second interbout rest interval. The first and second bouts were composed of 40 maximal effort repetitions; however, subjects performed repetitions in the third set until the torque value of 3 consecutive repetitions fell below 25% of the initial knee extensor peak torque value. The number of repetitions permitted in the third bout was truncated at 90. To ensure identical treatment interventions, the number of repetitions required by the subject to meet the established criteria of the third bout was recorded and used in the second treatment intervention.

### Testing Procedure

Upon arrival at the laboratory, subjects completed a detailed questionnaire designed to ensure compliance with the subject inclusion criteria and gather demographic and sport participation experience data. Once selected for the study, each subject was assigned a randomized order for pretreatment data collection of the 4 dependent variables. After pretesting, subjects performed the first exercise bout to induce muscular fatigue. To ensure that posttesting measurements were obtained in the fatigued state, only 2 dependent variables were assessed after the first exercise bout, while the other 2 were tested immediately after the second, identical exercise session. Posttesting session A measured knee joint kinesthesia and then anterior tibial translation, while posttesting session B measured muscle activity in response to landing followed by the single-leg balance assessment. To negate any compounding fatigue effects, posttesting sessions A and B were counterbalanced within sex.

### Data Analysis

Twenty-two balanced analyses of variance (ANOVAs), taking into account variations due to the individual, the treatment, and sex, were performed to determine whether the treatment intervention of muscular fatigue had a significant effect on the dependent variables. Based on quantities obtained from the result of the ANOVAs, linear contrasts were performed to determine whether the response in males due to exercise was equal to the response in females due to exercise. A preset value of \( P < .05 \) was selected to determine statistical significance.

### RESULTS

The pretreatment and posttreatment mean test scores, by group, for the dependent measures of anterior tibial translation, TTDPM moving into extension, TTDPM moving into flexion, single-leg balance, and EMG-obtained muscle activity of 6 test muscles in response to landing are presented in Tables 1 through 6, respectively. In order to accurately and effectively present the data and results of this investigation, Tables 1 through 6 contain, with permission, the previously published pretreatment data.\(^{27}\)

While results of the data analysis revealed that isokinetically induced muscular fatigue did not significantly affect anterior tibial translation, lower extremity balance, or TTDPM moving

| Table 1. Effect of Muscular Fatigue on Anterior Tibial Translation (Mean ± SD) |
|-----------------------------|-----------------------------|
| Group                  | Pretreatment* (mm) | Posttreatment (mm) |
| Female                  | 6.05 ± 1.46          | 6.06 ± 1.23       |
| Male                    | 4.80 ± 1.53          | 5.53 ± 1.66       |

* Pretreatment data reprinted with the permission of the American Journal of Sports Medicine.\(^{27}\)
Table 2. Effect of Muscular Fatigue on Joint Kinesthesia (Mean ± SD) in Degrees of Angular Motion

<table>
<thead>
<tr>
<th>Test</th>
<th>Group</th>
<th>Pretreatment*</th>
<th>Posttreatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>TTDPM† into Flexion</td>
<td>Female</td>
<td>2.81 ± 2.54</td>
<td>3.72 ± 2.47</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>1.89 ± 0.57</td>
<td>2.45 ± 1.14</td>
</tr>
<tr>
<td>TTDPM into Extension</td>
<td>Female</td>
<td>2.95 ± 1.47</td>
<td>4.48 ± 3.20†</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>2.11 ± 0.63</td>
<td>2.82 ± 1.29†</td>
</tr>
</tbody>
</table>

* Pretreatment data reprinted with the permission of the American Journal of Sports Medicine.27
† TTDPM indicates threshold to detection of passive motion.
‡ Indicates significant overall treatment effect (P < .05).

Table 3. Effect of Muscular Fatigue on Single-Leg Balance (Mean ± SD) in Degrees of Angular Motion

<table>
<thead>
<tr>
<th>Group</th>
<th>Pretreatment</th>
<th>Posttreatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Female</td>
<td>3.27 ± 1.44</td>
<td>3.37 ± 1.46</td>
</tr>
<tr>
<td>Male</td>
<td>6.00 ± 3.06</td>
<td>6.57 ± 2.74</td>
</tr>
</tbody>
</table>

* Pretreatment data reprinted with the permission of the American Journal of Sports Medicine.27

into knee flexion, muscular fatigue significantly increased TTDPM moving into extension (F<sub>1,49</sub> = 6.50, P = .014). However, this decrease in the ability to detect passive knee joint motion into extension was not significantly different between the groups.

Results of the EMG data analysis revealed that, overall, isokinetically induced muscular fatigue significantly increased the onset of contraction time of the medial hamstring (F<sub>1,49</sub> = 13.10, P = .001) and lateral gastrocnemius (F<sub>1,49</sub> = 5.62, P = .022) muscles, although there were no significant group differences. Muscular fatigue did not significantly affect the onset of contraction time of any of the other tested muscles or the amplitude of the first contraction of any of the 6 sampled muscles. For both males and females, muscular fatigue significantly increased the first contraction area of the vastus medialis (F<sub>1,49</sub> = 6.35, P = .015) and vastus lateralis (F<sub>1,49</sub> = 13.10, P = .001) muscles. Additionally, the vastus lateralis area increase in response to fatigue was significantly greater for the males compared with the females.

Table 4. Effect of Muscular Fatigue on Onset Time of First Contraction (Mean ± SD)

<table>
<thead>
<tr>
<th>Sampled Muscle</th>
<th>Group</th>
<th>Pretreatment (ms)*</th>
<th>Posttreatment (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vastus medialis</td>
<td>Female</td>
<td>39.20 ± 56.66</td>
<td>51.97 ± 113.53</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>30.60 ± 28.21</td>
<td>24.18 ± 36.46</td>
</tr>
<tr>
<td>Vastus lateralis</td>
<td>Female</td>
<td>40.51 ± 28.21</td>
<td>36.27 ± 19.85</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>52.94 ± 70.59</td>
<td>29.77 ± 32.17</td>
</tr>
<tr>
<td>Medial hamstring†</td>
<td>Female</td>
<td>175.57 ± 108.56</td>
<td>308.60 ± 179.47</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>182.44 ± 91.88</td>
<td>277.65 ± 146.14</td>
</tr>
<tr>
<td>Lateral hamstring</td>
<td>Female</td>
<td>187.01 ± 133.19</td>
<td>243.36 ± 184.09</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>217.63 ± 108.95</td>
<td>298.94 ± 227.28</td>
</tr>
<tr>
<td>Medial gastrocnemius</td>
<td>Female</td>
<td>241.10 ± 141.57</td>
<td>120.85 ± 111.48</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>289.09 ± 177.96</td>
<td>300.28 ± 163.79</td>
</tr>
<tr>
<td>Lateral gastrocnemius†</td>
<td>Female</td>
<td>193.90 ± 155.33</td>
<td>265.82 ± 128.22</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>144.19 ± 98.58</td>
<td>242.79 ± 189.57</td>
</tr>
</tbody>
</table>

* Pretreatment data reprinted with the permission of the American Journal of Sports Medicine.27
† Indicates significant overall treatment effect (P ≤ .05).

Table 5. Effect of Muscular Fatigue on First Contraction Amplitude (Mean ± SD)

<table>
<thead>
<tr>
<th>Sampled Muscle</th>
<th>Group</th>
<th>Pretreatment (mV)*</th>
<th>Posttreatment (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vastus medialis</td>
<td>Female</td>
<td>361.65 ± 255.49</td>
<td>369.90 ± 203.78</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>290.87 ± 173.62</td>
<td>444.17 ± 277.55</td>
</tr>
<tr>
<td>Vastus lateralis</td>
<td>Female</td>
<td>315.82 ± 162.24</td>
<td>307.73 ± 99.25</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>298.00 ± 231.27</td>
<td>421.47 ± 287.83</td>
</tr>
<tr>
<td>Medial hamstring</td>
<td>Female</td>
<td>163.49 ± 84.45</td>
<td>133.83 ± 88.63</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>134.20 ± 66.33</td>
<td>124.75 ± 69.71</td>
</tr>
<tr>
<td>Lateral hamstring</td>
<td>Female</td>
<td>156.00 ± 72.59</td>
<td>165.86 ± 103.72</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>84.84 ± 43.47</td>
<td>97.74 ± 85.40</td>
</tr>
<tr>
<td>Medial gastrocnemius</td>
<td>Female</td>
<td>225.86 ± 223.35</td>
<td>233.93 ± 155.49</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>134.13 ± 74.70</td>
<td>141.68 ± 91.36</td>
</tr>
<tr>
<td>Lateral gastrocnemius</td>
<td>Female</td>
<td>131.72 ± 64.90</td>
<td>140.00 ± 130.98</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>161.45 ± 73.82</td>
<td>183.78 ± 150.95</td>
</tr>
</tbody>
</table>

* Pretreatment data reprinted with the permission of the American Journal of Sports Medicine.27

Table 6. Effect of Muscular Fatigue on the First Contraction Area (Mean ± SD)

<table>
<thead>
<tr>
<th>Sampled Muscle</th>
<th>Group</th>
<th>Pretreatment (mV · s)*</th>
<th>Posttreatment (mV · s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vastus medialis†</td>
<td>Female</td>
<td>35.39 ± 18.93</td>
<td>44.39 ± 25.36</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>36.05 ± 33.53</td>
<td>63.47 ± 47.80</td>
</tr>
<tr>
<td>Vastus lateralis†‡</td>
<td>Female</td>
<td>27.75 ± 14.00</td>
<td>35.50 ± 10.89</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>28.59 ± 27.80</td>
<td>63.47 ± 51.48</td>
</tr>
<tr>
<td>Medial hamstring‡</td>
<td>Female</td>
<td>7.91 ± 6.04</td>
<td>6.37 ± 6.28</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>7.39 ± 6.20</td>
<td>4.75 ± 4.86</td>
</tr>
<tr>
<td>Lateral hamstring‡</td>
<td>Female</td>
<td>10.78 ± 8.34</td>
<td>12.52 ± 9.52</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>2.82 ± 2.66</td>
<td>1.85 ± 1.39</td>
</tr>
<tr>
<td>Medial gastrocnemius‡</td>
<td>Female</td>
<td>12.63 ± 15.43</td>
<td>12.72 ± 15.90</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>6.47 ± 5.42</td>
<td>6.72 ± 7.53</td>
</tr>
<tr>
<td>Lateral gastrocnemius‡</td>
<td>Female</td>
<td>6.24 ± 5.80</td>
<td>5.77 ± 5.20</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>3.76 ± 10.43</td>
<td>6.15 ± 4.88</td>
</tr>
</tbody>
</table>

* Pretreatment data reprinted with the permission of the American Journal of Sports Medicine.
† Indicates significant overall treatment effect (P ≤ .05).
‡ Indicates significant sex-by-treatment interaction.

DISCUSSION

We conducted this research investigation to examine the effect of muscular fatigue on the knee joint laxity, kinesthesia, balance, and muscular activity of male and female athletes participating in the collegiate sports of soccer and basketball. Since epidemiologic data have established that females participating in these sports are sustaining ACL injuries 2 to 8 times more frequently than their male counterparts, we were particularly interested in determining whether the effects of fatigue would be more pronounced in female athletes than in males participating in the same sport.1-10 It was hypothesized that, as a direct result of muscular fatigue or secondary to increased joint laxity, subjects would demonstrate aberrations in joint proprioception and alterations in joint-stabilizing muscle activity. We also hypothesized that these effects would be
significantly greater for the female subjects compared with the males.

For all subjects, muscular fatigue was induced in the knee joint musculature by having subjects perform multiple concentric flexion and extension contraction exercises using the Biodex Isokinetic Dynamometer. We selected an isokinetic dynamometer as the means of inducing muscular fatigue because of its ability to quantify muscle force production. Since the degree of fatigue was quantified by the subject’s completing knee flexion and extension exercises until the knee extensors were able to produce only 25% of their initial peak torque, data comparisons could be made between subjects and groups. Traditionally, muscular fatigue has been defined as the inability to generate force and has been characterized not only by a loss of force-production capability, but also by localized discomfort and pain. Based on this definition, we feel our subjects’ knee joint musculature was fatigued, since the quadriceps musculature demonstrated an inability to produce a preset amount of force. Unfortunately, we did not note the quantity of force produced by the hamstring musculature at the time the quadriceps musculature attained our predefined point of fatigue.

Before and after the treatment of muscular fatigue, the 4 dependent variables of anterior tibial translation, kinesthesia, balance, and muscular activity during a landing task were measured. In response to muscular fatigue, subjects demonstrated an overall decrease in the ability to detect joint motion moving into the direction of extension, an increase in the onset time of contraction for the medial hamstring and lateral gastrocnemius muscles in response to landing a jump, and an increase in the EMG area of the first contraction of the vastus medialis and vastus lateralis muscles when landing a jump. In addition, the increase in EMG area of the vastus lateralis after fatigue was greater for the male athletes compared with the females.

While muscular fatigue failed to significantly alter knee joint laxity in the subjects in our study, other authors agree that knee ligamentous structures probably undergo some increase in laxity during exercise, thereby placing athletes at risk for ligamentous injury. The exercise protocols selected for many studies of knee joint laxity subject the knee joint to repetitive stresses at a high strain rate, such as occurs while running, cutting, jumping, and performing other sport participation skills. Skinner et al documented a significant increase in anterior knee laxity in males as a result of an exercise protocol designed to produce muscular fatigue. Similar changes in ligamentous laxity as a result of exercise have been demonstrated by other researchers. In response to running 5.635 km (3.5 miles), Stoller et al demonstrated increases in torsional knee joint laxity measurements that remained above baseline 52 minutes after cessation of exercise. Female athletes have demonstrated increases in anterior, posterior, and total anterior-posterior laxity after sport participation. Investigating the effect of playing basketball, running, and performing squat power lifts on knee joint laxity, Steiner et al demonstrated an increase in knee joint laxity of female basketball players and runners subsequent to sport participation, but failed to showed increased laxity in subjects who performed squat power lifts or in the sedentary control group. Sakai et al periodically measured the anterior knee laxity of female semiprofessional basketball players during the course of a typical day. Anterior laxity did not change during the sedentary working hours of the subjects but increased significantly with game-style basketball participation and remained above baseline 90 minutes after exercise.

Increases in joint laxity subsequent to exercise are suggested to be primarily due to the fact that joint structures, particularly the ligaments, exhibit viscoelastic characteristics. Ligaments are composed of collagen and other structural proteins, and, therefore, when stressed, respond in a time-dependent and stress-dependent manner. When subjected to cyclic elongation, as occurs with walking or running, the viscoelastic properties of a ligament display a time-dependent decrease in load. This decrease in load, which essentially protects the ligament from failure by continually decreasing stress, is demonstrated clinically with increased ligamentous laxity.

Based on this concept, we proposed that an exercise protocol to induce muscular fatigue, which subjected the knee joint to repetitive or cyclic stress, would increase joint laxity. However, our study showed that knee joint laxity did not significantly increase after muscle-fatiguing exercise. This lack of a significant increase in joint laxity following exercise is consistent with the results of Steiner et al who demonstrated no significant increase in joint laxity after physical activities that placed high compressive loads on the joint. Even though isokinetic exercise, such as we used in this investigation, subjects the knee to repetitive stress, the resultant joint forces may be more compressive than shearing in nature. The dynamic forces occurring to the knee joint during isokinetic exercise have been investigated and related to activities of daily living, such as walking, stair climbing, and rising from a chair. Kaufman et al determined the peak tibiofemoral joint compression force and the peak anterior shear force during isokinetic knee flexion and extension exercises at 180°/s, the same angular velocity used in our study. They concluded that isokinetic exercise resulted in a compressive joint force that is roughly equivalent to ascending or descending stairs and an anterior shear force approximately equal to that occurring during walking. These findings suggest that isokinetic flexion and extension exercises do not simulate the joint forces occurring during activities of sport participation. Therefore, this method of inducing muscular fatigue may effectively create fatigued musculature without replicating the joint forces associated with sport activities such as running, cutting, and jumping, which appear to be necessary to induce alterations in ligament laxity.

After muscle-fatiguing exercise, our subjects demonstrated a significant decrease in knee joint kinesthesia, specifically the ability to detect joint motion when moving into the direction of knee extension. This decrease in joint kinesthesia contradicts
the work of Skinner et al, who, in their study investigating the primary receptors for joint position sense, concluded that muscular fatigue did not significantly alter knee joint kines-thesia. Since this observed decrease in joint kines-thesthesia occurred in the absence of increased joint laxity, a mechanism other than increased joint laxity is responsible. However, such a mechanism is not currently explainable and appears to be as yet unsupported in the literature. More importantly, our findings suggest that muscular fatigue alters kines-thesthesia, the ability to sense joint motion, in both male and female basketball and soccer players. Since deficits in knee joint kines-thesthesia may reflect a joint unable to sense, and perhaps respond to, joint forces, these athletes may be at increased risk of ligamentous trauma. While these inferences are purely speculative, the results of our study do demonstrate that male and female basketball and soccer players experience deficits in proprioception, secondary to muscular fatigue, to a similar degree.

While the ability to sense joint motion was altered as a result of muscular fatigue, the ability to respond to joint motion, as quantified through balance assessment, was not significantly affected. Our subjects' lack of balance ability change as a result of muscular fatigue contradicts the results reported by Johnston et al, who used another commercially available balance training device (KAT, Breg, Inc, San Marcos, CA) to demonstrate a significant decrease in lower extremity balance ability subsequent to an isokinetic exercise program designed to induce muscular fatigue. One plausible explanation for our findings of no significant decrease in balance ability after fatigue may relate to our method of measuring and qualifying single-leg balance ability. We chose to use a commercially available balance testing and training device, which provided us a means of objectively quantifying balance ability, but the computer-generated value we selected for quantifying balance may not have been sensitive enough to detect subtle changes. For our investigation, each balance test was qualified with a computer-generated stability index value, which was calculated by assessing the time and degree the platform was out of level, without consideration to the direction of platform displacement. Therefore, subjects could demonstrate 2 markedly different means of maintaining balance without demonstrating changes in the computer-generated stability index value. For example, a subject attempting to maintain balance could waiver medially and laterally for the entire time during 1 test trial and then waiver exclusively anteriorly and posteriorly for the second trial, and the device would generate very similar stability index values for these 2 trials. This testing device, however, calculates and displays a medial-lateral tilt value, which is calculated by assessing the time and degree the platform is medially and laterally tilted, as well as an anterior-posterior tilt value, which is calculated by assessing the time and degree the platform is anteriorly and posteriorly tilted. Therefore, we might have been able to detect any existing alterations in balancing as a result of muscular fatigue had we extracted the computer-generated medial-lateral tilt and anteriorthor posterior tilt data from the testing device.

Even though muscular fatigue did not significantly alter the subjects' ability to respond to joint forces when measured with lower extremity balance, EMG-assessed muscle activity was significantly affected by the muscular fatigue protocol. Previously documented EMG changes resulting from muscular fatigue have primarily been the product of investigations of EMG activity in response to sustained or isometric-type contractions. However, our investigation used EMG to measure muscle activation during a functional task. Results demonstrated that muscular fatigue significantly increased the onset of contraction time for the medial hamstring muscle and the lateral gastrocnemius muscle and significantly increased the EMG area of the vastus medialis and vastus lateralis muscles as subjects performed a landing task. These findings appear to suggest that the muscular fatigue protocol used in this investigation alters the muscle activity of the knee's dynamic stabilizers.

For both males and females, muscular fatigue significantly increased the onset of contraction time for the medial hamstring muscle and the lateral gastrocnemius muscle, 2 muscles that function to control anterior tibial translation. The underlying mechanism for this increase may be a decrease in conduction velocity, which has previously been shown to occur during fatiguing isometric-type contractions. Our findings are similar to those of Nyland et al and Wojtys et al. Nyland and associates used EMG to investigate the effect of lower extremity fatigue on ground reaction force production, lower extremity kinematics, and muscle activation during the landing phase of a run-and-rapid-stop maneuver. Employing a controversial and nontraditional probability level of \( P < .10 \), the authors concluded that, in the fatigued state, the onset of muscle activation of the quadriceps and hamstring muscles tended to occur later than was demonstrated in the unfatigued condition. Wojtys et al also demonstrated significant slowing of gastrocnemius muscle activity and quadriceps and hamstring muscle group activity in response to an anterior tibial translation force after fatigue.

The increase in contraction area of the vastus medialis and vastus lateralis demonstrated by our subjects, as a result of muscular fatigue, reflects the findings of investigations of the EMG characteristics of muscular fatigue. It has previously been established that, compared with resting muscle, fatigued muscle changes the EMG signal. Muscular fatigue appears to result in a reduction in membrane conduction velocity, while amplitude remains constant. This decrease in conduction increases the width of the muscle signal and, therefore, increases the area under the muscle signal curve. Mathematically, this is interpreted as an increase in the mean area of the muscle contraction. Interestingly, our study also revealed that the increase in contraction area of the vastus lateralis in response to muscular fatigue was significantly greater for the male athletes compared with the female athletes. Although the underlying physiologic explanation for this difference in response to muscular fatigue is unknown, it does suggest that muscular fatigue affects female and male athletes differently.
CONCLUSIONS

We conducted this study to investigate the effects of muscular fatigue on knee joint laxity and the neuromuscular characteristics of male and female basketball and soccer players. Moreover, we were particularly interested in determining whether such effects would be more pronounced in female athletes than in males participating in these sports. When subjected to muscular fatigue, both males and females demonstrated alterations in muscular activity and decrements in proprioceptive ability, without an increase in joint laxity. Therefore, muscular fatigue appears to affect knee joint proprioception in addition to preactivated, or compensatory, muscle firing patterns and, thus, may predispose both sexes of athletes to an increased risk for ligamentous injury.

Future research should continue to focus on inherent and postfatigue characteristics of male and female athletes participating in sports where a disproportionate number of ACL injuries are occurring. In addition to joint laxity and neuromuscular aberrations, other suggested causative factors, such as the influence of hormonal changes on ligamentous tissue properties and the reaction rate of the dynamic stabilizers after knee joint perturbation, should be investigated. Furthermore, future research should investigate knee joint laxity, neuromuscular responses, and functional ability subsequent to fatigue protocols that subject the knee to sport-specific forces.

REFERENCES


Muscle Preactivity of Anterior Cruciate Ligament-Deficient and -Reconstructed Females During Functional Activities

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Objective: Underlying the ability of the hamstrings to decrease tibial anterior shear is the time of firing in comparison with the quadriceps. This timing may be aided by neural programming during a planned or expected activity. It is theorized that individuals who have better programming ability will suffer fewer anterior cruciate ligament (ACL) injuries due to joint protection through muscular stabilization. A component of this dynamic restraint is the development of muscular tension before the knee is loaded. The objective of our study was to compare the muscular activity before footstrike in ACL-deficient (ACL-D), ACL-reconstructed (ACL-R), and control (C) females during functional activities.

Design and Setting: Active females were divided into groups based on their ACL status. The study was conducted in a neuromuscular research laboratory.

Subjects: Twenty-four female subjects (ACL-D = 6, ACL-R = 12, C = 6).

Measurements: Integrated electromyographic (IEMG) activity from the thigh (vastus medialis obliquus [VMO], vastus lateralis [VL], medial hamstring, and lateral hamstring) and leg (medial gastrocnemius and lateral gastrocnemius [LG]) and footswitch signals were recorded during downhill walking (15° at 0.92 m/s), running (2.08 m/s), hopping, and landing from a step (20.3 cm). IEMG activity was normalized to the mean amplitude of the sample and analyzed for area and mean amplitude for 150 milliseconds before heelstrike. Side-to-side differences were determined by t tests, and separate one-way analyses of variance (ANOVA) were used to detect differences among the 3 groups for each muscle of each activity.

Results: IEMG area side-to-side differences for the ACL-D group appeared in the LG (involved [I] = 36.4 ± 19.7, uninvolved [U] = 60.1 ± 23.6) during landing, in the VMO (I = 11.4 ± 3.8, U = 7.2 ± 3.1) and VL (I = 13.3 ± 2.7, U = 8.9 ± 1.9) during running, and in the VMO (I = 9.2 ± 4.2, U = 19.5 ± 7.3) during downhill walking. IEMG mean amplitude side-to-side differences for the ACL-D group appeared in the LG (I = 79.7 ± 30.3, U = 122.3 ± 34.9) during downhill walking and in the VMO (I = 78.6 ± 23.2, U = 45.8 ± 18.9) during the run; IEMG mean amplitude side-to-side differences for the ACL-R group appeared in the LG (I = 74.7 ± 40.0, U = 52.8 ± 14.3) during the hop. The ACL-D group had higher IEMG means than control in the VL (ACL-D = 12.9 ± 5.8, C = 7.1 ± 3.9), but lower in the VMO (ACL-D = 9.2 ± 4.2, C = 15.7 ± 3.6).

Conclusions: The side-to-side differences of the ACL-D and ACL-R groups, as well as the group differences between ACL-D and control, suggest that different muscle activation strategies are used by females when performing different dynamic activities. Therefore, muscle unit differentiation may be the cause of our results. These changes appear to be reversed through surgery or the associated postoperative rehabilitation.

Key Words: closed kinetic chain, preparation, muscle, activation

Recent interest in the higher incidence among females of anterior cruciate ligament (ACL) injury has prompted numerous studies surrounding potential causes. Arendt and Dick found the rate of ACL injury in females to be considerably more than that of males. Malone et al found the ACL injury incidence rate to be 8 times higher for females compared with males. Considering that 78% of these injuries are the result of noncontact mechanisms, attention has been placed on the neuromuscular control abilities of females who are ACL deficient (ACL-D) or reconstructed (ACL-R) and compared with their male cohorts.

Typically, males and females play the same sports at the same intensity levels. The court dimensions and area of the floor surface do not change, and only recently have shoes been designed for females. Putting aside the anatomical issues such as Q-angle, notch size, and ligament size, which are to date inconclusive, the ability to prevent anterior tibial shear by controlling knee position with dynamic activity is of interest.

It has been suggested that hamstring muscle activity decreases stress on the ACL at all joint positions. Muscle activation also increases the stiffness of the knee. It is
unclear, however, whether the timing of the hamstring contraction in comparison with the quadriceps contraction is the crucial element in preventing injury. The hamstring may not be strong enough to overcome stress on the ACL,10,11 yet greater hamstring electromyographic (EMG) activity is present in ACL-D individuals, who have a greater need to prevent anterior tibial translation (ATT) than individuals with healthy knees. The changes associated with ACL-D are decreased rectus femoris and vastus lateralis (VL) EMG activity, paired with increased biceps femoris EMG activity, compared with normal subjects.12,13 Many of these studies reported data that were collected during and separated by the portions of the gait cycle12,14–18 or reported for the length of the stance phase.13,19 Proprioception, both position sense and kinesthesia, is enhanced in athletes,20 diminished in ACL-D individuals,21 and improved with reconstruction.19,20 If the changes in proprioceptive abilities are linked to neural programming during a planned or expected activity, the muscular stabilization that is required before loading of the knee to prevent injury might be compromised. Our interest was in examining the muscle activity before landing. Our purpose was to compare the muscular activity before footstrike in ACL-D, ACL-R, and control (C) individuals during dynamic activities.

METHODS

Subjects

Twenty-four female subjects were grouped according to the status of their ACLs: 6 subjects were in the ACL-D group, 12 were in the ACL-R group, and 6 were assigned to a control group. The subjects in the control group were healthy and had no history of knee pathology. The subjects’ average age was 29.4 ± 10.4 years, height was 168.4 ± 10.7 cm, and weight was 61.2 ± 6 kg. All subjects in the ACL-D and ACL-R groups had completed their rehabilitation programs associated with their injuries and had returned to sporting activity. The minimum time from surgery (ACL-R) or injury (ACL-D) was 6 months. The ACL-D and ACL-R groups were rated equally in activity level, as the combined value for the Tegner Activity Score22 was 6.8 ± 1.5 and the combined value on the Lysholm Knee Scoring Scale23 was 92.9 ± 5.4. Institutional review board approval was granted at the University of Pittsburgh before the study began, and each subject gave informed consent before data collection.

Functional Activities

Four activities were used to generate dynamic muscle activity in the lower extremity. Downhill walking on a treadmill with a 15° decline at 0.92 m/s was continued for 15 to 20 steps to ensure that enough steps of a clear footswitch signal were available to determine heel contact. Running, which was completed at 2.08 m/s on a level treadmill, followed the same criteria regarding number of steps and footswitch-monitoring procedure. Hopping 10 steps was subject controlled for height and pace and was performed on the floor for approximately 15 meters, again to ensure adequate samples. Hopping strategies were not discussed except to ensure safety and adequate footswitch signals. To perform the landing task, subjects jumped from a 20.3-cm step and landed balanced on one leg. Performance strategies were not discussed for the landing task except to instruct the subject to land softly in order to avoid injury. All tasks were repeated because data could be collected only from one leg at one time. The testing order was as follows: downhill walking, running, hopping, and landing.

EMG Collection

Skin preparation for the EMG electrodes was carried out for all subjects. Each electrode placement point was cleaned with isopropyl alcohol and abraded with an emery board. Any visible hair was removed. This preparation was completed to improve application of the electrodes and reduce the acceptable impedance to below 2 kΩ. EMG activity was measured from the vastus medialis oblique (VMO), VL, medial hamstring, and lateral hamstring in each thigh and the medial gastrocnemius and lateral gastrocnemius (LG) in each leg. Electrode placement for the VMO bisected the muscle in an anteroposterior division and was at a point distal from the motor point of the muscle halfway to the insertion with the quadriceps tendon. The VL electrode point was halfway between the iliac crest and quadriceps insertion and halfway from the medial border with the vastus intermedius and the anterior edge of the iliotibial band of fascia. The medial hamstring electrodes were placed over the muscle belly halfway between the ischial tuberosity and the tibial insertion point, at least 5 cm proximal to the musculotendinous junction. The lateral hamstring electrodes were placed over the biceps femoris muscle halfway between the ischial tuberosity and the fibular insertion site, at least 5 cm proximal to the musculotendinous junction. The medial gastrocnemius electrodes were placed centrally in a mediolateral fashion and distal from the midpoint of the belly to the tendinous junction. The LG electrodes were placed in a similar fashion and similar orientation to those of the medial gastrocnemius, except that placement was slightly higher due to the more proximal orientation of the muscle. Two footswitches were placed on the plantar surface of the foot to indicate heel contact and toe-off point of the gait cycle.

Processing

The EMG signal was collected via a telemetry EMG system (Noraxon Telemyo, Noraxon, Scottsdale, AZ) through integration with a computer equipped with collection and analysis software (MyoResearch97, Noraxon, Scottsdale, AZ). The Telemyo system sampled the muscle activity at 1000 Hz with a common mode rejection ratio of 130 db and bandpass filtered (Butterworth) the signal at 15 Hz (low) and 500 Hz (high). The
signal was amplified (gain 500) and transferred using an 8-channel FM transmitter to a receiver, where it was further amplified (gain 500, total gain 1000). The signal was then digitized by an analog-to-digital converter (Keithley DAS-1000, Keithley Instruments, Inc, Taunton, MA), integrated, and stored using the MyoResearch97 software before further processing. The integrated EMG (IEMG) signal was normalized to the mean amplitude of the ensemble average of 5 gait cycles. The 5 cycles were identified by manually inserting markers that coincided with the foot contact signal (Figure 1). We recorded area and mean amplitude for 150 milliseconds before footstrike for statistical analysis.

Statistical Analysis

Differences between involved and uninvolved sides were determined by paired t tests on the mean amplitude and area of the EMG signal for each muscle during each activity. A one-way analysis of variance (ANOVA) was used to determine if there was a difference among the three groups for each muscle during each activity. Tukey post hoc analysis was completed, when indicated, to determine differences between the levels of the group variable. The level of statistical significance was set at \( P = .05 \).

RESULTS

Because of the normalization process used to compare the EMG signals, each value is reported as a percentage of the mean. For area IEMG, the \( t \) test revealed side-to-side differences between the LG (involved [I] = 36.4% ± 19.7%, uninvolved [U] = 60.1% ± 23.6%, \( t_5 = 2.35, P < .05 \)) of the ACL-D group during the landing activity. The ACL-D group also exhibited differences in the VMO (I = 11.4% ± 3.8%, U = 7.2% ± 3.1%, \( t_5 = 2.08, P < .05 \)) and VL (I = 13.3% ± 2.7%, U = 8.9% ± 1.9%, \( t_5 = 2.85, P < .05 \)) during running and the VMO (I = 9.2% ± 4.2%, U = 19.5% ± 7.3%, \( t_5 = 2.03, P < .05 \)) during downhill walking (Figure 2).

For mean amplitude of the IEMG, the ACL-D was different in the LG (I = 79.7% ± 30.3%, U = 122.3% ± 34.9%, \( t_5 = 4.14, P < .05 \)) during downhill walking and VMO (I = 78.6% ± 23.2%, U = 45.8% ± 18.9%, \( t_5 = 2.94, P < .05 \)) during the run. The ACL-R group exhibited a side-to-side difference when compared for mean amplitude of the IEMG on LG (I = 74.7% ± 40.0%, U = 52.8% ± 14.3%, \( t_{41} = 2.03, P < .05 \)) during the hop (Figure 3).

The ANOVA revealed group differences on the involved VL during the hop and VMO when walking downhill. The ACL-D had significantly higher IEMG area than the control group in VL (ACL-D = 12.9% ± 5.8%, C = 7.1% ± 3.9%, \( F_{2,23} = 4.19, P < .05 \)), but lower in VMO (ACL-D = 9.2% ± 4.2%, C = 15.7% ± 3.6%, \( F_{2,23} = 4.04, P < .05 \)). No other measures of muscle activity exhibited significant differences bilaterally or between groups (Figure 4).

DISCUSSION

During running, the ACL-D group exhibited increases in VMO and VL activity. The rehabilitation programs could account for this increase through the increased demand placed on the injured side. Frequently, individuals will exercise the injured side harder or with more concentration because they fail to respect the need to train bilaterally, and the injured side is the focus of the health care professionals who help them manage the injury. The lack of hamstring changes and the activity-dependent gastrocnemii differences in our study led us to another explanation. The increased signal could be the electrical response needed to generate muscle balance ratio during a given task. In this scenario, the higher activity is an attempt to increase the output of a weaker muscle. The likely explanation for the VMO decrease during the downhill activity is the attempt by the neuromuscular system to counteract or
limit the ATT force associated with this activity. This finding is consistent with those of Tibone and Antich\textsuperscript{25} and McNair and Marshall.\textsuperscript{26}

Contrasting results were found in the LG for landing (higher in area) and downhill walking (lower mean). These results could primarily be from foot position during the activity. In landing, since the activity involves slowing of the foot into dorsiflexion, there could be a higher level of activity because of increased tension. In contrast, downhill walking gait slows the foot into plantar flexion to avoid a drop-foot mechanism. This action increases demand on the tibialis anterior, resulting in a reciprocal inhibition to the posterior musculature and reducing EMG activity.

The LG differences were recorded during the various activities and therefore were not directly comparable, but they bring to light the issue of analysis technique. The mean amplitude is more robust to variance in the signal than the area and therefore less powerful to detect comparative differences. A third technique not used in this experiment is comparison of the peak signal, which marks the highest activity in the designated time period. Further research needs to be completed to determine whether the average activity, the total area of activity, or the maximum amount of activity is the best measurement technique for this type of comparison analysis.

Examining the results of this study revealed trends as to which muscles were consistently affected by this injury. The VMO showed differences bilaterally with the downhill walking and running activities. Group differences were also revealed. The VL also showed differences in running and landing and among groups. The LG revealed differences in downhill walking and landing. The point of repeating these results is to categorize them by muscle and group. All these bilateral differences are in the ACL-D group, while the ACL-R group revealed a difference only in the LG for the hop. Three points are important to this discussion. The first is the potential for different strategies within a muscle dependent on activity. Second, the improvements in proprioceptive ability may account for a return to bilateral normalcy. Third, our results could be due to divisions of muscles within units.

The movement strategy could change due to different activities.\textsuperscript{16} This argument was mentioned regarding the differences between the medial gastrocnemius and LG and is supported by our results indicating LG differences depending on activity (land, downhill walk, and hop, which are not detected in the medial gastrocnemius). As movement patterns change, the forces on the muscles change. Because preactivity was examined in this study, the anticipation of the activity was likely responsible for the differences before footstrike. ATT forces seem to change with different activities.\textsuperscript{9,10,11,27–31} This change in force, however, does not lead us to an expected finding. Typically, we would expect to see an increase in the hamstring activity in order to protect the joint, especially when the ACL is subject to additional stress or a position that stretches the remaining structures.\textsuperscript{4,5,12,15,32,33} We did not find an increase in mean activity or area of the hamstrings. In examining the quadriceps, the expected change in force does appear to have an effect on preactivity level. For example, the VMO activity is lower on the involved side during the downhill walk. This strategy is thought to decrease ATT.\textsuperscript{12,28} Although others\textsuperscript{25,26} have shown a decrease in portions of the quadriceps muscle, Huston and Wojtys\textsuperscript{4,5} suggest that the quadriceps are the dominating muscle in the athletic female based on reflex studies. Our results suggest less VMO activity during some movement patterns, indicating that, depending on the athlete’s functional pattern, the quadriceps may not be the dominating factor. It is yet to be determined whether the decrease in preactivity affects the activity level in the postfootstrike period. Further study is required to support the claim of quadriceps domination in females.

Improvements in proprioceptive ability may provide an explanation for why bilateral differences were found in the ACL-D group but not in the ACL-R group, except for the LG.
during the hop. It has been stated that kinesthesia and position sense improve with surgical intervention, but perhaps not to the level of the uninjured limb. In our study, the ACL-R group differed only in one muscle for one activity. Because of the surgical reconstruction, the ACL-R group may have developed better position sense and kinesthesia and was therefore able to exhibit more (equal to uninjured side) preparatory activity.

The third explanation for differences in the results within muscle groups is unit differentiation, where the different sections of a muscle are expected to act asynchronously. A natural expectation of the activity within a muscle for a given movement is that muscle sections such as the quadriceps (excluding the rectus femoris because of its 2-joint nature) would function in a similar style. That is, if the VMO had decreased in output going downhill in an attempt to reduce ATT, the VL would follow suit. In our experience, this did not occur. The explanation for this phenomenon is that muscle unit portions function differently depending on the movement pattern. In the quadriceps, the VMO and VL have been reported as responsive to medial and lateral knee stress, respectively. It has been shown that, within muscle, there are different excitations dependent on activity. These responses appear to apply to preparatory activity.

Further questions brought up by this study that require investigation are (1) whether EMG differences, and especially decreases, are the response of decreased muscle tone and (2) how EMG differences affect the muscle activity after foot contact. A correlation between preparatory and reactive muscle activity is warranted. Increased muscle activity before and after footstrike is important for stabilization. We speculate that the timing and order of contraction are also important and provide the basis for further investigation. An additional issue is whether these findings and associated explanations are true for males.

CONCLUSIONS

Side-to-side differences for the ACL-D and ACL-R groups and group differences between ACL-D and control suggest that, when performing different functional activities, ACL-D females use unique strategies involving the VMO, VL, and LG and that, therefore, these muscles require detailed examination. The quadriceps strategy may be explained by quadriceps (VMO) avoidance or VMO/VL ratio changes resulting from protective patterns or accommodation. Because a similar trend occurred with the gastrocnemius, muscle unit differentiation is the likely cause of our results. These changes appear to be reversed through surgery or the associated postoperative rehabilitation.

REFERENCES

24. Yang JF, Winter DA. Electromyographic amplitude normalization meth-


Reactive Muscle Firing of Anterior Cruciate Ligament-Injured Females During Functional Activities

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Objectives: The high incidence of noncontact anterior cruciate ligament (ACL) injuries in females has attracted research to investigate the capacity of muscles to reflexively protect the knee joint from capsuloligamentous injury. Numerous reflex pathways link mechanoreceptors in the ACL with contractile fibers in the quadriceps and hamstring muscles. Loads placed on the ACL modify reactive muscle activity through the feedback process of neuromuscular control and are critical for dynamic muscular stabilization. Noncontact ACL injuries may be the result of aberrations in reactive muscle firing patterns. Therefore, compensatory muscle activation strategies must be employed if functional stability is to be restored after injury or surgical reconstruction. The purpose of our study was to compare the amplitude of reactive muscle activity in females with ACL-deficient (ACLD), ACL-reconstructed (ACLR), and control knees during functional activities.

Design and Setting: Female volunteer subjects were stratified into groups based on the status of their ACLs. Each subject performed 4 functional activities, bilaterally, during a single test session.

Subjects: Twenty-four female subjects participated in this study (ACLD = 6, ACLR = 12, control = 6).

Measurements: Integrated electromyographic (IEMG) data were collected with surface electrodes from the vastus medialis, vastus lateralis, medial hamstring, and lateral hamstring during downhill walking (15°, 0.92 m/s), level running (2.08 m/s), and hopping and landing from a jump (20.3 cm). IEMG was normalized to the mean amplitude of 3 to 6 consecutive test repetitions. The mean area and peak IEMG of a 250-millisecond period after ground contact was used to represent reactive muscle activity. Side-to-side differences were determined using dependent t tests, and group differences were determined using a one-way analysis of variance.

Results: During running, the ACLD group demonstrated significantly greater area and peak IEMG activity in the medial hamstring in comparison with the ACLR group and greater peak activity in the lateral hamstring when compared with the control group. The ACLD group also demonstrated greater peak activity in the vastus medialis and a smaller area of IEMG activity in the lateral hamstring than the control group during running. During landing, the ACLD group demonstrated significantly less area of IEMG activity in the vastus lateralis when compared with the control group. No significant differences were identified between the ACLR and control groups, nor were side-to-side differences revealed.

Conclusions: Our results suggest that adaptations occur in the reactive muscle activity of ACLD females during functional activities. Strategies to minimize the anterior tibial translation in response to joint loading included increased hamstring activity and quadriceps inhibition. The reactive muscle activity exhibited in ACLD subjects is presumably an attempt to regain functional stability through the dynamic restraint mechanism. The absence of side-to-side differences suggests that these adaptations occur bilaterally after ACL injury.

Key Words: reflex, muscle activity

C ontemporary research regarding the disproportionate number of noncontact anterior cruciate ligament (ACL) injuries in females is beginning to focus on the role of the hamstring and quadriceps muscles in providing dynamic muscular stabilization.¹⁻⁶ Thigh muscle activation provides dynamic restraint by absorbing the high joint loads generated during athletic activities. Although capsuloligamentous structures like the ACL provide some static restraint capabilities, their primary role is to guide the adjacent skeletal segments during joint motion.⁷ Capsuloligamentous structures also possess neurosensory qualities that can modify thigh muscle activity through various reflex pathways.⁸ It is suggested that reactive muscle activity must occur with sufficient magnitude in a window of 30 to 70 milliseconds after the onset of joint loading in order to effectively protect the ACL.⁵,⁶ Failure of the dynamic restraint mechanism to control joint forces may expose the ACL to excessive forces and contribute to the incidence of noncontact ACL injuries in females. In addition, adaptations must occur to the dynamic restraint mechanism after injury if functional joint stability is to be maintained.
Research to establish the role of reactive muscle activity is valuable to clinicians and athletes for the prevention of injury or restoration of knee joint function through the dynamic restraint mechanism.

The feedback process of neuromuscular control is responsible for regulating reactive muscle activity. Mechanoreceptors located within capsuloligamentous and tenomuscular structures detect joint loads and initiate reactive muscle activity through several neural pathways. These neural pathways can involve fast monosynaptic stretch reflexes from muscle spindles, polysynaptic reflexes from capsuloligamentous mechanoreceptors, and longer cortical pathways involving the brain stem and cerebral cortex. The effects of ACL injury on these reflex pathways remain unclear. Variations in the reactive muscle activation strategies of females with ACL-deficient knees (ACLD) may result from deafferentated ACL mechanoreceptors and interruption of the reflex pathways or from subconscious attempts to regain functional joint stability through the dynamic restraint mechanism. Surgical reconstruction of the ACL (ACLR) may restore its mechanical function in the knee, but the issue of graft reinnervation and its effect on reactive muscle activity remain undetermined.

Furthermore, numerous rehabilitation exercises are designed to improve neuromuscular control, but research is still attempting to establish “typical” muscle activation patterns in uninjured, ACLD, and ACLR populations. Electromyographic (EMG) equipment assesses reactive muscle activity by measuring the efferent (motor) response of muscles to joint loading. Previous research has examined the sequence and timing of muscular activity; however, until recent technologic advances, the analysis and quantification of EMG amplitude during functional activities (running) were tedious and less reliable. Superimposing the EMG activity of multiple trials into one representative ensemble pattern increases the reliability of EMG amplitude measures and provides additional information about the dynamic restraint mechanism during functional activities.

Limited research using this method has focused on an isolated period of reactive muscle activity during functional activities. Branch et al compared a sample of ACLD subjects with uninjured subjects and found a decrease in the area of quadriceps activity and an increase in the area of medial hamstring activity during the stance phase of a cutting maneuver. These changes in the ACLD group can be considered reactive because they occurred after ground contact while the joint was loaded. Branch et al concluded that the increased hamstring activity was a protective mechanism to minimize anterior translation of the tibia. The concomitant decrease in quadriceps activity during the same period may indicate reflexive inhibition. Excessive quadriceps activity could exacerbate anterior tibial translation; thus, lower levels of activity would be beneficial to the dynamic restraint mechanism and functional joint stability. Our study assessed a 250-millisecond period of reactive muscle activity in response to joint loading for the purpose of establishing differences in measures of EMG amplitude among ACLD, ACLR, and uninjured females.

METHODS

Subject Characteristics

Twenty-four female volunteers (mean age = 29.4 ± 10.4 years; mean height = 168 ± 10.7 cm; mean weight = 61.2 ± 6 kg) were stratified based on the condition of their ACLs. The 2 experimental groups comprised 18 subjects (ACLD = 6, ACLR = 12) who had suffered complete unilateral ACL tears diagnosed by an orthopaedic surgeon. All ACLR subjects had received bone-patellar tendon-bone grafts, had completed a rehabilitation program, and had attempted to return to their previous levels of activity. Testing was conducted between 6 and 30 months after surgery. The experimental groups averaged 6.8 ± 1.5 on the Tegner Activity Score and 92.9 ± 5.4 on the Lysholm Knee Scoring Scale. Subjects with disability due to secondary meniscal damage or ligamentous injury in excess of grade I were excluded.

The control group consisted of recreationally active female subjects with no previous history of knee pathology. Subjects with any systemic disease or metabolic disorder that might interfere with sensory input or motor function, or both, were excluded. The same investigators performed all testing procedures for all subjects. The dominant limb was used for the control group and was determined for each subject by identifying the leg she would use to kick a ball. All subjects were required to complete a questionnaire and provide consent before participating, in accordance with the University of Pittsburgh’s Biomedical Institutional Review Board.

EMG Assessment

EMG data collection. The area and peak reactive muscle activity were collected bilaterally from 4 muscles: vastus medialis (VM), vastus lateralis (VL), medial hamstring (MH), and lateral hamstring (LH) (Figure 1). Each subject performed 4 functional activities: downhill walking (15°, 0.92 m/s), running (2.08 m/s), hopping (self-paced), and landing from a jump (20.3 cm) (Figure 2).

The side being tested and the order of functional activities were randomized. Self-adhesive Ag/AgCl bipolar surface electrodes (Multi Bio Sensors, Inc, El Paso, TX) detected myoelectric activity that was processed with the Noraxon Teleny system (Noraxon USA, Inc, Scottsdale, AZ). Electrodes measured 10 mm in diameter and were placed 25 mm apart after the skin was shaved, lightly abraded, and cleaned with a 70% ethanol solution. Electrode location was based on recommendations by Basmajian and DeLuca, and the acceptable impedance between electrodes was less than 2 kΩ. Two force-sensitive resistors (FSRs) were secured to the head of the first metatarsal and the heel of the leg being tested (Figure 3).
The FSRs were used to indicate the ground contact phase for each cycle of motion during the functional activities. Signals from the 4 muscles and FSRs were passed to a battery-operated 8-channel FM transmitter worn by the subject. A single-ended amplifier was used (gain 500) with Butterworth low-pass (15 Hz) and high-pass (500 Hz) filters and a common mode rejection ratio of 130 db. A receiver (gain 500, total gain 1000) converted the signal from analog to digital data with an A/D card (Keithley Metabyte DAS-1000, Keithley Instruments, Inc., Taunton, MA). The signal then passed to a computer, where raw EMG data were sampled with a frequency of 2500 Hz and further analyzed with Myoresearch software (Noraxon). Before each test, the signal was calibrated with the patient in a relaxed position in order to establish the baseline amplitude of EMG activity.

**EMG integration and normalization.** All analyses were performed on integrated EMG (IEMG) data, which are expressed in μV-milliseconds. The raw signal was full-wave rectified and averaged over a 15-millisecond moving window. With a sampling rate of 1000 Hz, this equals 15 data points that slide one data point at a time. EMG data integration requires 16 milliseconds of processing time; however, the EMG channels are synchronized with the FSRs to adjust for this delay.

To normalize IEMG data for time, a linear envelope was established based on signals from the FSRs. Markers were placed defining a 250-millisecond period after ground contact (foot strike) during each cycle of motion. Therefore, the beginning of the linear envelope was indicated by the subject’s initial contact with the ground, and the end was marked as a point 250 milliseconds after ground contact. This period of time was recorded to permit the collection of reflexive and voluntary muscle activity in response to joint loading.6,9 Several (3 to 6) consecutive cycles of motion were then combined, using Myoresearch software, to construct a profile of the reactive muscle activity during the linear envelope. This is referred to as an ensemble-averaged profile (Figure 4).14 Amplitude normalization was performed to reduce the physiologic population variability.14 The research of Yang and Winter13 compared several amplitude normalization procedures in an attempt to reduce the large intersubject variability associated with EMG data and improve reliability. It was observed that the sensitivity of EMG testing could be increased.

**Figure 1.** A, Electrode placement for the VM and VL and ground electrode over the proximal tibia. B, Electrode placement for the MH and LH muscles.
if the average pattern of EMG was constructed for specific functional activities (ensemble-averaged profile) and the mean or peak amplitude that occurs during this pattern was selected to normalize the amplitude of muscle activity. When compared with normalization procedures using a maximum voluntary contraction, 50% maximum voluntary contraction, and EMG per unit of force, the ensemble mean or peak amplitude provides the least intersubject variability during the dynamic types of muscle activation patterns occurring with functional activities.

Based on the results of Yang and Winter, the amplitude of reactive muscle activity for each subject was normalized to the mean amplitude of the ensemble profile for each functional activity. Amplitude normalization converted the IEMG data (µV·milliseconds) into a value that represents a percentage of the ensemble mean (%·milliseconds). Myoresearch software was used to calculate this value. The area and peak IEMG values were used to represent the amplitude of reactive muscle activity (Figure 5).

**Statistical Analysis**

The independent variable was the condition of the ACL. The dependent variables were measures of reactive muscle activation (area and peak IEMG). Multiple paired t tests were used to establish differences between the involved and uninvolved limbs. A one-way analysis of variance was used to determine differences among the 3 groups. Tukey post hoc analysis was performed when significant differences were established. A probability level of $P < .05$ was accepted to denote statistical significance.

**RESULTS**

During running, the ACLD group demonstrated significantly greater area and peak IEMG activity in the MH in comparison with the ACLR group and greater peak activity in the LH when compared with the control group. The ACLD group also demonstrated greater peak activity in the VM and less area of IEMG activity in the LH than the control group during running. During landing, the ACLD group demonstrated significantly less area of IEMG activity in the VL when compared with the control group (Table). No significant differences were identified between the ACLR and the control groups, nor were side-to-side differences revealed within the 3 groups.
DISCUSSION

The objective of our research study was to examine the role of the thigh musculature in providing dynamic restraint to the knees of female subjects. Our results suggest that, during some functional activities, ACLD females adopt reactive muscle firing strategies that are beneficial to the dynamic restraint mechanism and maintenance of functional joint stability. These strategies minimize anterior tibial translation in response to joint loading and include increased hamstring activation and quadriceps inhibition. The magnitude of muscle activation in ACLR subjects, however, did not differ significantly from uninjured females. This suggests that surgical reconstruction restores the mechanical function of the ACL, which is then recognized by the central nervous system and results in muscle activation patterns similar to healthy individuals. The possibility of graft reinnervation is controversial; however, regrowth of free nerve endings would provide proprioceptive feedback and could influence muscle activation patterns.12,18 Although this would support similarities in the muscle activation strategies of ACLR and healthy females, continued research is needed. The absence of side-to-side differences, specifically in ACLD subjects, suggests that neuromuscular adaptations after ACL injury occur bilaterally. Our study also supports the use of EMG amplitude normalization with ensemble means as a method for minimizing variability between subjects and identifying significant group differences in the amplitude of muscle activity during functional activities.

Feedback Motor Control

The feedback mechanism of motor control is characterized by numerous reflex pathways from joint and muscle receptors that reflexively coordinate muscle activity during the performance of a task.19–21 Muscle activity elicited through reflex pathways is again receiving attention for its role in the dynamic restraint mechanism. However, controversy still exists regarding the capacity of reactive muscle activity to contribute to functional joint stability in the ACLD subject.5,6

Several factors mediate the level of dynamic restraint provided by reactive muscle activity. These include the timing and magnitude of reactive muscle activity, as well as the existence of preprogrammed motor commands.5,22 The peripheral site where sensory feedback originates and the neural pathways it follows both contribute to the response time of
muscles. Signals that originate in muscle spindles act directly on the motor nerves (stretch reflex), whereas signals from other mechanoreceptors must pass through a series of synapses before stimulating a motor response. The reactive muscle activity observed in this study occurred quickly (<250 milliseconds) and appears to offer adaptations beneficial for dynamic restraint and the maintenance of functional stability in ACLD knees. Muscle spindles also elicit vigorous muscular contractions when compared with the relatively weak activity induced by loads placed on capsule and ligamentous mechanoreceptors. The ACLD subjects exhibited more reactive muscle activity despite ACL injury, emphasizing the importance of muscle spindle receptors rather than capsuloligamentous mechanoreceptors in modifying reactive muscle activity.

Preparatory muscle activity is a confounding variable that may have influenced the timing and magnitude of reactive muscle firing. Joint loads incurred during these functional activities may have been anticipated based on previous experiences. It has been established that the level of preparatory muscle activity, in anticipation of joint loading, will influence reactive muscle activation strategies. Muscle preactivation increases the sensitivity of muscle spindles, allowing unexpected joint perturbations to be detected more quickly. The stretch reflex response is also heightened in a pretensioned muscle, increasing its reactive capabilities. This sequence of events may have contributed to increases in reactive muscle activity if the stretch reflex response was superimposed on the preprogrammed muscle activity. The complex interaction between timing, magnitude, and existence of preprogrammed motor patterns will ultimately determine the level of dynamic restraint provided by reactive muscle activity.

Reactive Muscle Activity

Adaptations to the feedback motor control mechanism included both an increase in reactive hamstring activity and a decrease in quadriceps activity. In this study, reactive muscle activation was assessed by measuring the area and peak IEMG in the lower extremity for a 250-millisecond period after ground contact during several functional activities. McNair and Marshall conducted a similar investigation, simultaneously recording 128 milliseconds of EMG activity and ground reaction forces during a landing task. They demonstrated that ACLD subjects with greater hamstring muscle activation were able to reduce stress on the knee during landing. This supports the results of our study, and, although reactive muscle activity was observed in all of the subjects, only ACLD subjects exhibited increased hamstring muscle activation.

We concluded that reactive muscle activity is affected by the absence of sensory information and concomitant loss of mechanical restraint normally provided by the intact ACL. Various other structures containing peripheral mechanical receptors may have provided sufficient sensory information to mediate reactive muscle activity and, therefore, compensate for the reflexive influence normally projected by ACL afferents.

Modifying the amplitude of reactive muscle activity is an adaptation to increase hamstring muscle stiffness and resist excessive anterior translation of the tibia in the ACLD knee.

Quadriceps Avoidance

The results of our study also confirmed the existence of what Berchuck et al referred to as a “quadriceps-avoidance” gait adaptation in ACLD subjects. Previous research using motion analysis has revealed that, during walking, jogging, and running, ACLD subjects alter their gait to minimize anterior translation by inhibiting quadriceps muscle activation. Although Berchuck et al did not record EMG data, this finding was attributed to excessive shear forces created by quadriceps activation. Gauffin and Tropp were able to document similar results by measuring muscle activation patterns during a one-leg hop. Although hamstring activity was unremarkable, the ACLD group had significantly less quadriceps activity than the control group.

One issue arising from the results of this study contradicts the theory of a quadriceps-avoidance mechanism. A signifi-
Figure 4. A, VM muscle activity over 4 consecutive cycles of motion are combined to construct a profile of the reactive muscle activity during the 250-millisecond linear envelope. B, The pattern of muscle activity in the VM constructed from consecutive cycles of motion is referred to as the ensemble averaged profile.
Figure 5. Representation of the area and peak IEMG reactive muscle activity values for the VM and VL muscles during a 250-millisecond period after ground contact.

### Significant Differences in Reactive Muscle Activity During Functional Activities (Mean ± SD)

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>ACLD</th>
<th>ACLR</th>
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<tbody>
<tr>
<td></td>
<td>Area (% • ms)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MH</td>
<td>26.6 ± 5.6 CI (15.1 to 38.1)</td>
<td>30.3 ± 5.7* CI (19.1 to 41.5)</td>
<td>22.5 ± 18.4 CI (13.6 to 58.5)</td>
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<tr>
<td>LH</td>
<td>23.5 ± 4.1 CI (15.5 to 31.5)</td>
<td>30.1 ± 6.9† CI (16.57 to 43.6)</td>
<td>24.02 ± 8.8 CI (6.8 to 41.3)</td>
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<tr>
<td>Peak (%)</td>
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<tr>
<td>MH</td>
<td>232.9 ± 94.2 CI (48.3 to 417.5)</td>
<td>365.4 ± 123.3* CI (123.7 to 607.1)</td>
<td>205.8 ± 86.8 CI (35.7 to 375.9)</td>
</tr>
<tr>
<td>LH</td>
<td>186.6 ± 52.8 CI (83.1 to 290.1)</td>
<td>379.5 ± 105.5† CI (172.7 to 566.3)</td>
<td>222.8 ± 100.6 CI (25.57 to 419.9)</td>
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<tr>
<td>VM</td>
<td>284.1 ± 104.4 CI (89.5 to 498.7)</td>
<td>428.2 ± 110.2† CI (212.2 to 644.2)</td>
<td>391.5 ± 126.3 CI (144.0 to 639.0)</td>
</tr>
<tr>
<td>Landing</td>
<td>Area (% • ms)</td>
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<tr>
<td>VL</td>
<td>168.8 ± 49.6 CI (71.6 to 266.0)</td>
<td>109.7 ± 50.3† CI (11.1 to 208.3)</td>
<td>149.1 ± 64.8 CI (22.1 to 276.1)</td>
</tr>
</tbody>
</table>

* P < .05 between ACLD and ACLR.
† P < .05 between ACLD and control.
Cl, Confidence interval (mean ± 1.96 SD).
cantly greater peak VM activity was observed in ACLD subjects when compared with the control subjects. This would appear to exacerbate anterior translation but may also be interpreted as a mechanism to control knee joint deceleration through coactivation of the VM and hamstring muscles. The net effect of coactivation may increase overall joint stiffness and assist with dynamic restraint. Although further research is warranted, the results of our study agree with previous literature suggesting that ACLD subjects adopt reactive muscle activation strategies to minimize anterior tibial translation in response to joint loading.

CONCLUSIONS

Our results suggest that adaptations occur to the feedback mechanism of motor control in ACLD females. Significant differences were identified in the reactive muscle activation strategies by measuring the area and peak IEMG activity in the thigh musculature during functional activities. Strategies to minimize anterior tibial translation in response to joint loading included increased hamstring activity and quadriceps inhibition during a window of 250 milliseconds. The reactive muscle activity exhibited in ACLD subjects is presumably an attempt to regain functional stability through the dynamic restraint mechanism. However, ACLR subjects did not demonstrate significant differences when compared with uninjured subjects. The absence of side-to-side differences suggests that adaptations to the reflex pathways occur bilaterally in ACL-injured females. This study may serve as a platform for future research with larger samples including the effects of time, sex, and various surgical or rehabilitation strategies.

REFERENCES

An Investigation of Postural Control in Postoperative Anterior Cruciate Ligament Reconstruction Patients

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Objective: To investigate quadriceps strength and static and dynamic balance in the anterior cruciate ligament (ACL)-reconstructed patient and to compare these findings with an age-matched, injury-free control group.

Design and Setting: A 2 × 2 mixed-design analysis of variance (group × leg) was applied to the static posture, dynamic balance, and strength data. In addition, Pearson product-moment correlations were calculated to determine the strength of the relationships among the dependent measures. All data were collected in the Motor Control Laboratory at Indiana University.

Subjects: The experimental group was composed of 20 individuals who had undergone ACL reconstruction with a patellar tendon autograft. The control group comprised 20 participants with no history of significant orthopaedic injuries to the lower extremities.

Measurements: The dependent variables were sway path linear mean for the static condition, dynamic-phase recovery time after perturbation for the dynamic measure, and quadriceps peak torque for strength.

Results: We found significant differences between the ACL and control groups on the measures of dynamic-phase duration and peak torque. The static sway variable did not show a significant difference.

Conclusions: Evaluation of the postural control system under 2 conditions, static and dynamic, showed differences between the ACL and control groups for the dynamic condition only. These results suggest the presence of independent control mechanisms for the control of static and more dynamic postures. In addition, because there were no differences between the injured and noninjured legs of the ACL group, the theory of a central postural control scheme is supported.

Key Words: balance, posture

Over the past 20 years, both athletes and athletic trainers have witnessed monumental improvements in the treatment of anterior cruciate ligament (ACL) ruptures. Today, an estimated 50,000 reconstructions are performed worldwide each year.1 For an athlete, rupturing the ACL typically results in the end of the competitive season. This contrasts with years past, when rupturing the ACL resulted in the end of a competitive career. Most of the advances responsible for allowing the return to preinjury activity have resulted from improvements in surgical techniques and rehabilitation procedures. Along with these technical and procedural advances have come directed experimental research related to ACL injury. One specific area that continues to flourish and that is being addressed from a variety of perspectives is the study of the neurologic structure and function of the ACL. For example, some reports have detailed the neural network of the ACL,2-7 while others have focused on the role of the ACL in proprioception8,9 and postural control.10

Although some questions concerning the neural innervation of the knee have been addressed through animal2,3,11 and human3-6,12 models, the exact neurologic importance of the ACL remains equivocal. However, researchers generally agree that the ACL does contain mechanoreceptors.2-6,11,13 Other work in this area has identified a direct pathway from the ACL to the central nervous system via the posterior articular and sciatic nerves.14 Additional work by Pitman et al15 revealed a direct connection between the human ACL and the cerebral cortex via the use of evoked potential measurements from the scalp.

A primary reason that ACL neurology has become so intensely studied relates to speculation that sensory information disruption at the knee results in repeated episodes of microtrauma.2 Specifically, when the central nervous system has decreased sensory information from the knee, there is a decreased ability to adequately stabilize the lower extremity,16 initiating a repetitive cycle of sensory impairment and microtrauma.2 In support of this theory, proprioceptive deficits related to passive movement have been found in patients with chronic ACL injuries,8 and, following ACL rupture, static postural control is decreased.9,16 However, little is known about the dynamic aspects of postural control after ACL reconstruction.
Although static postural control is a valuable measure of somatosensory integration, a need exists for postural measurements that target the dynamic aspects of postural control. Moreover, authors have expressed concern that measurement of static postural control fails to provide critical information related to factors that might predispose individuals to injury during functional activities. The concerns related to static balance have spurred an increased effort to develop a tool for the assessment of the dynamic components of posture and balance. Although static measures of stability are valuable, one possible limitation is their questionable relationship to dynamic balance and function.

The purpose of our study was to investigate quadriceps strength and static and dynamic balance in the ACL-reconstructed patient and to compare these findings with an age-matched, injury-free control group.

METHODS

Subjects

A total of 40 individuals agreed to participate in this study. Twenty healthy individuals who reported no history of significant orthopaedic injury or balance-related disorders served as the control group. Significant orthopaedic injury was defined as an injury with symptoms persisting for longer than 2 weeks. The control group comprised 7 females and 13 males of mean age 24.0 ± 4.07 years, height 175.30 ± 9.21 cm, and weight 75.41 ± 16.22 kg. For the ACL-reconstructed group, mean age was 23.4 ± 5.79 years, height was 172.72 ± 9.65 cm, and weight was 70.91 ± 17.84 kg. The 12 females and 8 males had undergone complete reconstruction of the ACL with a patellar tendon graft in an arthroscopically assisted procedure. In all cases, the surgery was performed within 30 months of testing, and no procedures were more recent than 3 months (mean, 9.52 months). Each subject was functionally stable and was cleared by the surgeon for participation in this study. The ACL participants were additionally screened, via a questionnaire, for any potentially confounding conditions (e.g., arthritis or leg length differences). Individuals were excluded if they had sustained a significant injury to either lower extremity other than the ACL rupture or if they had injured any other knee ligaments at the time of the ACL rupture. Individuals who had undergone minor meniscal treatment were included.

Before testing, each participant read and completed a subject informed consent form, as approved by the Committee for the Protection of Human Subjects at Indiana University, and a participant questionnaire requiring demographic and injury information.

Participants were tested on the following protocols: (1) functional leg dominance determination, (2) isokinetic strength test, (3) static balance evaluation, and (4) dynamic balance evaluation.

Leg Dominance

Functional leg dominance was determined with 3 functional tests: ball kick test, step-up test, and balance recovery test. Three trials were conducted for each test. During the ball kick test and the step-up test, the leg used to kick the ball and the leg used to step up was identified as dominant. The balance recovery test consisted of the experimenter's nudging the subject off balance by applying a force on the spine at the midscapular level. The leg the subject used to recover balance was identified as dominant. The leg used as the dominant leg by the participant in 2 of 3 trials for each test was identified as the dominant leg for that test. After the 3 tests were completed, the results were examined, and the dominant leg in 2 of the 3 tests was determined to be the functionally dominant leg for this study. A detailed explanation of these tests can be found in Hoffman et al.

Strength Testing

A Cybex II dynamometer (Lumex, Ronkonkoma, NY) was used for testing the strength of the quadriceps muscles. The dynamometer, interfaced with a personal computer, was configured to measure peak torque generated at 60°/s; 60°/s was chosen as the testing speed because the primary focus of the strength evaluation was determining peak torque. If the focus of this study had been to measure functional strength, a velocity spectrum of faster speeds would have been used. Each participant was seated with the hip and knee flexed to 90°. The joint line of the knee was aligned with the rotational axis of the dynamometer head, and the lower end of the torque arm was secured just superior to the level of the malleoli. Each participant was secured at the thigh, waist, and chest and performed 1 set of 5 repetitions after a warm-up session. The peak value from the 5 repetitions was determined to be the peak torque and was used in the analysis.

Static Balance Evaluation

During the static balance evaluation, the participants were instructed to assume single-leg stance on a Kistler Force Platform (Kistler Instrument Company, Amherst, NY), place hands on hips, and focus on a visual target approximately 1.0 m away placed at eye level. Additionally, the participants were instructed to hold the hip, knee, and ankle of the nonsupport leg at a self-selected angle without allowing the 2 legs to touch. After a verbal signal from the participant indicating the assumption of a comfortable and stable stance, a 20-second trial was recorded. Each participant of the experimental group performed 4 20-second trials on both the involved and uninvolved legs; each participant of the control group performed the same trials on both the dominant and nondominant legs. The center-of-pressure excursions were monitored at a sampling rate of 50 Hz. The dependent variable used for the static evaluation was sway path linear mean. Sway path linear mean is the average distance (mm) traveled per sample interval (20
milliseconds). It was calculated by summing the excursions of the center of pressure between each sample and dividing by the number of samples. A comprehensive explanation of the calculation of this variable has been detailed by Hufschmidt et al.20

Dynamic Balance Evaluation

For evaluation of dynamic balance, each participant was tested for 20 seconds in a stance similar to the stance used in the static condition. However, to assess dynamic balance, recovery time from perturbation was measured. At a random point between seconds 8 and 12, an electrical perturbation was delivered to the tibial nerve of the support leg. The stimulation induced an involuntary contraction of the triceps surae, resulting in posterior displacement of the participant’s center of gravity over the base of support. This random perturbation forced the participant to make corrective movements with the leg and hips in order to re-establish a stable posture. If a subject moved hands from hips or touched the ground with the nonstance foot, the trial was repeated. A detailed description of this methodology appeared in Hoffman and Koeja.21

To produce the perturbation, soleus M-waves were elicited according to procedures outlined by Hugon.22 Briefly, surface recording electrodes (Ag/AgCl) were placed over the soleus muscle belly bilaterally. A stimulating electrode (1 cm²) was placed in the popliteal fossa for current delivery, and a dispersal pad (3 cm²) was placed superior to the patella on the distal thigh. A percutaneous electrical stimulus (1.0-millisecond square-wave pulse) was applied to the posterior tibial nerve in the popliteal fossa to elicit the maximum M-wave. Before testing, the maximum M-wave was established. During each trial, the peak-to-peak M-waves were recorded to assure perturbation consistency.

The intensity of the stimulation used for perturbation on each leg was individually set above the level that elicited a maximum soleus M-wave (eg, 4X motor threshold). Since the maximum M-wave indicated activation of all the alpha motoneurons of the soleus motoneuron pool, consistency of perturbation for each participant was assured.

Computerized scanning and graphing of each trial’s sagittal plane center-of-pressure movement allowed separation of the dynamic trials into 3 phases: prestimulation, active, and recovered (Figure 1). The prestimulation phase included all data from the start of the trial to the point of rapid center-of-pressure acceleration (perturbation). The active phase included all data from the point of rapid acceleration of the center of pressure to the point where the participant returned to a level of sway similar to that measured in the prestimulation phase. The recovered phase included the remaining portion of the trial.

A computer program was designed to scan the data and to determine the points used to separate the trials into the 3 phases. The first step in the analysis was to determine the beginning of the active phase, which was easily detected due to the rapid acceleration of the center of pressure from the perturbation. The second step was to establish the threshold level used to determine when the participant had recovered. This was done by determining the sway variability of the prestimulation phase and applying that variability as a threshold to the data from the point of stimulation to the end of the trial. By scanning from the point of perturbation forward, the program determined the point where the participant had recovered from the perturbation.

Statistical Analysis

Zero-order correlations at a .05 probability level were determined to establish the relationships among the 3 dependent variables (peak torque, sway path linear mean, and dynamic-phase duration). Since none of these correlations were significant, univariate analyses were used to analyze each dependent variable. Specifically, a 2-factor analysis of variance (group X leg) was performed on each dependent variable. All significant interactions were broken down into simple main effects for interpretation.

RESULTS

The zero-order correlations are presented in Table 1. A summary of all group and leg means is presented in Table 2.
Table 2. Summary Table of Group and Leg Means ± SD

<table>
<thead>
<tr>
<th>Variables</th>
<th>Control</th>
<th>ACL</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Leg 1*</td>
<td>Leg 2†</td>
</tr>
<tr>
<td>Strength</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak torque (Nm)</td>
<td>249.76 ± 81.86</td>
<td>241.37 ± 79.99</td>
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<tr>
<td>Static condition</td>
<td>0.86 ± 0.12</td>
<td>0.88 ± 0.12</td>
</tr>
<tr>
<td>Sway path linear mean (mm)</td>
<td>2.54 ± 0.73</td>
<td>2.77 ± 0.64</td>
</tr>
<tr>
<td>Dynamic condition</td>
<td></td>
<td></td>
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<tr>
<td>Dynamic-phase duration (s)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Dominant leg for the control group and involved leg for the ACL group.
† Nondominant leg for the control group and uninvolved leg for the ACL group.

Strength

The analysis of peak torque at 60°/sec demonstrated a significant group-by-leg interaction ($F_{1,38} = 49.56, P < .001$) (Figure 2). Investigation of the interaction showed a significant simple main effect for the ACL group ($F_{1,38} = 78.75, P < .001$) and a nonsignificant effect between legs in the control group ($F_{1,38} = 1.17, P = .286$). Specifically, there was a significant reduction in the peak force generated by the ACL leg when compared with the uninjured leg.

Static Condition

The analysis of the static condition sway path linear mean showed no significant main effects or interaction (Figure 3).

Dynamic Condition

The primary dependent variable for this study, dynamic-phase duration, showed a significant main effect for group ($F_{1,38} = 4.94, P = .032$), with the ACL group having longer durations (3.06 seconds versus 2.65 seconds) but no main effect for leg ($F_{1,38} = 0.04, P = .840$) (Figure 4).

DISCUSSION

The methods used to analyze the data in this study allowed us to compare postural sway data from a variety of perspectives. Specifically, they allowed for the separation of the dynamic trials into 3 parts. The first part of the dynamic trials contained static sway data from the beginning of the trial to the onset of the perturbation. The second part of the dynamic trials contained sway data obtained while the participant was responding to the perturbation and therefore was the active, or dynamic, portion of the trial. Finally, the third part of the trial contained sway data that was obtained after the participant had recovered from the perturbation. Breaking the trials into these parts allowed us to compare the 3 phases. Theoretically, before the perturbation (prestimulation phase) and after the point of recovery from the perturbation (recovered phase), the participant was in a relatively quiet single-leg stance. Based on this premise, the data from these 2 parts of the perturbation trials (prestimulation and recovery) could be compared with the static sway trials. Additionally, it was also of interest to determine whether, after the perturbation, the subjects had truly returned to a level of stability that was equal to the static trials. These results showed no differences in the amount of sway in any of these comparisons. These findings provide some level of assurance that the subjects did not...
alter their standing strategies before or after being perturbed. From a methodologic standpoint, this is very important in demonstrating that, although the participants were aware that they were going to be perturbed, their prestimulation static sway was not affected.

Two common mechanisms known to alter afferent joint activity (somatosensory information) are direct mechanoreceptor damage and joint effusion. The concept of joint pathology affecting somatosensory input to the central nervous system was first thoroughly outlined by Freeman and Wyke. These authors suggested that injury to the connective tissue of a joint damages the mechanoreceptors of the capsule and ligaments. In addition, they reported that damage to the joint mechanoreceptors alters feedback to the central nervous system for the control of that specific joint.

Other authors report that joint injury to the mechanoreceptors manifests changes in a different way. These authors suggested that mechanoreceptor damage disrupts a central postural control mechanism. Based on this theory, joint damage to mechanoreceptors should affect the postural control of both the injured and uninjured legs as measured by single-leg tests. Conversely, if postural control changes result directly from mechanoreceptor damage, causing only localized joint impairment, then deficits should be confined to the injured joint or limb, as reported by Freeman and Wyke.

Independent of the exact mechanism of decreased postural control associated with ACL injury, it has been documented that ACL injury negatively affects postural control. As mentioned above, the second mechanism known to affect joint mechanoreceptors is articular joint effusion. Although this mechanism has been studied much less than mechanoreceptor damage, very small amounts of fluid introduced into the knee capsule have resulted in inhibition of the quadriceps muscle as a result of altered afferent activity from increased joint capsule pressure. If more advances in the treatment and rehabilitation of ACL rupture are to occur, the exact mechanism responsible for sensory alterations and detailed neural pathway mapping must be established. Although none of the subjects in this study had a knee effusion, the effects of recent effusions cannot be dismissed.

Many areas of research provide supporting evidence that the ACL contains a vast neurologic supply. Moreover, research supports the existence of direct connections between neurologic structures of the ACL and the spinal cord, as well as supraspinal areas. In addition, it has been shown that ACL rupture disrupts the postural control system, which receives sensory information from the visual, vestibular, and somatosensory systems. Rupture of the ACL directly affects only the somatosensory weighting of information in the postural control equation.

Our strength findings parallel the reports of others who detail quadriceps strength deficits after ACL reconstruction. The peak torque values of the quadriceps indicated strength differences between the reconstructed and the contralateral leg. This indicates that, although there is clear evidence of contralateral neural connections associated with strength, the ACL rupture and reconstruction do not appear to affect force production of the contralateral leg.

The static sway variable of the linear sway path mean showed no difference between the groups or between the legs of the ACL group. This finding is particularly interesting when evaluated in conjunction with the difference between groups on the phase duration of the dynamic balance testing. Our previous study has shown low correlations between static and dynamic measures of postural control. This finding lends support to the idea that static postural control and dynamic balance are governed by different mechanisms.

Participants in the ACL group demonstrated significantly longer phase durations than the participants in the control group, even though no differences between the involved and uninvolved legs of the ACL group were detected. These findings suggest a neurologic crossover effect from the injured to uninjured leg and support the use of a central postural control mechanism. We are not the first to report a decrease in the postural control of the uninjured leg of patients after ACL rupture. Other authors measured the single-leg static postural control of patients with unilateral ACL deficiencies and reported differences between the ACL and control groups, with no difference between the legs of the ACL group. They attributed their findings to a decrease in overall physical activity of the participants in the ACL group. We have taken a more theoretical approach to explaining our results.

Our explanation is based on the idea that the central nervous system is a very plastic entity that can make alterations based on functional demands. Simply, when the ACL is ruptured, the involved leg is compromised because a major mechanical structure has been injured. Unilateral ACL rupture results in an asymmetry between the involved and uninvolved legs. The mechanism the body is able to use, which quickly reestablishes symmetry, is to reduce the function of the
uninvolved leg. By decreasing the function of the uninvolved leg, the magnitude of the asymmetry is lessened. Although this decreases the overall postural control of the system to some degree, it re-establishes symmetry between the legs of the patient. Similar findings in a related area (functional testing) have shown functional decreases in the uninvolved limb after ACL rupture when compared with a control group. The results suggested that, in activities where the knee was exposed to great levels of stress, the involved leg exhibited a functional profile similar to the uninvolved leg. However, both legs of the ACL group showed decreased functional ability compared with a control group. The authors concluded that a change in the central control of posture had affected both the involved and the uninvolved legs of the ACL group. In addition, these authors suggested that the phenomena of no differences between the involved and uninvolved legs when both legs are actually affected may be problematic for previous studies that were limited to between-leg comparisons of individuals.

The goals of our study were to investigate aspects of static balance, dynamic balance, and quadriceps strength. Our current results did not indicate differences between the groups in the measurement of static balance. Although Friden et al reported decreased static postural control in both the involved and uninvolved legs of participants with ACL ruptures, this result is possibly due to the use of different static variables of static sway measurement. The results of both studies suggest a decrease in the general control of posture after ACL rupture.

In conclusion, participants who had undergone ACL reconstruction demonstrated differences from a control group in both strength and recovery from perturbation without demonstrating differences in a measure of static balance. Although Friden et al. reported differences in the dynamic balance measure and the strength measure, these variables were not correlated in either the ACL or control groups. The results suggest the disruption of a central control mechanism of posture, since the dynamic balance measure did not show differences between the legs of the ACL group but did show group differences between the ACL and control groups.

ACKNOWLEDGMENTS

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REFERENCES


Crossover Cutting During Hamstring Fatigue Produces Transverse Plane Knee Control Deficits

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Objective: To assess the effects of eccentric work-induced hamstring fatigue on sagittal and transverse plane (axial) knee and ankle biodynamics and kinetics during a running crossover cut directional change (functional pivot shift).

Design and Setting: A pretest-posttest, single-group intervention experimental design was employed. All data were collected in a biodynamics laboratory.

Subjects: Twenty healthy athletic females were trained for 3 weeks in crossover cutting before testing.

Measurements: Data were sampled during 3 unfatigued and 3 fatigued (20% eccentric isokinetic knee-flexor torque reduction) crossover cut trials. Three-dimensional kinematic and ground reaction-force data were sampled at 200 Hz and 1000 Hz, respectively, and joint moment estimates were calculated. Data were standardized to initial force-plate heelstrike for comparisons of mean differences between conditions using paired t tests with Bonferroni adjustments. Pearson product-moment correlations compared kinematic and eccentric hamstring-torque relationships.

Results: During internal rotation phase I, between heelstrike and impact absorption, mean internal rotation velocity increased by 21.2°/s ± 114°/s. During internal rotation phase II, mean peak transverse plane knee rotation during propulsion decreased by 3.1° ± 9°. During internal rotation phase II, mean peak ankle plantar flexor moment onsets occurred 12.7 ± 53 milliseconds earlier, and this activation demonstrated a moderately positive relationship with the onset of mean peak knee internal rotation during propulsion and a weak negative relationship with mean peak hamstring torque/lean body weight.

Conclusions: The increased knee internal rotation velocity during phase I indicates transverse plane dynamic knee-control deficits during hamstring fatigue. Earlier peak ankle plantar-flexor moments and decreased internal rotation during phase II in the presence of hamstring fatigue may represent compensatory attempts at dynamic knee stabilization from the posterior lower leg musculature during the pivot shift portion of the crossover cut. The weak relationship between decreased hamstring torque/lean body weight and delayed knee internal rotation during propulsion further supports greater dependence on ankle plantar flexors for dynamic knee stabilization compensation.

Key Words: biomechanics, injury mechanisms, functional movement assessment

Noncontact mechanisms may account for up to 78% of anterior cruciate ligament (ACL) injuries,1,2 and athletic females are at particular risk. Numerous investigators have reported increased knee injury incidence for females in sports such as soccer,3 team handball,4 and basketball.5-8 Multiple factors, including less muscular power,9 more frequent lower extremity anatomical malalignment,10 increased knee joint laxity,10,11 hormonal influences on knee joint laxity,12 and poor fundamental motor skills caused by poor training during the developmental years11 have all been associated with this increased ACL injury incidence.

The crossover cut is a running directional change that is reportedly one of the most hazardous noncontact situations for the knee ligaments.13 Crossover cutting demands coordinated lower extremity muscular activation to dynamically control the knee through rapid triaxial joint deceleration during the impact forces of initial ground contact and then during the ensuing rapid acceleration of forward propulsion in a new running direction. The stresses placed on the knee during crossover cutting have led to its being described as the functional equivalent of a clinical pivot shift maneuver.14 The crossover cut is executed by planting the foot ipsilateral to the new running direction (Figure 1) and then crossing the contralateral lower extremity anteriorly to provide acceleration in the new running direction (Figure 2). Directional momentum change occurs during the plant-and-cut phase of the crossover cut. As terminal deceleration from the approach direction occurs over the planted foot, the pelvis and trunk are rotated toward the new direction. Following this, the contralateral lower extremity swings in the new direction to assist with acceleration. The
stance lower extremity, after completing its deceleration function and after the pelvis and torso have been rotated, provides the primary acceleration force in the new direction.13

The hamstring muscles serve as dynamic ACL synergists providing joint-control forces primarily in the sagittal and transverse planes, with greater contributions to dynamic knee stability at ≥25° of flexion.15–20 In the transverse plane, the hamstrings help to provide dynamic control of internal and external tibial rotation. During closed kinetic chain tasks such as crossover cutting, the hamstrings are assisted in sagittal and transverse plane dynamic knee control by the quadriceps femoris and proximal hip and distal lower leg musculature.13,21,22

Eccentric muscle activation is vital to dynamic joint stability,23,24 and the hamstrings work in concert with the ACL in both the sagittal and transverse planes.25–27 Anterior translation and internal rotation of the tibia normally occur as coupled motions,28 and fatigued or weak hamstrings would theoretically be less effective in controlling the magnitude or velocity of either of these potentially ACL-injurious motions.

Using a 3-dimensional mathematical model to assess the transverse plane rotational restraints in 4 cadaveric knee joints, Blankevoort and Huiskes29 found that the ACL was tensioned mainly by an internal rotation moment (P < .05). They further stated that the relative inclinations of the medial and lateral tibial surfaces caused an axial translation (traction effect) to be coupled to the axial rotation, whereby the tibial and femoral insertions of the ACL moved farther apart during internal knee rotation, resulting in further tensioning. Using a cadaveric sample of 14 knees, Andersen and Dyhre-Poulsen30 reported that the ACL was an important restraint to internal rotation, particularly between 10° and 30° of flexion. Based on these findings, the internal knee rotation demands of crossover cutting would be particularly stressfull to the ACL and the anterolateral capsuloligamentous structures. The purpose of our study was to determine the effects of eccentric work-induced hamstring fatigue on knee and ankle kinematics and net joint moment magnitudes and timing during the stance phase of a crossover cut.

METHODS

Instrumentation

Video analysis system. Four high-speed video cameras (NAC Model HVRB-2000, NAC Inc, Tokyo, Japan) sampled interlaced image-field data at 200 Hz. Two cameras were positioned on opposite sides of a runway so that each marker could be viewed by at least 2 cameras, as required by the direct linear transformation procedure.31 A VP-310 Data Acquisition System (Motion Analysis Corp, Santa Rosa, CA) interfaced with a Sun 3/260 minicomputer (Sun Microsystems Inc, Mountain View, CA) phase locked the cameras to enable synchronized data collection. All data were analyzed using KinTrak version 3.0 software (Motion Analysis Corp).32 Local
segmental coordinate system and joint dimension data were collected and processed using Expert Vision software version 2.01 (Motion Analysis Corp). Force plate system. Ground reaction forces were sampled concurrently with kinematic data using a piezoelectric force plate (Model 9261A, Kistler Instrumentation Corp, Winterthur, Switzerland). Vertical (Z), anterior-posterior (X), and medial-lateral (Y) ground reaction force analog signals were digitally sampled at 1000 Hz. Amplified analog signals were input to an analog-to-digital board (Model 2, 821-F-165E, Data Translations, Marlboro, MA) and digitally stored on a minicomputer.

Subjects

Twenty healthy college-aged females who were involved in intramural athletics (soccer, basketball, flag football, or tennis) participated in this investigation. Subjects ranged in age from 18 to 23 years (mean = 21.1 ± 1.6), in weight from 50.8 to 63.5 kg (mean = 60.1 ± 3.6 kg), and in height from 149.9 to 172.7 cm (mean = 163.3 ± 5.7). Subject lean body weight was determined using triceps brachii and iliac crest skinfolds and the Sloan formula No. 2 for females (Skyndex Electronic Bodyfat Calculator, Caldwell, Justiss & Company, Inc, Fayetteville, AR). Mean subject lean body weight was 46.1 ± 2.7 kg. Subject weight was limited to ≤63.5 kg, given the limited eccentric torque capacity of our isokinetic device (Biodex Clinical Data Station Model 892–905, Biodex Corp, Shirley, NY). Only individuals who passed a low back and lower extremity injury screening were allowed to participate. Stance lower extremity preference was deemed the lower extremity that subjects chose for stance when attempting a soccer kick. For ease of data collection and analysis, only individuals with left stance limb preference participated in this study. Subjects were also questioned regarding the regularity of their menstrual cycles and oral birth control use. All subjects had regular menstrual cycles. Subjects were scheduled so that data collection and analysis, only individuals with left stance limb preference participated in this study. Subjects were also questioned regarding the regularity of their menstrual cycles and oral birth control use. All subjects had regular menstrual cycles. Subjects were scheduled so that data collection took place intermenses to negate hormonal influences on ACL cellular metabolism. Before participating, subjects were informed of possible risks and signed a consent form. This study was approved by the University of Kentucky Medical Internal Review Board.

Preactivity Warm-up

Crossover cutting was preceded by subjectively low-intensity stationary cycling (Monark 817E, Quinton Fitness Equipment, Seattle, WA) at 2 kiloponds resistance (10 minutes), followed by bilateral static hamstring, ankle planter flexor, hip adductor, trunk extensor, hip extensor, and quadriceps femoris stretching for 4 repetitions of 20 seconds’ duration each. These activities were performed to promote normal neuromuscular function during cutting and to prevent injury.

Crossover Cut Maneuver Training

For 3 days/week over 3 weeks before biodynamic testing, subjects were trained in the crossover cut technique (15 to 20 cuts/session) with emphasis on heelstrike landing and a cutting angle of as close to 90° from the approach direction as possible. During these sessions, a submaximal approach velocity of between 2 and 2.5 m/s (as determined by the primary investigator with a handheld stopwatch) over an approach distance of 2.5 m from the force-plate center was used to avoid injury during testing and to promote performance consistency.

Eccentric Isokinetic Hamstring Exercise Training

During the final week of crossover cut training, subjects were also trained in eccentric isokinetic hamstring work to become familiar with eccentric hamstring-activation timing, and the fixed speed-accommodating resistance concept of isokinetic exercise. During training and testing, an isokinetic velocity of 30°/s and a 305.2-N·m torque limit were used. Subject positioning, stabilization, and dynamometer input shaft gravitational moment corrections were performed using standard protocol. Knee range of motion during isokinetic training and testing was between 30° and 90° of flexion as determined by the primary investigator with a handheld goniometer. This range of motion was used to enable consistent active input shaft torque initiation throughout the test range of motion (particularly at terminal extension) to avoid sudden stops and starts during the fatigue protocol. Knee-testing fixture lengths and pad positions were noted to ensure replication during the eccentric isokinetic hamstring-fatigue protocol. To isolate the hamstrings, the primary investigator applied manual resistance to the input arm (in the direction opposite the muscle group being tested, with a 40.7-N·m eccentric torque limit) to return the input arm to its starting position. This enabled the hamstrings to be trained or tested with minimal quadriceps femoris activation. This method replicated the fatigue protocol. Approximately 5 repetitions were performed during each training session.

During the last training session, mean peak eccentric hamstring torque was determined from 5 maximal effort repetitions (mean = 93.5 ± 9.5 N·m). The dynamometer was calibrated according to the manufacturer’s protocol before data collection. Subjects followed a consistent protocol with verbal encouragement to facilitate the desired volitional effort during all testing.

Eccentric Isokinetic Hamstring Fatigue Protocol

Before initiating the fatigue protocol, subjects performed 3 maximal-effort repetitions to reconfirm their mean peak eccentric isokinetic hamstring torque and to create a horizontal cutoff cursor representing 80% of this maximal volitional effort (not observed by subjects). An eccentric fatigue model was selected to replicate the primary func-
tional demands placed upon the hamstrings during the crossover cut stance phase. The exercise setting of Biodex Advantage software version 2.0.4 (Biodex Corp, Shirley, NY) was used during this protocol to enable investigator observation of each torque curve. Subjects performed continuous maximal effort repetitions until a 20% peak torque reduction was observed. Fatigue was operationally defined as a 20% torque reduction to provide a torque capability deficiency that was significant, but also safe and functionally relevant. Subjects were considered to have experienced 20% eccentric work-induced hamstring fatigue when 3 consecutive repetitions were less than 80% of the predetermined mean peak torque. Repetitions performed before hamstring fatigue ranged from 25 to 77 (mean = 45.4 ± 15).

Retroreflective Marker Placement

Before cutting, subjects had 9 retroreflective markers secured to the left lower extremity, denoting the local segmental coordinate systems of the foot, leg, and thigh. Markers were placed so that each segment (foot, leg, and thigh) was defined by 3 markers.22 A single marker placed near the fifth lumbar vertebra spinous process was used for calculating approach velocity. After crossover cutting trial data collection, subjects had 2 additional markers placed at the left hip, knee, and ankle to enable approximate joint center and segment length calculations within their respective local segmental coordinate systems (Figure 3).

Video Field Calibration

Before data collection, a calibration file was collected, denoting the locations of known video field control points using KinTrak version 3.0 software (Motion Analysis Corp). These points consisted of 4 sets of 5 retroreflective markers (positioned at 15.2 cm, 45.7 cm, 76.2 cm, 106.7 cm, and 137.2 cm from the runway surface) suspended on strings (z-axis) from tripods positioned at the video field corners, defining a 1.22-m (x-axis) by 0.61-m (y-axis) spatial plane. We positioned 3 additional markers in a triangular pattern on the force-plate surface to identify its orientation within the global coordinate system (as defined by the control points) for subsequent inverse dynamic analysis. Spatial plane calibration used standard direct linear transformation procedures.31

Kinematic and Kinetic Analysis

Video calibration file and crossover cut trial tracking were performed using Expert Vision version 2.01 software (Motion Analysis Corp). A vector-transformation program converted calibration file data from a global coordinate system to an anatomically relevant local segmental coordinate system and determined approximate joint centers and thigh, leg, and foot segment lengths.26 Following this, crossover cut trial data were tracked and input into the KinTrak program for kinematic analysis and then combined with ground reaction-force data to compute net joint moments using inverse dynamics. Standard KinTrak program approximations for center of mass, moment of inertia, and relative mass were used for net joint moment calculations.32 We subsequently assessed mean differences between conditions for stance limb kinematic and kinetic variable magnitude and onset of occurrence at critical points during the crossover cut stance phase.

Convention of Kinematic Description

Kinematic analysis defined complete knee extension as 0° and neutral ankle dorsiflexion as 90° (greater for increased dorsiflexion). Our biomechanical definition of neutral sagittal plane ankle position contrasts with the clinical definition of 0°. Transverse plane knee rotation was determined by the relationship of the leg to the thigh, such that neutral rotation was defined as 0°, relative leg internal rotation was negative, and relative leg external rotation was positive. Positive or negative net joint moments denoted the primary muscular activity occurring at a given joint relative to joint kinematics according to the right-hand rule.37

Determination of Cutting Angle and Approach Velocity

The angle formed by the intersection of a line through the central portion of the lateral calcaneus and the fifth metatarsal head marker of the stance limb foot and the video field x-axis was used to approximate the cutting angle, such that toeing out was represented by an angle of less than 90° and toeing in was represented by an angle of greater than 90°. Approach velocity was calculated from fifth lumbar vertebra marker horizontal displacement at 0.25 milliseconds before force-plate contact.

Design and Statistical Analysis

We collected data (3 trials unfatigued and 3 trials fatigued) on 5 subjects/week (4 groups of 5 subjects). Subjects wore the...
same tennis shoe model and brand (Chris Evert Model, Converse, Inc, Reading, MA) for marker placement and shoe-force platform interface consistency.

Peak trial means and standard deviations for knee and ankle kinematic and kinetic variables were determined. Paired t tests with Bonferroni adjustments for multiple comparisons assessed mean differences between unfatigued and fatigued conditions. Differences were deemed statistically significant when \( P < .0167 \) (0.05/3). Pearson product-moment correlations were used to compare kinematic and eccentric hamstring torque relationships. SAS for windows version 6.11 (SAS Institute Inc, Cary, NC) was used for all statistical calculations.

**RESULTS**

Variables that reportedly relate to crossover cutting intensity\(^{15,22,38}\) are presented in Table 1. Transverse plane peak knee and sagittal plane ankle kinematic data are presented in Table 2. Transverse plane kinematic analysis of the crossover cut revealed 2 distinct knee internal rotation phases after heelstrike in all trials. The initial knee internal rotation (Phase I) occurred immediately after heelstrike, before crossover cut directional change. This event is believed to represent sudden, distal-to-proximal kinematic changes as the forces of impact are attenuated. The magnitude and velocity of occurrence of these changes are largely dependent upon both the vigor of the cut and the ability of eccentric (deceleratory) lower extremity muscular forces to provide dynamic stability and protect noncontractile joint structures (Figure 4). A second knee internal rotation (Phase II) occurred as subjects attempted propulsion in the new running direction. This event is believed to represent the functional pivot shift portion of the crossover cut; the leg is maintained in relative internal rotation as the hip and thigh are externally rotated over the planted foot. Hamstring fatigue resulted in increased mean knee internal rotation velocity during phase I, decreased peak knee internal rotation during propulsion, and earlier maximal ankle plantar-flexor moment onsets (Table 2). The increased knee internal rotation velocity during Phase I suggests decreased or modified dynamic knee control in the transverse plane during impact-force attenuation. Hamstring fatigue resulted in earlier peak ankle plantar-flexor moment onsets, suggesting dynamic compensations to decelerate knee internal rotation during Phase II (propulsion), but not during Phase I (impact-force attenuation). The moderate positive correlational relationship between maximal ankle-dorsiflexion onset and maximal knee internal rotation during propulsion \((r = 0.71, P = .001)\) supports this (Figure 5). The weak inverse relationship between mean peak hamstring torque/lean body weight and maximal knee internal rotation onset during propulsion \((r = -0.52, P = .03)\) (Figure 6) further suggests an increasing contribution for dynamic transverse plane knee control from the ankle plantar flexors during hamstring fatigue. Repetitions to fatigue did not correlate even weakly with any other variable.

**DISCUSSION**

The similarities between conditions for cutting intensity indicator variables strengthen the argument that differences between conditions were related to the effects of hamstring fatigue on dynamic knee control and not merely subjects’ attempts to volitionally avoid ligamentously stressful knee positions. Increases in knee internal rotation velocity immediately after heelstrike during impact attenuation (Phase I) indicate transverse plane dynamic knee control deficits during hamstring fatigue. As researchers have alluded to at the ankle and subtalar joint,\(^{16,17,22,39}\) the sudden velocity increases associated with these displacements may be more related to ACL injury than the ultimate magnitude.\(^{39,40}\) Controlled deceleration either through dynamic muscular activation\(^{16}\) or via bracing (or other proprioceptive garments), properly fitting and supportive footwear, or foot orthoses\(^{39}\) may be vital to ACL

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unfatigued Hamstring</th>
<th>Fatigued Hamstring</th>
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<tr>
<td>Approach velocity</td>
<td>2.34 ± 0.2 m/s</td>
<td>2.32 ± 0.3 m/s</td>
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<td>86.1° ± 6°</td>
<td>87.1° ± 7°</td>
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<tr>
<td>Impact knee flexion</td>
<td>19.3° ± 9°</td>
<td>19.8° ± 10°</td>
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<td>Peak knee flexion</td>
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<td>57.3° ± 10°</td>
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<tr>
<td>Peak impact vertical ground reaction force</td>
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<td>1205 ± 285 N</td>
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<tr>
<td>Peak propulsion vertical ground reaction force</td>
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<td>1148.6 ± 185 N</td>
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<td>Force-plate duration</td>
<td>356.7 ± 49 ms</td>
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Table 2. Transverse Plane Peak Knee and Sagittal Plane Ankle Kinematic Data (mean ± SD)
injury prevention. Earlier peak ankle plantar-flexor moment onsets and decreased knee internal rotation magnitude with propulsion (Phase II, functional pivot shift) during hamstring fatigue are believed to represent compensatory attempts at dynamic knee control from the lower leg musculature. These compensations, however, were not evident after hamstring fatigue for Phase I (impact-force attenuation), suggesting that compensations for dynamic knee control are either not necessary during this phase or are not attainable via neuromuscular means. The inverse relationship between mean peak hamstring torque/lean body weight and maximal knee internal rotation onset during propulsion with hamstring fatigue suggests that transverse plane knee control is being provided by another source, and our results in the aggregate strongly implicate the ankle plantar flexors. Based on these results, knee rehabilitation programs should attempt to restore normal synchronous knee and ankle arthrokinematics and neuromuscular activation timing before focusing on more conditioning-oriented strength and power capabilities. From an injury prevention standpoint, offseason conditioning programs may need to place greater emphasis on these components via sport- and position-specific functional movement challenges of progressive speed, cadence, duration, and distance.

CONCLUSIONS

Eccentric work-induced hamstring fatigue created decreased dynamic transverse plane knee control, as evidenced by increased knee internal rotation during impact-force attenuation (Phase I). Earlier peak ankle plantar-flexor moment onsets and decreased knee internal rotation with propulsion (Phase II) during hamstring fatigue may represent compensatory attempts at dynamic knee stabilization during the reportedly ligamentously stressful functional pivot shift phase of the crossover cut. These compensations, however, were not evident during the knee internal rotation of impact-force attenuation (Phase I), suggesting that this phase is less controllable dynamically by...
neuromuscular activation. Although hamstring torque capability or endurance did not relate to improved transverse plane knee control, fatigue resistance of the lower leg musculature appears to be vital to this function. This lends support to knee rehabilitation and injury prevention programs that focus on coordinated lower extremity closed kinetic chain tasks, such as minisquats, single-leg vertical and horizontal hopping, lateral shuffles in a minisquat position, back pedaling, and quick multidirectional movement responses to cues. These tasks should be performed with the aforementioned progressions and with an emphasis on movement quality. When a movement lacks control, and when the athlete cannot correct by following verbal or visual cues, or both, the task should be stopped. Continued performance in the presence of faulty technique increases the likelihood of the athlete’s sustaining a training-induced knee injury.

REFERENCES

Hormonal Changes Throughout the Menstrual Cycle and Increased Anterior Cruciate Ligament Laxity in Females

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Objective: To determine whether women experience significantly greater anterior cruciate ligament (ACL) laxity in conjunction with estrogen and progesterone surges during a normal 28- to 30-day menstrual cycle.

Design and Setting: Serial estrogen and progesterone levels were measured via radioimmunoassay procedures to identify the follicular and luteal phases of a subject's menstrual cycle and to determine periods of peak hormonal surges. Concomitant ACL laxity measures were taken using a knee arthrometer. Hormone levels and ACL laxity were assessed on days 1, 10, 11, 12, 13, 20, 21, 22, and 23 of the menstrual cycle. Day 1 corresponds to the menstrual phase, when estrogen and progesterone levels are at their lowest. Days 10 through 13 correspond to peak estrogen surge (follicular phase), and days 20 through 23 correspond to peak progesterone surge (luteal phase).

Subjects: Seven active females between the ages of 21 and 32 years with at least one apparently healthy knee (no known knee anomalies) volunteered for participation in this study. Each subject stated that she experienced a normal (28- to 30-day) menstrual cycle and was not currently taking any type of hormone therapy (e.g., birth control medication).

Measurements: Blood was drawn on days 1, 10, 11, 12, 13, 20, 21, 22, and 23 of each subject's menstrual cycle, and ACL laxity measurements were assessed immediately after the blood draws. Estrogen and progesterone levels were determined via radioimmunoassay procedures, and ACL laxity was determined using a knee arthrometer.

Results: A within-subjects, repeated-measures analysis of variance was applied to determine the presence or absence of significant differences in ACL laxity values over the course of a subject's menstrual cycle. We found a significant difference in ACL laxity when comparing baseline levels of estrogen with peak levels of estrogen. A significant increase in ACL laxity was also noted when comparing baseline levels of progesterone with peak levels of progesterone.

Conclusions: ACL laxity increased significantly throughout the menstrual cycle when comparing baseline with peak levels of estrogen and progesterone.

Key Words: estrogen, progesterone, knee arthrometer, radioimmunoassay

More females are participating in sports as a result of Title IX implementation; having become much more athletically active, females subsequently have sustained a significant percentage of total sports injuries.1–4 Interestingly, it appears that female athletes have a disproportionately greater incidence of knee injuries than their male counterparts.5 According to the NCAA Injury Surveillance Survey, females have an increased rate of knee injury and anterior cruciate ligament (ACL) rupture compared with males in basketball, soccer, and gymnastics.5 The ACL is the most commonly disrupted ligament in the knee,6 and its injury is occurring at an increasing rate in women's athletics.

The ACL extends posteriorly and laterally from the area anterior to the intercondylar eminence of the tibia to the posterior part of the medial surface of the lateral condyle of the femur. In general, the ACL prevents the tibia from moving anteriorly during weightbearing. It also stabilizes the tibia against abnormal internal rotation and serves as a secondary restraint against valgus and varus stress. The ACL works in conjunction with the thigh muscles, especially the hamstring muscle group, to stabilize the knee joint. It is most vulnerable to injury when the leg is partially flexed and in a weightbearing position, the tibia is externally rotated, and the knee is in a valgus position. This is an especially vulnerable position for females, who tend to demonstrate greater genu valgum than males due to a wider pelvis. Excessive genu valgum may predispose an individual to patellofemoral disorders and an increased ACL injury risk.

Typically, the ACL can sustain injury from a direct blow to the knee or from a single-plane force. The single-plane injury occurs when the lower leg is rotated while the foot is fixed to the playing surface, such as when an athlete suddenly decel-
erates, plants, and makes a sharp “cutting” motion, causing an isolated tear of the ACL.

Alarmingly, many female ACL injuries are the result of noncontact mechanisms: quick stopping and cutting motions in sports such as basketball, soccer, and gymnastics.⁷ The unusual conditions under which the injuries are occurring are bringing more attention to female ACL injuries. The mechanism of the increased injury rate remains uncertain; however, possible explanations include sex differences in ligament or muscle strength, training history, anatomy, and conditioning techniques.

A hormonal influence on knee joint laxity has been suggested, along with these sex-related factors, as being associated with the increased ACL injury rate among female athletes.⁷,⁸ The identification of estrogen and progesterone receptors in the fibroblasts of the human ACL suggests that pregnancy-related hormones may have an effect on the structure of this ligament.⁹ Unlike her male counterpart, the menstruating athlete experiences cyclical changes in hormone levels throughout her reproductive years. The pregnancy-related hormones estrogen and progesterone fluctuate throughout the female menstrual cycle (Figure 1).

The duration of the menstrual cycle ranges from 24 to 35 days, averaging 28 days. Events occurring during the menstrual cycle can be divided into 3 phases: (1) the menstrual phase, (2) the follicular phase, and (3) the luteal phase.¹⁰ The menstrual phase is caused by a sudden reduction in estrogen and progesterone and lasts for approximately the first 5 days of the cycle. The follicular phase lasts from days 6 to 13 in a 28-day cycle. It is during this phase that the developing follicle increases its secretion of estrogens.¹¹ Consequently, estrogens are the dominant ovarian hormones during this phase of the menstrual cycle. The luteal phase of the menstrual cycle is the longest in duration, lasting from days 15 to 28 in a 28-day cycle. It is the time between ovulation and the onset of the next menses. After ovulation, luteinizing hormone secretion stimulates the development of the corpus luteum. The corpus luteum then secretes increasing quantities of estrogens, progesterone, and relaxin.¹¹,¹² If fertilization and implantation do not occur, the rising levels of these hormones will decrease to their initial, lowest levels when the cycle begins.¹⁰

Although it has been reported that estrogen and progesterone receptors have been identified on the ACL,⁹ to date there is no published information available as to whether or not ACL laxity changes in response to peak estrogen and progesterone levels during the course of the menstrual cycle. The purpose of our study was to determine whether females experience significant differences in ACL laxity in conjunction with estrogen and progesterone surges during a normal 28- to 30-day menstrual cycle.

**METHODS**

**Subjects**

Seven female subjects ranging in age from 21 to 32 years (mean age = 26.9 ± 4.2 years, height = 170.5 ± 5.7 cm, weight = 62.7 ± 4.9 kg) participated in this study. Disqualification criteria included the presence of any of the following

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Figure 1. Estrogen and progesterone fluctuations throughout the menstrual, follicular, and luteal phases of the normal 28- to 30-day menstrual cycle.
conditions: (1) bilateral knee pathology, (2) use of hormone therapy, or (3) a 90-degree tubercle-sulcus angle of more than 10°. All participants stated that they experienced a normal (28-to 30-day) menstrual cycle. Each participant had at least one apparently healthy knee (no known knee anomalies), which was used for ACL laxity assessment during the course of the study. All participants stated that they were not currently taking any type of hormone therapy (eg, birth control medication) that might affect normal hormone level fluctuations. Because of the tendency of females to display a greater Q-angle than males, thus predisposing them to excessive genu valgum, we decided to eliminate participants with excessive genu valgum. To identify excessive genu valgum, a 90-degree tubercle-sulcus angle (Figure 2) was measured by palpating the transepicondylar axis of the femur and drawing a line perpendicular to that axis, which was compared with a line passing through the center of the patella and the tibial tuberosity. An angle of 0° has been defined as normal, whereas an angle of 10° or more is abnormal.13 All participants had a measured 90-degree tubercle-sulcus angle of less than 10° (mean tubercle-sulcus angle = 5.1° ± 1.6°). Informed consent was received from each subject in accordance with institutional review board guidelines from the University of Utah, Salt Lake City, UT, and The Orthopedic Specialty Hospital, Murray, UT. The investigation was approved by the University of Utah Human Investigation Committee and The Orthopedic Specialty Hospital.

**Instruments**

A 21-gauge needle was used in conjunction with an 8.5-mL Vacutainer (Becton Dickinson Vacutainer Systems, Franklin Lakes, NJ) for all blood draws for the purpose of determining serial estrogen and progesterone levels. ACL laxity measurements were assessed with the KT-2000 knee arthrometer (MEDmetric, San Diego, CA), and values were plotted on an X-Y plotter for 67, 89, and 133 N of pull force.

**Procedures**

Each subject reported to The Orthopedic Specialty Hospital, Murray, UT on the day of her onset of menses. At this time, a blood sample and an ACL laxity measurement were taken. Blood samples were immediately taken to the Cottonwood Hospital Blood Laboratory, Murray, UT, for radioimmunoassay procedures. Estrogen and progesterone levels were recorded to the nearest pg/mL and ng/mL, respectively. Immediately after blood sampling, an ACL laxity measurement was taken using the KT-2000 knee arthrometer. Total tibial translation relative to the femur was plotted graphically on an X-Y plotter for 67, 89, and 133 N of force. Displacement was recorded to the nearest 0.5 mm for 133 N of force. This same procedure was completed on days 10, 11, 12, 13, 20, 21, 22, and 23 of the participant’s menstrual cycle to determine peak levels of estrogen and progesterone during the follicular and luteal phases.

**Statistical Analysis**

A within-subjects, repeated-measures analysis of variance was used to determine the presence or absence of significant differences in knee laxity values over the course of the subject’s menstrual cycle. Differences were considered statistically significant at an \( \alpha \) level of 0.05 or less. All statistical analyses were performed using a personal computer and SPSS for Windows software (version 6.01, SPSS, Inc, Chicago, IL).

**RESULTS**

Means and standard deviations for estrogen and progesterone changes, as well as ACL laxity changes, throughout the subjects’ menstrual cycles are listed in the Table. Phase I corresponds to day 1 of the menstrual cycle (menstrual phase) and represents baseline levels of estrogen and progesterone. Phase II corresponds to days 10 through 13 of the menstrual cycle (follicular phase), or peak estrogen surge. Phase III corresponds to days 20 through 23 of the menstrual cycle (luteal phase), or peak progesterone surge. We found a significant difference (\( F_{1,6} = 3.56, P = .048 \)) in ACL laxity when comparing baseline levels of estrogen (Phase I) with peak levels of estrogen (Phase II). A significant difference (\( F_{1,6} = 13.41, P = .006 \)) in ACL laxity was noted when comparing baseline levels of progesterone (Phase I) with peak levels of progesterone (Phase III) (Figure 3).

**DISCUSSION**

The purpose of our study was to determine whether women experience significant differences in ACL laxity in conjunction with estrogen and progesterone surges during a normal 28- to
The pregnancy-related hormone relaxin is thought to be associated with ligamentous relaxation of the pubis and pelvis to accommodate the size of the fetus and fetal passage during birth. However, there is no definitive evidence for this. Recently, it has been speculated that the hormones estrogen and progesterone may exhibit an increased ligamentous laxity effect, to date no research has examined comparisons between ACL laxity values and measured levels of estrogen, progesterone, or relaxin.

For a hormone to have an effect, a receptor must be present to accommodate that particular hormone. Recent evidence reveals that estrogen and progesterone receptors are present in the ACL. More recently, these researchers used in vitro experimentation to establish a possible link between estrogen levels and fibroblast metabolism. Using rabbit ACLs, they found that collagen synthesis by the ACL fibroblasts significantly decreased with increasing local estradiol concentration in a dose-dependent manner and concluded that estrogen may have an effect on the structure of the ACL. We found that ACL laxity increased with increasing levels of circulating estrogen associated with the follicular phase, which supports the theory that increased levels of estrogen may have an effect on the ACL. In another study, researchers reported a greater number of ACL injuries during the ovulatory (follicular) phase of the menstrual cycle and concluded that hormone fluctuations need to be considered as a possible factor in increased incidence of ACL injuries among women. Their data were collected via an interviewer-administered questionnaire of young females. The questionnaire investigated the time of injury as compared with the phase of the menstrual cycle. Our results agree with the suggestion that, if increased estrogen levels result in increased laxity, female athletes may be at increased risk for ACL injury during times when these hormones are at peak levels.

The differences found in our study, comparing ACL laxity values between baseline and peak levels of progesterone, support the evidence mentioned above that fluctuating levels of hormones experienced during the menstrual cycle have an effect on female ACL laxity. Although significant differences were found between ACL laxity and peak levels of estrogen and progesterone, it should be noted that no measurements (hormone assays or ACL laxity measurements) were taken between the days of the follicular phase and the luteal phase (approximately days 15 to 20 of the menstrual cycle), and it is not known what changes, if any, occurred between the follicular and luteal phases of the menstrual cycle. Because no measurements were taken between the follicular and luteal phases, the difference in ACL laxity found during the luteal phase may actually have occurred earlier or may have been a delayed effect of estrogen. It is possible, as well, that increased

### Hormonal and ACL Laxity Changes Throughout The Menstrual Cycle (Mean ± SD)

<table>
<thead>
<tr>
<th>Phase of Menstrual Cycle</th>
<th>Estrogen (pg/mL)</th>
<th>Progesterone (ng/mL)</th>
<th>ACL Laxity (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase I (menstrual phase)</td>
<td>160.00 ± 66.24</td>
<td>.60 ± .40</td>
<td>5.6 ± 1.34</td>
</tr>
<tr>
<td>Phase II (follicular phase)</td>
<td>778.00 ± 255.43*</td>
<td>.64 ± .31</td>
<td>6.4 ± 1.64*</td>
</tr>
<tr>
<td>Phase III (luteal phase)</td>
<td>395.00 ± 134.57*</td>
<td>14.00 ± 5.44*</td>
<td>7.0 ± 1.66*</td>
</tr>
</tbody>
</table>

* Indicates significant changes compared with Phase I.

30-day menstrual cycle. Estrogen and progesterone plasma levels were measured during the 3 phases of a single menstrual cycle for 7 women. The follicular and luteal phases of the menstrual cycle were identified to establish peak values for these hormones. ACL laxity measurements were then compared with the baseline and peak levels of estrogen and progesterone. If estrogen and progesterone influence ACL laxity, there should be a change in ACL laxity during the menstrual cycle.

Our results support the theory that hormonal changes experienced during the menstrual cycle may have an increased ACL laxity effect in women. In this study, the greatest ACL laxity was associated with the luteal phase. The literature shows that, during the course of a normal menstrual cycle, women tend to experience surging levels of estrogen and progesterone throughout the menstrual cycle. Estrogen and progesterone are lowest during the menstrual phase of the cycle. During the follicular phase, estrogen levels rise dramatically as a result of rising levels of luteinizing hormone, while progesterone remains relatively low. During the luteal phase, progesterone levels increase as a result of the development of the corpus luteum. The results of estrogen and progesterone assays obtained in our study agree with the above-mentioned hormone fluctuations experienced during the normal menstrual cycle (Table).

Some researchers have speculated that the increased joint laxity of females compared with males may contribute to the increased incidence of knee injuries among female athletes. It has also been suggested that pregnancy-related hormones, specifically estrogen and progesterone, may have an effect on increasing joint laxity. The pregnancy-related hormone relaxin is thought to be associated with ligamentous laxity increase in increasing joint laxity.
female ACL laxity could be a combined effect of estrogen and progesterone. Future research on this subject should include daily ACL laxity measurements throughout the entire menstrual cycle.

It is not known whether the differences in ACL laxity were the direct result of increased levels of circulating estrogen and progesterone. Changes in female ACL laxity may be due to conditions other than varying levels of estrogen and progesterone, specifically changing levels of relaxin. Relaxin has been found in the peritoneal fluid of nonpregnant, midluteal-phase females at greatly reduced levels, compared with levels found during pregnancy, and is thought to be secreted from the corpus luteum.11,12 Our study did not measure varying levels of relaxin throughout the normal menstrual cycle. Future research should examine the possibility of relaxin receptors on the ACL. Also, future research should look at relaxin levels, as well as the combination of estrogen, progesterone, and relaxin, and the relationship to female ACL laxity.

A number of factors affect displacement of the knee joint: starting position of the joint (angle of knee flexion), external constraints on motion, applied force (load, direction, and point of application), muscle tone (quadriceps and hamstring relaxation), and ligament laxity.18 Many investigators have observed that anterior laxity resulting from disruption of the ACL is best detected with the knee in 15° to 45° of flexion.18-21 Because anterior-posterior laxity is altered by the angle of flexion of the knee, it is important that participants are placed in the same angle of flexion for each measurement.18 The thigh support used in this study positioned the knee at approximately 35° of flexion. Both limbs of the participants were positioned in the same degree of rotation by means of a footrest, which constrained external rotation of the tibia. The base of the footrest is scaled, and the starting position of each subject was noted and maintained throughout subsequent ACL laxity measurements. Muscle tone was measured by manually assessing the participant’s quadriceps and hamstrings and verbally instructing the subject to relax. Because this technique is fairly subjective in nature, it was impossible to ascertain whether true muscle relaxation was obtained. The test administrator for this investigation was experienced and had previously demonstrated acceptable intertester and intratester reliability, reducing the likelihood that the ACL laxity values obtained were compromised due to this phenomenon. An intraclass correlation for a single tester for 133 N of force for right leg anterior displacement has been reported to be 0.932.22

CONCLUSIONS

Although the subject sample size in our study was small, the results demonstrate a definite relationship between greater female ACL laxity and surging levels of estrogen and progesterone during a normal menstrual cycle. Because the women who participated in this study exhibited increased ACL laxity throughout the course of their menstrual cycle, it cannot be concluded that increased laxity increases the risk of ACL injury during these times of peak hormone levels. It is possible that increased ACL laxity may actually be the result of a protective mechanism designed to allow the ligament to elongate rather than rupture, in which case increased levels of circulating reproductive hormones may not be a contributing factor to increased female ACL ruptures. Because we do not yet know whether circulating hormones contribute to the increased incidence of ACL injuries, future research on this topic should focus on when during the menstrual cycle ACL injuries are occurring.

This is the first known study to examine the relationship between female sex hormones and ACL laxity. The results demonstrate that female ACL laxity significantly increases in conjunction with surging levels of estrogen and progesterone during the normal menstrual cycle. Due to the increased participation of women in sports and the increased ACL injury rate in female athletes compared with males, more research is needed to address the causative factors and the role of prevention in decreasing the rate of knee injury among female athletes. Our results, which indicate the importance of considering female sex hormones as one of several factors that may be contributing to the female ACL injury epidemic, provide sound justification for further research in this area.

ACKNOWLEDGMENTS

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REFERENCES


Anterior Cruciate Ligament Injury in Female Athletes: Epidemiology

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Objective: To present epidemiologic studies on anterior cruciate ligament (ACL) injuries in female athletes.

Data Sources: MEDLINE was searched from 1978 to 1998 with the terms "anterior cruciate ligament" and "female athlete," among others. Additional sources were knowledge base and oral, didactic, and video presentations.

Data Synthesis: Epidemiologic studies have focused on level of participation, specific sports, sex differences and contributing factors, injury mechanism, prevention programs, and outcomes studies. Female athletes have a significantly increased risk of noncontact ACL injuries over male athletes in soccer and basketball.

Conclusions/Recommendations: I believe that appropriate intervention programs can reduce these alarming rates of ACL injuries.

Key Words: mechanism of injury, position of no return, outcomes studies, prevention programs

Although the medial collateral ligament is the most commonly injured ligament, the anterior cruciate ligament (ACL) is the most frequently injured single ligament associated with limited range of motion. In 1985, it was estimated that 50000 knee surgeries were performed each year in the United States. One study showed an incidence of 60 knee ligament injuries per 100000 health members per plan year. Males accounted for 72% and females for 28%; 65% of the injuries occurred during sports activities.

The true incidence of noncontact ACL injuries and the actual numbers of athletes affected are difficult to determine; determination would require following a large number of athletes participating on different levels over several seasons. In studying the incidence of this injury, the numerator is the number of ACL tears, and the denominator can be, for example, the number of athletic exposures (ie, number of hours of practices and games) or the number of participants. For valid comparisons of statistically significant numbers, epidemiologic studies must involve a large number of subjects over an appropriate number of years.

Epidemiologic studies have focused on level of participation, specific sports, sex differences and contributing factors, injury mechanism, prevention programs, and outcomes studies. A significantly increased risk of noncontact ACL injury has been noted in female soccer and basketball athletes when compared with male athletes in the same sports. I believe that appropriate intervention programs can reduce these alarming rates and allow female athletes to participate with less risk of ACL injury. In this paper, the results of these studies will be addressed and suggestions for preventing ACL injuries will be made.

LEVEL OF PARTICIPATION

College Level

In 1982, the National Collegiate Athletic Association instituted the Injury Surveillance System, which collects injury information from athletic trainers at a geographic cross-section of Division I, II, and III institutions. In 1997–1998, data on 15 sports (football, men’s and women’s soccer, field hockey, women’s volleyball, men’s and women’s gymnastics, wrestling, ice hockey, men’s and women’s basketball, spring football, softball, and men’s and women’s lacrosse) were collected. From 1990–1991 through 1997–1998, female basketball players incurred 2.89 times the ACL injuries of male basketball players, and female soccer players sustained 2.29 times more ACL injuries than male soccer players. All mechanisms of injury (noncontact, contact and collision, surface contact, and ball contact) were considered together.

As the years have passed, females have continued to experience more injuries than males, but injury rates within the sexes have not changed. That is, even though the female athletes are starting to play earlier and may now have better coaching and improved skills, their injury rate has not declined.

Female basketball players received an average of 0.68 ACL injuries in games versus 0.10 in practices, while the rates for male basketball players were 0.14 (games) and 0.05 (practices). Similarly, female soccer players incurred an average of 1.12 injuries in games and 0.09 in practices, while the rates for males were 0.45 (games) and 0.06
High School Level

In studies of Texas high school football and girls' and boys' basketball injuries,6,8,11 knee injuries were most common in girls' basketball, with a 2.1 times greater risk of knee injury per hour of exposure in females. Males had more injuries (543 injuries/973 participants) than females (436 injuries/890 participants) for injury rates of 0.55 in males and 0.49 in females. Compared with the males, female basketball athletes sustained 3.75 times more ACL injuries per exposure hour. The risk of injury in both males and females was greater during games than during practices.

When New Jersey high school basketball athlete injury patterns were compared,16,52 females had a greater number of total and season-ending knee injuries, and ACL injuries occurred 3.52 times more often than in males. Both patellofemoral injuries and medial meniscal tears occurred more often in females than in males.

Other studies of high school sports injuries include one by Garrick and Requa.7 In 870 participant seasons pairing 9 sports, the overall injury rates for noncontact injuries were similar in males and females. Zillmer, Powell, and Albright10 noted a greater incidence of significant knee injuries in female basketball players, especially during games at the varsity level. Beachy et al12 performed an 8-year prospective longitudinal study of injuries in Hawaiian high schools. Girls lost fewer days to knee injuries (0.31) than boys (0.39), but ACL injuries were not specifically investigated. By teams, females lost more days to injury than males (0.37 to 0.31) and more days per athlete per injury (0.34 to 0.24).

Further longitudinal prospective studies are needed. A National Athletic Trainers' Association-sponsored study directed by John Powell, which researched injuries over a 3-year period, is currently being presented. Data from this injury surveillance high school study will be presented in an upcoming issue of the Journal of Athletic Training.

Olympic Level

At the 1988 US Olympic trials, 80 males and 64 females participated.20,53,54 A significant number of females sustained knee injuries requiring surgery when compared with males: 20 knee injuries requiring 25 surgeries, 8 of them ACL reconstructions, versus 6 knee injuries in the males, requiring 6 surgeries, 3 of them ACL reconstructions (Table 1).20

Military Level

When young female cadets first entered the military academies, they showed stress fracture rates that were increased over those of the male cadets.22 As the training became more equalized, these rates also equalized.21 At West Point, the incidence of complete ACL tears was not significantly different between male and female intramural and varsity athletes.21 However, despite the lack of difference and the small number of subjects studied, there was a trend toward a higher incidence of ACL injuries in gymnasts and basketball players.21 These findings are in contrast to findings at the US Naval Academy, where women midshipmen had a statistically significant increased incidence of ACL injuries, with a relative risk of 9.74 for military-related training; specifically, the obstacle course was associated with a 2.44 times greater risk of overall ACL injuries. The ACL injury rates for males and females in coeducational soccer, basketball, softball, and volleyball were not significantly different.25 Further work is being conducted with military populations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Males</th>
<th>Females</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of participants</td>
<td>80</td>
<td>64</td>
<td>144</td>
</tr>
<tr>
<td>Athletes with knee injuries</td>
<td>11†</td>
<td>34</td>
<td>45</td>
</tr>
<tr>
<td>ACL Injuries</td>
<td>3</td>
<td>13</td>
<td>16</td>
</tr>
<tr>
<td>Number of injuries required surgery</td>
<td>62‡</td>
<td>20</td>
<td>82</td>
</tr>
<tr>
<td>Number of procedures</td>
<td>6</td>
<td>25</td>
<td>31</td>
</tr>
<tr>
<td>Type of procedure</td>
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<tr>
<td>Arthroscopy</td>
<td>3</td>
<td>17</td>
<td>20</td>
</tr>
<tr>
<td>ACL reconstruction</td>
<td>3</td>
<td>8</td>
<td>11</td>
</tr>
</tbody>
</table>

* Reprinted with permission from Adis International Limited, Auckland, New Zealand. † and ‡ indicate a statistically significant difference between male and female athletes († P < .0001; ‡ P < .0007).
SEX DIFFERENCES AND CONTRIBUTING FACTORS

In order to reduce the rate of ACL injuries in the female athlete, we must focus on those factors that can be modified. These factors include playing style, preparation, and skill acquisition from a very young age. Contributing factors are intrinsic (not controllable), extrinsic (controllable), or both (partially controllable) (Table 2).

INJURY MECHANISM: NONCONTACT ACL, POSITION OF NO RETURN

By understanding the mechanisms of injury in sport, we can design intervention programs to reduce the risk of injury. Observations of ACL injury mechanisms in basketball show the athlete coming down in an uncontrolled landing, either catching the ball or trying not to go out at the baseline. A whiplike snap of the lower extremity is seen as the ACL tears. In visualizing this high-risk “position of no return,” we comprehend the importance of a “get-down,” knee-flexed, 2-footed balanced position. Figure 1 diagrammatically shows the position of no return and the safe position, from the joint positions of the back, hips, knee, and foot. In the no-return position, the hip abductors and extensors have shut down, and the pelvis and hip are uncontrolled. Muscle groups that would normally upright the individual are unable to perform this function due to their mechanical disadvantages and the lengthening of the muscle groups.

Noncontact injury patterns are similar in males and females. Figure 2 includes still photographs and line drawings of this mechanism of injury. Athletes injure their knees as they come down from a shot. Note the relatively extended knee initially; by the second frame, the ACL has failed. Hip and trunk-pelvis-hip control were previously lost, and lower extremity alignment was hip internal rotation and adduction, knee valgus, and tibial external rotation on a pronated, externally rotated foot. Figure 3 shows a left knee from the left and the back. The initially abducted hip goes into relative internal rotation and adduction on a pronated, externally rotated foot. At first, there is relatively little knee flexion; then the body weight goes forward as the body flexes over the legs, and, again, extreme valgus stress occurs after the ACL has failed. The hip and knee positions of rotation and less flexion are observed as the ACL fails. The gluteus maximus and hamstrings are unable to protect the ACL.

PREVENTION PROGRAMS

The role of neuromuscular training in reducing the risk of serious knee injuries was studied in high school volleyball and basketball players.26 A 6-week preseason training program to reduce landing forces and increase hamstring power using plyometrics was instituted.26 After 1 season of tracking 1263 athletes, untrained females demonstrated a knee injury rate 3.7 times higher than that for trained females and 4.6 times higher than that for males. Based on the results of this study, neuromuscular training appears to reduce the risk of injury in female volleyball and basketball players.

A prospective, controlled study of proprioceptive training was conducted in 40 Italian semiprofessional and amateur soccer teams, which included 600 male players.28 Over 3
seasons, arthroscopically verified ACL injuries occurred in only 10 of the trained athletes and in 70 of the untrained athletes. In terms of injuries per team per season, the trained group’s rate was 0.15, while the untrained group’s rate was 1.15.

Injury prevention programs have been established for certain sports, such as skiing. Equipment changes have had an impact on the reduction of tibial fractures and equipment-related lower extremity injuries. Modern boots have a more proper fit with a rigid shell and fixed forward-lean angle, ski bindings have a low friction and standardized multidirectional release function, and skis have improved turning characteristics. Vermont skiing patrollers and instructors who underwent training to reduce the risk of ACL injuries showed a 62% drop in serious knee sprains when compared with a control group that received no such training.

An injury prevention program for basketball was presented in 1989. By focusing on improving technique with accelerated, rounded turns off the inside leg, flexed-knee landings, and 3-step stops with flexed knees, 2 Division I Kansas schools reduced the rate of ACL tears by 89% in 2 years. Video analysis of injury patterns in basketball has resulted in teaching programs to train athletes, coaches, and physicians.

FUNCTIONAL OUTCOMES STUDIES

A well-designed, prospective outcomes study compared ACL-injured patients with and without reconstructions. Patients who underwent ACL reconstructions had higher levels of arthrosis by radiographs and bone scans. Studies of autogenous, ipsilateral bone-patellar tendon-bone graft ACL reconstructions have shown that males and females do equally well, even though females required more physical therapy visits.

Many knee rating scales have been developed, including Noyes (Cincinnati), International Knee Society (presently being revised), Mohtadi, Irrgang et al (Pittsburgh), Shapiro et al (SF-36), Tegner and Lysholm, and Gillquist. Researchers have also compared the various knee rating systems. Presently, studies are using several scales. No one scale has been shown to be the best.

CONCLUSIONS

A primary goal in treating athletes is prevention of the injury. We cannot restore an ACL-injured knee to normal with a reconstruction. Analyzing data collected from multiple centers and large numbers of athletes over time will allow us to identify high-risk individuals early and to institute appropriate intervention programs.

REFERENCES


21. Taylor DC, Uhrochak JM, Anciero RA. Anterior cruciate injury rate difference between males and females at the United States Military Academy [abstract]. In: Final program and book of abstracts of the ACL Study Group; March 28–April 3, 1998; Beaver Creek, CO.


Assessment and Evaluation of Predisposing Factors to Anterior Cruciate Ligament Injury

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Objective: Injury to the knee, specifically the anterior cruciate ligament (ACL), constitutes one of the most serious disabling injuries in sports. Women are reportedly at an increased risk. Prevention depends on identifying possible risk factors that may contribute to an athlete’s susceptibility to injury. The major objective of this article is to lay the groundwork for standardization of a screening protocol (1) by providing rationale for the use of selected variables that might be good predictors of noncontact ACL injury and (2) by describing appropriate measurement indices to further investigate their predictive power. Standardization of a screening protocol is the first step in developing both a reliable and valid assessment tool with predictive value for injury and outcome strategies to meet the special needs of patients.

Data Sources: MEDLINE was searched from 1980 to 1998 using the terms “anterior cruciate ligament injury,” “knee joint stability,” “postural malalignments,” “structural abnormalities,” “static structural measures,” “musculoskeletal strength imbalances,” “isokinetic testing,” and “functional performance tests.”

Data Synthesis: Many different factors, both extrinsic and intrinsic, have been investigated in the search for predictors of noncontact ACL injuries. Based on a literature review, 3 factors in particular have garnered considerable attention from clinicians and researchers: static postural malalignments with special reference to excessive foot pronation, knee recurvatum, and external tibial torsion; lower extremity musculoskeletal strength; and neuromuscular control considerations. However, much of the information known about the predictive value of these variables is inconclusive and conflicting at best, prompting the need for additional investigation.

Conclusions/Recommendations: Screening evaluations are routinely employed as part of clinical work-ups when athletes are healthy and in top form. The data collected have the potential to provide clinicians with important baseline information for maximizing structural and functional outcome strategies when deficiencies in test results are observed in subgroups of athletes matched for age, sex, and training or performance expectations.

Key Words: postural malalignments, static structural measures, functional performance tests

Many theories have been proposed as to why female athletes participating in sports involving running, cutting, and jumping maneuvers incur a disproportionate number of noncontact injuries to the anterior cruciate ligament (ACL). The incidence, severity, costliness, and potential for long-term disability resulting from ACL tears make their prevention a high priority in the medical and research communities. Preventive measures begin with an investigation of possible risk factors that may contribute to an athlete’s susceptibility to injury. Many different factors, both extrinsic and intrinsic, have been investigated in the search for predictors of noncontact ACL injuries. These factors include, but are not limited to, lower extremity malalignments,1–5 ligamentous laxity,6–10 lower extremity muscular strength considerations,4,6,9,11–13 neuromuscular control or proprioception,14–23 hormonal influences,24–27 intercondylar notch width,28–32 and the biomechanics of player technique.11,32–38 Much of the information known about the predictive value of these variables is inconclusive and conflicting at best. Variables that were long assumed to have credence have turned out to have questionable predictive value upon further investigation.9 For example, ever since Nicholas10 related ligamentous-capsular-muscular looseness to an increased susceptibility to knee ligament rupture in professional football players, this factor has been targeted for its predictive value. Subsequent investigations by Godshall,5 Grana and Moretz,7 and Kalenak and Morehouse3 did not support the relationship between joint stability and injury. However, in a more recent study, Woodward-Rogers et al5 found anterior knee laxity to be highly correlated with ACL injuries. Further research from a prospective standpoint is needed to define which factors are important and have predictive value in order to develop and implement appropriate outcome interventions to minimize injury.

The purpose of this article is to present a screening methodology, with special reference to the female athlete, for investigating only those aforementioned variables that are measurable and easily obtainable by clinicians. The challenge for clinicians lies in selecting the variables to be measured, implementing appropriate measurement indexes, and assessing...
the practicality and reliability of the measurements for stan-
dardization of a screening protocol that has broad-based
medical and research applications across many investigators
and clinical sites. A literature review supports the selection of
the following variables for their predictive value: lower ex­
tremity malalignment considerations with special reference to
excessive foot pronation, knee recurvatum, and external tibial
torsion; lower extremity musculoskeletal strength considera­
tions specific to the quadriceps and hamstrings; and neuromuscular control.

LOWER EXTREMITY MALALIGNMENTS

Sahrmann defines ideal posture as the state of muscular
and skeletal balance that protects the supporting structures of
the body against injury or progressive deformity, regardless of
the attitude in which these structures are working or resting, ie,
erect, lying, running, squatting, jumping, etc. Faulty alignment
of limbs or skeletal segment deviations detract from the
efficiency of limb motion, result in higher levels of energy
consumption and mechanical stress, and contribute to potential
or actual pathology of the neuromusculoskeletal system. During periods of loading with excessive and altered force
application, the supporting structures, particularly the liga­
ments, experience microstructural damage over time in addition
to alteration of their neurosensory role, increasing the
likelihood of functional instability. In circumstances of faulty
postural alignments, it is theorized that the joints are already in
positions that have a preloading effect on the ligaments,
subjecting them to complete structural failure under internal forces well below critical stress limits.

The impetus for studies relating lower extremity malalign­
ment considerations to knee problems, especially patellofemoro­
al and ligamentous pathologies, has stemmed from known
structural differences between males and females. Females
have a wider pelvis, increased femoral anteverision, increased
physiologic laxity, increased genu valgum and genu recurvata­
um, more external tibial torsion, and more forefoot pronation.
These anatomical considerations can create faulty
alignment positions that are common to ACL injury mechanisms reported in sports characterized by running, jumping,
and pivoting maneuvers.

According to Ireland et al, a mechanism for complete structural failure of the ACL is a situation in which the body is
in a position of forward flexion, the hip in adduction, the femur
in internal rotation, the knee in 20° to 30° of flexion, the tibia
in external rotation, and the foot in pronation. Fu and Stone noted that the most frequent noncontact ACL injury mecha­
nism observed in athletes participating in soccer, football, and
skiing is with the tibia in external rotation and the knee in
valgus. Conversely, in basketball, the most common injury
mechanism, resulting primarily from jumping maneuvers, is
hyperextension of the knee with tibial internal rotation.
Mechanisms producing ACL injury are related to foot fixation,
hyperextension, and torsional stresses. Injuries occurring as a
result of these mechanisms often include a component of
deceleration/landing forces. Boden and Garrett reviewed
mechanisms of ACL injury in 40 videotapes to ascertain the
events surrounding the injuries. Sixty-two percent were non-
contact, 19% were sustained while executing a deceleration or
landing maneuver, and the average knee flexion angle at the
time of injury was 20°. Lower extremity malalignments that
allow these positions to occur can increase stress on the ACL and
have a preloading effect that, in combination with the uncontrolled movements, leads to traumatic injury.

The mechanical effectiveness of force-transferring or force-
generating levers of the lower extremity must be enhanced to
maximize knee joint stability and functioning. This begins
with a detailed examination of lower extremity alignment.
Such an examination permits recognition of anatomical or
biomechanical abnormalities that could predispose an athlete to
knee injury. To reiterate, structural variables that might have
predictive value for ACL pathology include excessive foot
pronation, knee recurvatum, and external tibial torsion, in
addition to a combination of postural faults that will be
elaborated on as the discussion progresses. Structural measures
used to quantify the degree of malalignment associated with
each of these variables will be described, their rationale for use
will be explored, and illustrations will be included where
appropriate.

Excessive Foot Pronation

A risk factor contributing to alterations in lower-extremity
kinematics that may increase an individual’s susceptibility to
musculoskeletal injury is excessive foot pronation. Investigations of movement dysfunction of the foot relative to
pronation tendencies frequently focus on the subtalar joint
(STJ) because of its significant role in force attenuation. The
STJ is a single-axis joint that acts like a mitered hinge
connecting the talus and the calcaneus. The joint also
includes the posterior surface of the navicular bone, which
articulates with the head of the talus. According to Mann, it
is the determinative joint of the foot that affects the perform­
ance of the more distal articulations and modifies the forces
imposed on the skeletal and soft tissues transmitted upward
through the ankle, knee, and hip joints, in addition to the pelvis
and spine. In normal gait kinematics, at the time of heel strike,
there is eversion through the STJ that reaches a maximum as
the foot is loaded during the contact phase of the gait (foot-flat
position) until heel rise and lift-off. Eversion through the STJ
is one of the components of foot pronation. Excessive motion
of the STJ in the direction of eversion influences more
pronatory effects of the foot. The occurrence of pronation, to a
degree, is important during the support phase of the gait since
it provides proper shock absorption to the stresses of standing,
walking, jogging, and sprinting. Pronation is referred to as
the decelerating phase of movement and is accompanied by
tibial internal rotation. An important observation is
whether the foot remains pronated during the period of heel
rise and lift-off. If excessive or prolonged pronation of the foot occurs beyond the first half of the stance phase, the tibia undergoes additional internal rotation, resulting in abnormal forces transmitted upward through the kinetic chain. The ACL tightens with tibial internal rotation. Therefore, excessive foot pronation may produce a preloading effect on the ACL. An association has been shown between excessive pronation tendencies and ACL injuries.

A composite measure of excessive pronation routinely employed by researchers is the navicular drop test. This test describes the distance between the original height of the navicular taken in a seated, STJ-neutral position to the final weightbearing, compensated position of the navicular in relaxed stance. Establishing STJ-neutral position (Figure 1), defined as the position of maximum congruency between the talus and the calcaneus, is a prerequisite to measuring navicular drop (Figure 2).

Woodford-Rogers et al measured navicular drop in an ACL-injured group consisting of 14 football players and 8 gymnasts and an age-, sex-, and sport-matched control group. The investigators found that the ACL-injured group had greater amounts of navicular drop, suggesting increased pronation. Beckett et al found that subjects with ACL injuries had greater amounts of pronation as measured by navicular drop than noninjured subjects and concluded that hyperpronation of the foot and ankle may increase the risk of injury to the ACL. They reported a mean navicular drop of 6.9 mm in 50 healthy subjects as compared with a mean of about 13 mm in patients with ACL injuries. Similarly, Loudon et al studied the relationship between static posture and ACL injury in female athletes. Of the variables assessed, excessive pronation as measured by the navicular drop test was a significant discriminator between the ACL-injured and noninjured groups.

Navicular drop is not the only measurement for assessing excessive pronation tendencies. Measurement of rearfoot valgus or rearfoot-to-leg orientation (Figure 3) is considered an acceptable indicator of pronation. Also, since STJ movements are associated with dorsiflexion, which occurs primarily at the ankle joint, assessment for restricted dorsiflexion of the ankle with the knee flexed and extended should be included as part of the screening protocol. Foot and ankle rigidity combined with STJ compensations contribute to early knee deformation.

**Genu Recurvatum**

Another risk factor involving lower extremity alignment considerations that may increase an athlete’s susceptibility to ligamentous injury is genu recurvatum, or knee hyperextension. It is usually an acquired structural abnormality secondary to changes in distal skeletal joint alignments and compensatory movement patterns and is characterized by soft tissue laxities of the posterior, posteromedial, and posterolateral joint structures. Genu recurvatum results from an occasional hyperextension moment during ambulation that stresses the soft tissue ligamentous structures with repetitive and chronic loads. Each degree of deformation over time can produce tensile strain on the ACL and result in ACL impingement in the intercondylar notch.

Loudon et al demonstrated that genu recurvatum in combination with excessive foot pronation can result in greater strain on the ACL. They found an increased susceptibility for
Figure 2. Navicular drop test. (1) Place the subject in a sitting position with the feet flat on a firm surface and the knees flexed to 90°. (2) Establish subtalar neutral position. (3) Identify and mark the most prominent point of the navicular tubercle while maintaining subtalar neutral position (A). (4) With an index card placed on the inner aspect of the hindfoot, mark the level of the navicular on the card. (5) Instruct the athlete to stand without changing the position of the feet. Equal weight should be distributed on both feet. (6) Mark the resulting lower position of the navicular on the card (B). (7) Calculate the distance in millimeters between the original height of the navicular (with the STJ in neutral) and its final weightbearing position.

ACL injury in female athletes displaying a combination of these variables as compared with those subjects displaying only pronation or no postural faults.

Measures of genu recurvatum (Figure 4), in addition to hyperextension of the fingers and elbows and abduction of the thumb to reach the forearm (Figure 5), generally indicate joint angles of the right foot by placing the stationary arm along the tibia and the movable arm along the calcaneus (B). (6) Record the results and replicate the procedure for the opposite extremity.
Figure 4. Knee recurvatum. (1) Position the athlete supine with the knee maximally extended and the foot in a neutral position. (2) Grasp the forefoot with one hand and stabilize the distal segment of the femur with the other hand. Lift the forefoot upward to achieve passive hyperextension at the knee joint. Care should be taken to maintain the posterior aspects of the knee and thigh on the table. (3) Measure the distance (with the help of an assistant) from the posterior border of the heel to the table in centimeters. (4) Use a goniometer to quantify the angular degree of hyperextension. Align the goniometer laterally along the long axis of the fibula and laterally along the longitudinal axis of the femur from the greater trochanter to lateral femoral condyle. (5) Record the 2 measurements and replicate the procedure for the opposite extremity.

Figure 5. Thumb to reach forearm. Document (yes or no) whether the athlete can passively appose the thumb to the flexor surface of the forearm. Test both extremities.

The relationship between physiologic joint laxity and ligamentous injury requires further investigation.

Rotational Alignment: External Tibial Torsion

Rotational alignment considerations or differences in tibial torsion warrant discussion as a risk factor for injury.19,44,59,60 Torsional deformities are assessed using the thigh-foot angle measurement popularized by Staheli.59 The thigh-foot angle is defined as the angular difference between the axis of the thigh and the foot as viewed directly down with the knee flexed to 90° (Figure 6). The mean value for thigh-foot angle is approximately 10° of external rotation during most of childhood.59,60 With increasing age, the angle becomes more externally rotated. Huegel et al2 investigated the influence of lower extremity rotational alignment in the female population on the incidence of noncontact ACL. Data suggested that differences in thigh-foot angle, used as an assessment of external tibial torsion, may play a predisposing role. The authors concluded that a tendency toward foot plant in a position of increased external rotation may result in increased tightening of the ligament, which can increase susceptibility to injury.

Other Malalignment Considerations

It is important to remember that 2 or more postural faults may compensate for each other, as in the case of external tibial torsion and femoral anteversion.60 Similarly, an increased Q-angle can result from increased femoral anteversion, exces-
sive external tibial torsion, or excessive pronation. Therefore, the selection of skeletal measurement indexes must take into account these compensation tendencies and must be included in the screening protocol. Femoral anteversion is characterized by excessive internal rotation of the femoral shaft in stance. It is defined as the projection of the angle between the long axis of the femoral neck and the axis through the femoral condyles in the transverse plane. This angle measures approximately $15^\circ$ in the mature adult. Variations in the angle of torsion will cause compensatory changes in lower extremity rotation to maintain the femoral head within the acetabular cavity. These changes can predispose an individual to musculoskeletal conditions. Q-angle is defined as the angle formed between the line of resultant force produced by the quadriceps muscles and the line of the infrapatellar tendon. The physiologic valgus of the knee gives an angle, Q, between the pull of the muscle and that of the tendon. The normal Q-angle ranges from approximately $10^\circ$ to $15^\circ$ with the knee in full extension. The importance of an increased Q-angle and its contribution to patellofemoral disorders (for which the primary biomechanical cause is malalignment of the knee extensor mechanism) is well documented. However, its role in ACL injuries is less clear and requires further study. See Figure 7, A, B, and C, for a descriptive method for measuring femoral anteverision, and see Figure 8 for measuring Q-angle.

MUSCULOSKELETAL STRENGTH

Stabilization of the knee results from a complex interrelationship that exists among bony geometry, capsuloligamentous structures, and muscles. Dynamic stabilization is supplied primarily by the neuromusculoskeletal action of the quadriceps and the hamstrings. The hamstrings are in a position to act as antagonists to the ACL by providing both rotatory stability and resistance to anterior drawer. If the stabilizing influence of appropriate muscle action is compromised, the potential for injury to the capsuloligamentous structures is heightened.

Strength imbalances have been suggested as possible predisposing factors to injury. Knapik et al found that female athletes with one hamstring more than 15% weaker than the other were 2.6 times more likely to sustain a lower extremity injury and reported that such left-right imbalances occurred in 20% to 30% of female athletes. Additionally, athletes with a flexion/extension ratio (H/Q ratio) of less than 0.75 were 1.6 times more likely to be injured. Moore and Wade found that H/Q strength ratios of females were significantly lower than those of males at $60^\circ$, $180^\circ$, and $300^\circ$ per second. Wojtys et al reported that females had H/Q ratios in the 40% range.

Moul investigated differences in selected predictors of ACL tears between male and female NCAA Division I collegiate basketball players from the same institution participating in identical conditioning programs. Sex differences in quadriceps and hamstring strength were examined isokinetically. Significant differences were noted between healthy male and female athletes for the eccentric hamstrings-to-eccentric quadriceps ratio bilaterally. The author postulated that a deficit in eccentric hamstring strength relative to eccentric quadriceps strength could predispose an athlete to an ACL injury during stressful athletic activities, particularly deceleration or landing maneuvers. During these activities, flexion moments are occurring at the knee and hip. Palmitier et al reported that eccentric contraction of the hamstrings promotes hip stabilization, while eccentric contraction of the quadriceps promotes knee stabilization. In closed chain conditions, the hamstrings act as a powerful hip extensor. Forceful hamstring contraction is induced to stabilize the hip flexor moment, which helps to neutralize the tendency of the quadriceps to cause anterior translation of the tibia on the femur.

The importance of hamstring strength in ACL-deficient (ACLD) patients during stressful athletic activities further underscores the role of the hamstrings in enhancing stability of the knee. It has been reported that hamstring substitution occurs among ACLD patients when the knee is flexed. The flexed position, which is characteristic of landing and deceleration maneuvers, occurs as well in other activities, such as twisting, pivoting, and stopping from a run. Branch et al demonstrated increased activity in ACL synergist muscles and decreased activity in ACL antagonist muscles in 10 ACLD subjects and 5 normal control subjects during sidestep cutting maneuvers. ACLD patients who perform sports activities under stressful conditions can protect against the rotational and translational stresses at the knee joint by increasing hamstring contraction as the limb is striking the ground. However, the muscle contraction must occur before the destabilizing loads occur. Wojtys and Huston found that the maximal response time of the uninjured extremity of ACL-injured athletes was longer than in noninjured controls. Furthermore, in the noninjured leg of ACLD athletes, the quadriceps was the first muscle group to fire in response to anterior tibial translation. Neuro-muscular firing order and timing may be just as important to the stability of the knee as strength considerations are.

Standard clinical examination of thigh muscle strength and reciprocal muscle group strength ratios can be accomplished though isokinetic testing. Isokinetic data acquisition provides reliable, objective information on a variety of muscle performance parameters. However, to assess the preparedness of athletes for sport participation or sport reentry necessitates ambulatory testing methodology that can provide unique information not obtainable with standard clinical examination. Functional performance testing offers the opportunity for objective and quantitative assessment of athletes under conditions that replicate sport-specific activities. Still, it is important to select variables that focus on the measures directly related to the physical aspects of the problem: in this case, challenging knee joint stability.

NEUROMUSCULAR CONTROL

Clinical research assessing muscle activation patterns of the knee for dynamic stability as well as training programs to
Figure 7. Femoral anteversion. (1) Position the subject prone with the knees over the table edge. (2) Flex the knee to 90° and maintain this position by holding the ankle with 1 hand. With the other hand, palpate the greater trochanter. (3) Rotate the femur laterally by moving the leg held at the ankle inward (A) and rotate the femur medially by moving the leg outward (B) until the greater trochanter is at its most lateral position and thus parallel to the examining table. (4) Measure this angle with a goniometer (with the help of an assistant) using the femur's center of rotation as the axis, the perpendicular line to the table as the stationary reference, and the spine of the tibia as the motion arm reference (C). (5) Record the results and replicate the procedure for the contralateral extremity.

Figure 8. Q-angle. (1) Place the subject in a standing position with the feet straight ahead and hipwidth apart. (2) Bisect the patella in the sagittal and transverse planes, creating a center point of axis of rotation on the patella. (3) Mark the apex of the anterior superior iliac spine and the tibial tubercle. Place the stationary arm of a long-arm goniometer in line with the anterior superior iliac spine and the rotating arm in line with the tibial tubercle. Maintain the goniometric axis of rotation on the center point of the patella. (4) Record the angular measurement and duplicate the procedure for the opposite extremity.

restore neuromuscular status after injury, frequently employs cutting, pivoting, landing, hopping, and balancing maneuvers. For example, Lephart et al described 3 objective functional performance tests for athletes presenting with ACL insufficiency. The tests (including the cocontraction semicircular test, carioca test, and shuttle run) were developed with 2 goals in mind: (1) to obtain an objective measurement of function by reproducing the activities required to perform common sport skills, and (2) to challenge dynamic knee stability by producing rotational forces at the knee, causing tibial subluxation and mimicking acceleration and deceleration forces due to sudden directional and velocity changes. Other tests of function that
are routinely employed to challenge the knee similarly include balance activities, \textsuperscript{37,72} one-leg vertical jump, \textsuperscript{37,73,74} single-leg hop for distance, \textsuperscript{73,75} timed hop, \textsuperscript{73,75} triple hop for distance, \textsuperscript{75} running in a figure eight, \textsuperscript{76,77} running up and down a staircase, \textsuperscript{76} and sidestepping maneuvers. \textsuperscript{72}

There are limitations to performance tests, and consideration needs to be given to maximizing their results, eg, when using one-leg hop tests to determine abnormal lower extremity symmetry. Barber et al \textsuperscript{73} reported that more than half of the ACLD patients assessed for sport reentry activities had normal scores on the one-leg hop test but reported limitations with activities. However, when 2 one-leg hop tests were combined and compared with a single test, scores were abnormal. In a similar study involving ACLD patients, Noyes et al \textsuperscript{75} reported higher percentages of abnormal scores when at least 2 one-leg hop tests were used, as compared with one (60\% versus 42\% to 50\%).

Data from isokinetic testing and ambulatory testing should be evaluated collectively to provide a comprehensive picture of the functional status of the athlete. The relationship between isokinetic data and functional performance tests is not yet clear. Several researchers report no association, \textsuperscript{79,80} while others report correlations between the 2 parameters depending on the variables measured. \textsuperscript{73,75,77,78}

**LIMITATIONS OF A MULTI-INSTITUTION APPROACH**

Reliability of data is known to be influenced by examiners and patient populations. Therefore, maximizing measurement reliability is an important consideration, since the proposed model involves several investigators at different clinical sites. One method to minimize measurement error under these circumstances is to standardize test procedures. \textsuperscript{81} This requires careful planning relative to the method of protocol administration, the description of the measurement procedures, the time required to administer the tests, the equipment required, multiple practice or test trials with calculation of a mean, rest intervals, and the nature of the scoring system. \textsuperscript{82} Clinicians must prudently attend to these test parameters in order to create valid comparisons of the data collected. Once the data are accumulated, analyzed, and consolidated into a composite picture, clinicians can develop a better understanding as to which measurements should be excluded from the screening protocol because they are difficult to take and offer examiners little confidence in the results. Monitoring the performance of the model and retooling it with data over time are essential to establishing predictive validity.

**SUMMARY**

A description of variables that might have predictive value for noncontact ACL pathology has been presented in an attempt to standardize a prospective screening protocol for the collection and interpretation of a comprehensive set of measurements. The variables, thought to be measurable and easily obtainable by clinicians and researchers, focus on static postural malalignments, along with lower extremity muscular strength and neuromuscular control considerations. Examining the relationship of these variables to lower extremity kinetic chain forces has the potential to aid clinicians in predicting ligamentous challenges, specifically abnormal stress to the ACL, that may occur with altered loading patterns.

A standardized, prospective screening protocol consisting of these variables is currently in use across the country as part of a multi-institution effort to determine whether common variables exist among female athletes who sustain noncontact ACL injuries. Such a protocol, advantageous from a research perspective, also has short-term clinical relevance. Screening evaluations are routinely employed as part of clinical work-ups to establish musculoskeletal profiles when athletes are healthy and in top form. This approach gives clinicians an opportunity to maximize both structural and functional outcomes strategies when deficiencies in test results are observed in subgroups of athletes matched for age, sex, and training and performance expectations.

The variables included in the screening protocol and their various interactions have the potential to provide a range of possible intervention strategies to decrease injury incidence. These strategies can range from maximizing structural outcomes through orthotic and footwear interventions \textsuperscript{40,42,48} to maximizing functional outcomes through postural \textsuperscript{13,42,43,47,48} and training interventions. \textsuperscript{20,32-37} It would be premature to address which of the protocol’s variables are amenable to intervention strategies. The first step is to develop and implement a reliable and valid assessment tool for scrutinizing the predictive value of the selected variables. Those variables identified as reliable predictors of ACL injury can then be interpreted by clinicians for their degree of amenability to intervention strategies.

The measures described in this paper represent only part of the knee-screening protocol characterizing the multi-institution effort. A protocol of this nature would be incomplete without a questionnaire that solicits important information about the athlete’s prior injury history, present knee status, conditioning and training experiences, and equipment considerations. Additionally, an assessment tool, designed primarily for physicians, that includes manual tests of knee pathology is required to document ligamentous integrity and other pertinent anatomical considerations.

Readers interested in securing the screening protocol in its entirety, for the 2-fold purpose of (1) establishing outcomes interventions for their athletes and (2) contributing to a comprehensive database representing a systematic collection of measurements from numerous investigators that, upon ongoing interpretation, has the potential for predictive value for noncontact ACL tears, are invited to contact me.
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REFERENCES


47. Sahrman SA. Diagnosis and treatment of muscle imbalances associated with musculoskeletal pain. Continuing education seminar sponsored by Frankfort Hospital; September 1987; Philadelphia, PA.


Using Surface Electromyography To Assess Sex Differences in Neuromuscular Response Characteristics

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Objective: To provide an overview of the continuum of muscular responses that typically occur with joint perturbation. The applications and limitations of surface electromyography (sEMG) in evaluating these responses are also addressed. Research applications assessing sex differences in these neuromuscular response characteristics are discussed along with suggestions for future research.


Data Synthesis: It is widely accepted that efficient neuromuscular control is essential to dynamic joint stability and protection. Many studies have established the significant role of the muscles, and particularly the hamstrings, in providing knee stability. By observing the timing, phasing, and recruitment of reflexive muscular activation after a loading stress to the knee, we can better understand the coordinative mechanisms necessary to protect the joint and prevent ligament injury. A number of research models have employed the use of sEMG to evaluate neuromuscular responses at the knee after joint loading or perturbation. However, very few studies have specifically addressed potential sex differences in these response characteristics.

Conclusions/Recommendations: From the limited research available, it appears that a sex difference may exist in some aspects of neuromuscular responses. However, further research is needed to explore these differences at the knee and their potential role as predisposing factors to the higher incidence of anterior cruciate ligament injuries in females. Future studies should examine sex differences in neuromuscular response characteristics at the knee under functional, weight-bearing conditions while controlling for training and other confounding variables. The limitations of sEMG should be considered when interpreting neuromuscular response studies.

Key Words: dynamic stability, electromechanical delay, reflex, reaction time, anterior cruciate ligament

The increased incidence of anterior cruciate ligament (ACL) injury in females is a growing concern within the sports medicine community.1-10 At the present time, there are no clear explanations for the disparity in injury rates between males and females, although considerable research has attempted to identify potential predisposing factors.1,6,11-26 With the sharp increase in both the participation and competitive level of females in sports in recent years, it has been suggested that females have not received adequate training or skill preparation to compete at the level in which they are engaged.1,3,14 Therefore, the ability of the neuromuscular system to adequately respond to the substantial joint forces incurred at the knee during sport activity and to provide sufficient joint protection has been suspect. Whether a difference in muscular activation, timing, or recruitment patterns, or a combination of these, exists between males and females may be a significant finding in our attempt to explain the higher incidence of ACL injury in the female athlete. While it appears from the limited research available that certain sex differences may exist in muscular response characteristics,14,27,28 more research is needed to establish this relationship as a potential predisposing injury factor. It is widely accepted that efficient neuromuscular control is essential to dynamic joint stability and protection. The ACL provides as much as 86% of the static resistance to pure anterior tibial translation.29 However, forces (both internal and external disturbances) incurred at the joint during sport activity are often beyond the capacity of the passive ligamentous constraints, thus requiring the addition of active muscular forces to maintain joint equilibrium and stability.23,30,31 Many studies have established the significant role of muscular activation about the knee, particularly that of the hamstrings, in improving knee stability.30-37 Research indicates that timely activation of the hamstring muscles can assist in protecting the ACL from mechanical strain by stabilizing the tibia, thus reducing anterior and rotary tibial translation.30,32-34,36,38,39 Therefore, the speed at which muscular activation and subsequent force development can be generated may be an important

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determinant in providing dynamic joint stability and ligament protection.

It is important to note that no study to date has specifically demonstrated whether, in fact, reflexive muscular activation and joint stiffening can occur quickly enough to protect the joint once an injurious force is applied to the ligament. In fact, research indicates evidence to the contrary. However, researchers have yet to adequately address the contribution of intrinsic muscle stiffness or preparatory alterations in muscular tension at lower applied loads that may prevent excessive joint excursion or provide some measure of immediate joint stiffening until a reflexive response can be generated. Clearly, more research is needed to fully elucidate the capacity of neuromuscular response mechanisms to protect the ACL during joint perturbations.

The evaluation of neuromuscular response characteristics around a particular joint can assist the clinician or researcher in understanding muscular activation and recruitment patterns both during and after a loading stress to the joint. By observing these response characteristics, we can better understand the coordinative mechanisms necessary to protect the joint and prevent injury under sudden loading conditions. Surface electromyography (sEMG) is a valuable tool that may be well suited to provide this assessment if its limitations are realized. Therefore, our purpose is to discuss the research applications, as well as the limitations, of sEMG in the assessment of neuromuscular response characteristics. Our objective is to provide an overview of the continuum of muscular responses that typically occur with joint perturbation and how sEMG can be used to evaluate these responses. Research applications assessing sex differences in neuromuscular response characteristics with sEMG will also be addressed, along with directions for future research.

**ASSESSMENT OF NEUROMUSCULAR RESPONSES USING EMG**

sEMG has been used extensively in biomechanical applications to describe and quantify a muscle or muscle group's activity or performance about the knee. sEMG can assist the clinician or researcher in determining when a muscle is activated, the timing of that activation in relation to a stimulus or event, and its sequential firing with other muscles. sEMG has also been used extensively in an attempt to quantify or characterize the force output of the muscle, as well as to determine the relative contributions of muscle or muscle groups for a given activity. Muscle fatigue can also be assessed by evaluating the frequency parameters of the myoelectric signal obtained. Our discussion will focus primarily on the evaluation of temporal responses, including the timing and sequential activation of muscles.

In order to fully appreciate the information that can be obtained from evaluating neuromuscular response characteristics with sEMG, an understanding of the various neuromuscular responses that occur and how EMG detects and visualizes these responses is useful.

**Neuromuscular Response Mechanisms**

The motor unit represents the smallest functional unit of the neuromuscular system and consists of a single motor neuron and all the muscle fibers it innervates. Each muscle fiber comprises a collection of myofibrils that run the length of the muscle fiber and are formed by a series of sarcomeres arranged end to end. The sarcomere represents the smallest contractile unit of the muscle and contains the contractile myofilaments, actin and myosin.

In order for the muscle tissue to function, it requires communication with the central nervous system (CNS) (ie, spinal cord and higher cortical centers) via peripheral nerves. A single peripheral nerve consists of both somatic and autonomic fibers that work in tandem to make appropriate adjustments with the body in response to environmental change. While autonomic nerves control smooth and heart muscle and exocrine glands, somatic nerves provide motor input from the CNS to skeletal muscle and sensory feedback from muscle and joint structures back to the CNS.

Alpha motor (efferent) neurons consist of a cell body located in the anterior horn of the spinal cord, a relatively large-diameter axon, and terminal branches that innervate a group of muscles fibers. Upon stimulation of the motor neuron, all the muscle fibers within a particular motor unit fire nearly simultaneously. Depending on the strength of contraction required, smaller motor units are recruited first, followed by the larger motor units to allow for a gradual increase in force.

Sensory (afferent) neurons, on the other hand, transmit information away from muscle, ligament, tendon, and capsular structures to the CNS for the neuromuscular response. This information is provided by specialized receptors, or mechanoreceptors, that function as transducers, converting mechanical energy in the form of physical deformation into electrical energy or action potentials. Collectively, these receptors provide the CNS with information regarding the position, displacement, velocity, and acceleration of the joint. Mechanoreceptors can either be rapidly adapting, to primarily sense rapid changes in deformation, position, or acceleration, or slowly adapting, to sense both static position and position changes of a particular joint structure. These receptors are further classified as low or high threshold, indicating the mechanical sensitivity of these receptors to a stimulus.

Specific mechanoreceptors have been identified based on their morphology and function. Mechanoreceptors found in muscle and tendon include the muscle spindle, sensing changes in length, and the Golgi tendon organ, sensing changes in tension. Mechanoreceptors found within joint structures have been classified by Freeman and Wyke as types I through IV. Type I mechanoreceptors are thought to resemble Ruffini-type endings and are characterized as low-threshold, slow-adapting receptors. Type II receptors are analogous to the Pacinian corpuscle with low-threshold, rapidly adapting characteristics. Golgi tendon-like organs are representative of type III receptors, which are high threshold receptors with sEMG.
old and very slow adapting. Given their high threshold, these receptors, found exclusively in ligament structures, are thought to provide feedback at the end range of motion once sufficient tension is produced. Type IV receptors, also known as free nerve endings, have been identified in all joint structures except menisci and primarily provide feedback on pain stimuli. In recent years, each of these receptors has been found in the human ACL.

Once a mechanoreceptor exceeds its threshold and is activated, the action potential is rapidly conducted along the large-diameter myelinated afferent neuron to ultimately stimulate the appropriate reflexive muscular response. Generally, reflexive responses have been categorized as either monosynaptic (spinal) or long loop (intermediate) and always occur before any voluntary activity. Given the substantially shorter latencies of these reflexive responses, their importance in providing rapid response to perturbation is evident.

**Monosynaptic reflex.** The simplest reflex arc is a monosynaptic reflex, which comprises one afferent, stimulated by its sensory receptor, directly synapsing with an alpha motor neuron to cause muscular excitation or inhibition. This type of reflex, also termed the M1 response, spinal reflex, or short-loop reflex, originates at the spinal cord level and is generated by a local stimulus that results in a gross, quick movement requiring no cortical input. For example, an elongation of this reflex is the tendon tap. While the length of this reflex is also the fastest, monosynaptic reflexes have been reported to occur within 20 to 60 milliseconds after initiation of a stimulus.

**Long latency reflex.** The long latency reflex, or late reflex response, represents a delay that exceeds monosynaptic latencies but precedes the earliest voluntary response times. Other terms that have been used for this delayed reflex include intermediate response or reflex, polysynaptic reflex, or long loop. While researchers have attempted to explain the origin and function of these reflexes, total agreement is lacking. However, most feel that long latency reflexes represent a spinal reflex consisting of one or more interneuron synapses between the sensory and motor neuron that receive convergent input from higher brain centers and other afferents capable of modifying the reflex response. While the length reported for the monosynaptic response latency is fairly consistent at about 20 to 30 milliseconds, the latency reported for the long-loop response appears to be quite varied. Some authors report typical latency times for this response in the 50- to 60-millisecond range, while other authors indicate much longer latency times, on the order of 100 to 150 milliseconds.

**Voluntary muscular control.** All reflexive activity, whether monosynaptic or intermediate, precedes the earliest voluntary response and therefore provides a more rapid response to perturbation or an injurious situation. Because of the considerable cortical input required for voluntary motor control, these responses occur at a significantly greater delay. Response times for voluntary movement have been reported to have a minimum delay of 170 milliseconds, while Chan et al. reported shorter voluntary responses of 117.7 milliseconds in the quadriceps and 157.1 milliseconds in the gastrocnemius following light tendon taps. Substantially longer delays (as much as 400 milliseconds) have been reported in the literature as well.

**Response variations.** While most experts agree that voluntary responses are too slow to protect the joint from sudden perturbations, reflexive muscular activation may be sufficient to elicit a timely corrective or protective stiffening response in order to prevent further joint deformation. However, these responses are known to vary considerably depending on the activity state of the muscle, movement velocity, joint angle, weightbearing status and trunk position, and prior training. Responses can also be inhibitory. An “silent period,” representing a reflexive pause in firing of a contracting muscle, can occur in response to a stimulus such as a shock to skin or peripheral nerve, a tendon tap, a sudden decrease in load against which a muscle is contracting, or a sudden increase in load in an antagonist. This “silent period” was demonstrated by Marsden during random trials of sudden unloading of the thumb while moving against a constant force.

In summary, both monosynaptic and long-latency muscular reflexes, whether excitatory or inhibitory, appear to be important in providing a rapid and appropriate response to an imposed perturbation. However, if this feedback is provided by high-threshold Golgi tendon receptors in the ACL, it is likely the initiated muscular responses would not occur quickly enough, given that the delays in force generation would be greater than the time required to reach ligament failure. However, it remains plausible that intrinsic responses and sensory feedback provided by other joint structures at lower threshold may occur before ligament loading and prevent joint deformation from reaching the point of ligament failure. For instance, if the muscle senses tension before the ligament does, there may be time to stiffen the joint through both intrinsic mechanical as well as the stretch reflex mechanisms. Furthermore, Johansson and colleagues present evidence that low-threshold receptors in the cruciate ligaments may influence the sensitivity of the muscle spindle and provide preparatory stiffening of the muscle before excessive loading. Clearly, more research is needed to determine the efficacy of these proprioceptive feedback mechanisms in stabilizing the joint under sudden loading conditions. In addition, determining whether males and females differ in neuromuscular activation or mechanics in response to proprioceptive feedback may provide a potential explanation for the disparity in ACL injury rates. To that end, sEMG is one tool that has been and can be used to study neuromuscular response mechanisms and potential sex differences in muscular activation and recruitment.
Physiologic Basis and Characteristics of the Recorded EMG Signal

In order to quantify and characterize reflexive muscular responses, electromyography is used to record and analyze the electrical activity of the muscle. Electromyography is concerned with the development, recording, and analysis of myoelectrical signals derived from motor unit activity. As the nerve action potential arrives at the motor endplate, it is propagated out and away in both directions along each muscle fiber within the motor unit. In order to observe a single muscle fiber action potential, an indwelling microelectrode must be inserted within the muscle fiber. sEMG, on the other hand, uses electrodes applied to the surface of the skin and represents the extracellular recording of the muscle fiber action potentials at the skin surface.

In order to fully appreciate what is contained in the sEMG signal, it is important to know what these potentials look like graphically (Figure 1). With sEMG, 2 electrodes are typically used, and the electrical (voltage) difference or fluctuation between the 2 electrodes is recorded on the oscilloscope. In the absence of a motor unit action potential, the voltage difference between the 2 electrodes is zero and the signal is at baseline on the oscilloscope. However, when the motor unit is activated and an action potential is propagated along the muscle membrane, an electrical change is recorded by the overlying electrodes that coincides with the depolarization and subsequent repolarization of the muscle membrane. Since the potential is recorded extracellularly, the surface of the muscle membrane, which is normally electropositive, becomes electronegative as depolarization occurs (Figure 2). As this electronegativity reaches the first (proximal) electrode, it becomes negative with respect to the second (distal) electrode, and a positive deflection is recorded on the oscilloscope. As the action potential continues down the membrane across the second electrode and repolarization occurs at the first electrode, a negative deflection will be seen on the oscilloscope. Therefore, as an action potential passes by the 2 recording electrodes, a biphasic waveform results from the changing polarity (Figure 3).

Due to the increased distance of the electrodes from the muscle fiber and the larger recording area inherent in sEMG, the signal that is picked up consists of activity from multiple muscle fibers arising from one or more motor units. Therefore, as Figure 1 demonstrates, rather than a clean biphasic waveform, the myoelectric signal derived from sEMG provides a more general representation of muscular activity, recording one or more motor unit action potentials arising from all discharging units within the vicinity of the electrodes.

Limitations of sEMG

Although a useful tool, electromyography is not without limitations, and, therefore, the methods and interpretations reported in the literature should be critically evaluated. A number of factors can seriously affect reliability issues by greatly influencing the quality and content of the myoelectric signal. DeLuca and others have identified several factors, both intrinsic and extrinsic, that can greatly influence the signal that is detected and recorded by the differential electrodes.

Intrinsic factors refer to the physiologic, anatomical, and biochemical characteristics of the muscle, which are typically...
outside the control of the researcher. These factors include 1) the number of active motor units at any one time that can affect signal amplitude and duration; 2) the fiber-type composition of the muscle, which can influence firing rate; 3) fiber diameter, which can influence amplitude and conduction velocity; 4) depth and location of the active fibers relative to the electrodes, which will determine the extent of spatial filtering, amplitude, and the frequency of the signal; 5) the amount of tissue (skin and adipose) between the electrodes and the muscle affecting spatial filtering; and 6) the variations in impedance and electrical properties within and between muscle tissue, fatty tissue, and skin that can affect the propagation of the current.56,57,89,90

Extrinsic factors are more within the control of the investigator and refer to the actual electrode configuration, which can largely determine the quality and quantity of the detected signal.56,58 The area and shape of the electrodes used will determine how large an area of the muscle is being recorded.56,88 Area is affected by both the size of the electrode used57,85 and the interelectrode distance that is chosen.56,57,86,88 The position of the electrodes over the muscle is also an important factor. Surface electrodes are limited to the detection of motor unit action potentials that arise from fibers in close proximity to the electrode site and will record muscle fiber activity only within 1 to 2 cm of their locations.58,86 Furthermore, the longitudinal and horizontal placement of the electrode in relation to the muscle can have considerable impact on the acquired signal.56,57 It becomes apparent that even slight changes in electrode configuration or orientation can significantly alter the signal obtained both within and across subjects. Unfortunately, no standards exist as to the proper configuration or dimensions of surface electrodes for a given purpose.56 Therefore, to insure reliability of data and comparisons across trials and subjects, the application method and size, type, spacing, and location of electrode placement must be standardized, adequately reported, and controlled.85,88,91

Signal artifact can also greatly affect the fidelity of the signal and, thus, signal reliability and interpretation. Artifact is defined as the components of the EMG signal that are not produced by the electrical activity of the intended muscle and are instead produced by crosstalk (activity of nearby muscles not under study),56,57,85,88,92,93 electrical interference from nearby electrical devices,57,59,85,88,92 or movement artifact.57,85,88,92 Signal artifact can be detected anywhere within the EMG instrumentation and at any point during the recording process.89 However, the influence of artifact can be greatly minimized with proper electrode configurations, adequate skin preparation, high-quality instrumentation, stabilization of electrodes and lead wires, and an electromagnetically shielded or quiet-environment recording.57,85,88,92

Clearly, there are a number of anatomical, physiologic, and technical factors that must be considered and controlled when conducting EMG research, since they can greatly influence the EMG signal.56,85 Additionally, how the signal is processed and analyzed can result in serious measurement error. Therefore, appropriate documentation and reporting of the instrument parameters, detection methods, and processing techniques are essential if one is to truly understand and accurately interpret or replicate research findings. To that end, the Ad Hoc Committee of the International Society of Electrophysiological Kinesiology was developed in 1980 to address recommendations for the standardization of EMG instrumentation, documentation, and data reporting.91 These recommendations are outlined in each issue of the Journal of Electromyography and Kinesiology and can be accessed from the Journal of Athletic Training web page at http://www.nata.org/jat.

**Temporal Measurement of Reflexive Activation**

The most basic information that can be derived from the EMG signal is whether or not a muscle is active or at rest.93 The timing and phasing of this muscular activity has been used to determine muscular response characteristics such as reaction time,4,23,24,55,65,71 electromechanical delay (EMD),27,28 and firing patterns* in response to a stimulus.

**Muscle reaction time.** Muscle reaction time is a valuable tool in determining how well the joint detects a disturbance and how quickly the muscles respond to a stimulus or perturbation. Muscle reaction time or latency refers to the time it takes from the onset of the stimulus for the action potential to reach the intended target muscle, as indicated by electrical activity recorded in the EMG signal.59 For time-response studies, a contact switch or similar mechanical device can be interfaced with the EMG to accurately mark when the stimulus occurs and thus provide reliable measures.

**Electromechanical delay.** Electromyography has also been used extensively to quantitatively measure the time lapse between the change in electrical activity and the actual force generation in the muscle.27,28,71,93 It is important to realize that the EMG signal reflects only the electrical activity of the muscle, which is not synonymous with the production of tension. In fact, a natural EMD exists between neural activation of the muscle as recorded electrically by EMG and the actual generation of force.56,93 EMD can be measured using a force transducer (or similar device) interfaced with the EMG to detect and quantify when muscular tension is developed after neural activation (Figure 4). This delay can be quite variable due to factors such as fiber-type composition and firing rate dynamics of the muscle, velocity of movement, viscoelastic properties and length of the muscle and tendon tissues, activity state, and coactivity of other muscles.56,89,93 EMDs reportedly vary anywhere from 30 to 50 milliseconds93 to as much as a few hundred milliseconds.56 Considering this additional time lapse and the need to develop sufficient muscular tension rapidly enough to provide dynamic joint stability, EMD should be considered when evaluating muscular responses to an imposed perturbation or injurious stress.

References 23, 30, 39, 49, 52, 53, 55, 94, 95.
Recruitment and coactivity patterns. When muscle reaction time and EMD measures are collected on more than one muscle or muscle group, activation patterns such as recruitment order and coactivity around a joint can also be evaluated. To measure muscular firing patterns, such as the order of activation of various muscle groups about a joint, all that is required of the measurement device is to determine when one muscle is active in relation to the other muscles under observation. In addition to the order of recruitment, the relative extent to which a muscle responds or contributes to joint stabilization under a given condition can also provide useful information. This relative response can be determined by comparing the percentage of each muscle’s activity to its maximal voluntary isometric contraction (% MVIC). The % MVIC is typically calculated by dividing the amplitude of the EMG signal during the activity under study by the amplitude obtained during a controlled MVIC of the muscle.

Determining onset time. Determining the exact time a muscle becomes activated after a stimulus can be influenced by a number of factors. With sEMG, the onset of myoelectric activity will reflect the combined latency (both nerve and muscle) of the fastest muscle fibers in the vicinity of the electrodes. While the average conduction velocity of the motor neuron is around 100 m/s, the average conduction velocity of the muscle fiber is approximately 4 m/s. Therefore, latency is dependent on the length of the peripheral nerve (ie, the distance the action potential must travel before reaching the motor endplate), nerve conduction velocity, terminal nerve fiber conduction velocity, transmission delays at the neuromuscular synapse, and muscle fiber conduction velocity. As a result, factors such as electrode placement and distance from the motor point, individual physical characteristics, and mechanical or physiologic characteristics of the muscle can significantly influence the relative or absolute differences found in latency measures. Furthermore, the methods used to determine the onset of muscle activity can also greatly influence the latency measures obtained.

To accurately determine the onset of muscle activity, the clinician or researcher must be able to confidently and consistently identify when EMG activity begins or significantly deviates from static or baseline activity. To do so, the EMG signal must exceed a threshold that can be defined in some way, either visually (subjective) or by a statistically predetermined level (objective). As is true in most EMG methodology, while there is no universally accepted method for determining precisely when muscle activity onset occurs, a number of methods have been used to aid in this determination.

One subjective method is to use the raw signal along with visual recognition, using subjective criteria to determine when muscle activation occurs or to mark the point at which EMG activity begins or changes abruptly from baseline activity. The subjectivity of this assessment poses serious threats to measurement reliability, particularly between investigators. Furthermore, under conditions where the muscle is already contracting and considerable baseline activity is present, the exact moment muscle activity deviates from baseline is often obscured and difficult to determine visually.

An alternative, more objectively defined method is to use a computer-assisted analysis program to identify a muscular event based on statistical criteria. An example of a computer-assisted analysis is to take a representative sample of the baseline activity, statistically determine the mean value and standard deviation of the signal, and then use 2 or 3 standard deviations from average baseline activity as the threshold for detection. Using a 2-standard deviation threshold allows the researcher to be 95% confident that a significant change has occurred in muscle activity that is not a result of random occurrence. However, while these computer-assisted methods yield more reliable measures, they are unable to confirm the validity of the measure or event. As such, some level of visual recognition by an experienced investigator is still required. Paramount to any onset detection or statistical analysis method used, it is essential that the chosen method be well defined and consistently used if measurement reliability is to be achieved. This applies equally to any signal-processing techniques that can also influence measurement reliability and validity.

Signal processing. Oftentimes, the raw signal must be processed in order to more clearly distinguish and separate meaningful or significant events. Processing techniques usually involve some type of filter or mathematical average in order to reduce the number of data points and provide a clearer representation of signal activity. Two common signal-processing techniques often used are root mean square smoothing and signal averaging. EMG data is typically collected at 1000 Hz or one data point every millisecond. When processing the raw signal with a root mean square, all data points are converted to a singular polarity (rectified) by squaring them (Figure 5A) and then averaging over a user-defined time interval. By choosing longer time intervals (ie, time duration over which data points are averaged), fewer data points will be produced, which will result in a smoother signal over a given time series (Figure 5B). This method effectively filters the signal to provide a more general representation of muscular activity. Signal averaging takes this a step further by superimposing multiple trials or tracings on one another to
produce a composite or averaged signal that is representative of activity across all trials (Figure 5C). However, in order to use signal averaging, data must be acquired at the same precise time and duration across all trials. This can be accomplished through a trigger-sweep data-collection mode using a mechanically reliable triggering device to clearly define when a trial begins or ends.100

When processing methods are used before the determination of muscle activity onset, it is important to realize that, any time the raw signal is processed or filtered, a loss of EMG information results and the actual rise time of the signal may be significantly altered, affecting the researcher’s ability to determine the exact time of muscle activity onset.89,93 Therefore, while processing may be necessary to assist the researcher in yielding more consistent and systematically accurate measures, statistically significant changes may occur from processing alone. To exemplify this fact, Gabel and Brand99 studied the effects of various processing methods on measurement variation and statistical significance, comparing left and right differences in EMG signals for the vastus lateralis and medial gastrocnemius during gait. Their purpose was to determine whether the number of gait cycles averaged or the degree of filtering (smoothing) had any effect on the statistical results obtained from the variance ratio, coefficient of variation, Pearson r, analysis of variance, and t test. Their results demonstrated that all statistical tests were affected to some degree (with some influenced more than others) by the degree of filtering or averaging, or both. Given their findings, the ability to compare results across studies using different processing techniques would seem questionable. Furthermore, since this study was carried out on 2 healthy subjects with no lower limb clinical pathology, their findings also demonstrated that statistically significant variations can be found in the absence of clinically significant differences. Therefore, in order for results of sEMG data to be clinically meaningful, to be accurately interpreted, and to allow comparisons across studies, it is essential that investigators justify and report in detail the type and method of signal processing used, as well as the statistical test used to determine muscle activity onset time.

In summary, the absolute measurement of muscle response times via sEMG can be influenced by a number of factors. Each of these factors alone can result in significant variations in latency measures that may obscure or confound clinically significant variations. Unfortunately, the manner in which EMG has been used to assess neuromuscular response characteristics in terms of instrumentation, signal processing, and data acquisition is varied and at times quite confusing and poorly understood; no standardized procedures currently exist in this regard. Additionally, many research papers fail to adequately report their procedures, which prevents others from being able to replicate or validate their findings.92 What appears then to be the most important factor when assessing neuromuscular response characteristics with EMG is not necessarily which methods are used, but whether the methods are consistent, well defined, and well controlled for all trials and tests to ensure that a measure is reliable, valid, and comparable with other studies.56,59,93

RESEARCH APPLICATIONS ASSESSING SEX DIFFERENCES IN NEUROMUSCULAR RESPONSES

Given the role of musculature in maintaining joint equilibrium and stability at the knee, there has been considerable interest in investigating neuromuscular response characteristics and their association with ACL injury. A number of research models have employed sEMG to evaluate activation patterns at the knee after joint loading or perturbation (ie, a mechanical stress placed on the joint either internally or externally).1 However, most of these models have evaluated this relationship from a postinjury, rehabilitative reference point rather than a preinjury, predictive one. Very few studies to date have specifically addressed potential sex differences in neuromuscular response characteristics.14,27,28 We found only one published study that specifically addressed this relationship at the knee.14

Sex Differences at the Knee

Huston and Wojtys14 appear to have been the first to assess sex differences in neuromuscular responses at the knee. Their purpose was to identify potential physiologic differences between males and females with regard to anterior tibial laxity, isokinetic measures (strength, endurance, and time to peak torque at 60°/s and 240°/s), and neuromuscular responses

| References 14, 23, 24, 30–32, 39, 48, 49, 52, 55, 71. |
(muscle reaction time and muscle recruitment order) after anterior tibial translation. An anterior tibial translation device, first described by Wojtys and Huston,\textsuperscript{55} was designed to apply an unanticipated, anteriorly directed force to the posterior aspect of the lower leg with the subject in a semisected, partial weightbearing position and the knee flexed to 30°. Potentiometers placed on the patella and tibial tuberosity were used to quantify the relative tibial displacement in relation to the femur. sEMG electrodes were placed over the midbelly of the medial and lateral quadriceps, medial and lateral hamstrings, and the gastrocnemius muscles to record spinal, intermediate, and voluntary response times and recruitment patterns in response to the perturbation. These response times represented the time delay between the initiation of the anterior tibial translation force stimulus and the onset of the nonosynaptic reflex, long-loop reflex, and voluntary responses, respectively. Onset for each response was determined based on time of occurrence and signal shape characteristics.\textsuperscript{14}

Female athletes participating in Division I basketball, field hockey, gymnastics, and volleyball were compared with Division I football players and nonathlete male and female controls.\textsuperscript{14} The findings identified no differences in spinal, intermediate, or voluntary response times after anterior tibial translation. However, a different muscle recruitment order was observed at the intermediate reflex response levels in the female athlete group compared with all other groups. At this response level, female athletes more often initiated the quadriceps first, while the male athlete and control groups preferentially activated the hamstrings first in response to anterior tibial translation. No difference in recruitment patterns at the spinal and voluntary response level were found between sexes. Sex differences were also found with isokinetic testing, in that female athletes took significantly longer to reach peak torque in their hamstrings compared with male athletes, both at 60°/s and 240°/s. While no correlation was found between muscle strength and response times, the 5 strongest female athletes used a voluntary muscle recruitment order favoring initial activation of the hamstrings, while the 5 weakest favored initial activation of the quadriceps.

This model effectively demonstrates an objective and well-controlled method by which to quantify dynamic muscular activation in response to an unanticipated knee perturbation. Furthermore, it demonstrates the use of isokinetic dynamometers to provide a measure of mechanical force delay within the muscle. While time to peak torque is not a true measure of EMD, this measure does account for delays in mechanical force production not accounted for in the myoelectrical activation time recorded via EMG. However, it would seem reasonable that true EMD could also be measured if EMG data were collected simultaneously with an isokinetic dynamometer or other force transducer and if the precise time at which force was initiated (rather than peaked) could be determined.

This study also demonstrates some of the previously discussed limitations and reliability concerns associated with EMG measures. Inadequate reporting of instrumentation, of signal processing, and of the method used for determination of muscle activity onset time makes it difficult for others to replicate their findings. In addition, the time delays reported by Huston and Wojtys\textsuperscript{14} for spinal and intermediate reflexes appear to be substantially longer than those reported by others.\textsuperscript{48,58,71,73,75} Therefore, reporting whether the signal was processed and the method by which muscle activity onset time was determined is essential if one is to adequately interpret the findings of Huston and Wojtys or compare their results with others.

**Sex Differences at Other Joints**

Force plates (and similar force transducers) have been used with EMG at other joints in order to measure sex differences in EMD in addition to myoelectric response times. Winter and Brookes\textsuperscript{28} measured both myoelectric and electromechanical response delays in males and females during a rapid, voluntary plantar flexion movement. With the subject seated, the ball of the foot was positioned on a force platform to record muscular force generation, and the heel was placed over a pressure pad to record initiation of joint movement. Surface recording electrodes were placed over the lateral surface of the soleus to monitor myoelectric activity. In response to an auditory stimulus, subjects were asked to plantar flex the foot as quickly as possible. Time delays from stimulus to EMG activity, EMG activity to initial force generation, EMG activity to initiation of heel movement, force generation to heel movement, and total reaction time (stimulus to heel movement) were quantitatively measured. Their results indicated no differences in myoelectric response times, but they did find significant differences in EMD, both in time from force generation to heel movement and in EMG activity to heel movement. The methods were well reported in this study, and standard error values as well as test-retest coefficients of variation were also reported. Reporting these error coefficients provides a sense of how variable the data are between tests and provides a basis with which to compare statistically significant findings. While the authors did not include in their discussion the relationship of these measures to their findings, it appears that the statistically significant differences obtained were only slightly greater than the standard measurement error.

Similarly, Bell and Jacobs\textsuperscript{27} compared myoelectric response times and EMD in males and females during a maximal contraction of the elbow flexors after a visual stimulus. Subjects were assigned to one of 4 groups based on sex and maximum biceps force generation (ie, weak and strong males, weak and strong females). Subjects were asked to quickly and maximally contract the biceps in response to a light stimulus while holding a bar attached to a force transducer. With the light stimulus acting as a trigger to begin data recording, EMG activity (over the belly of the biceps) and force measures were recorded for a 2-second interval. Both onset of EMG and force generation were determined via computer software using threshold-detection methods. Results indicated no difference in
myoelectric response time among the 4 groups. However, the EMD in both male groups was significantly shorter than in both female groups. No correlation was found between response times and strength.

These studies suggest that intrinsic, mechanical properties within the muscle may differ between males and females, with males having the ability to initiate a more immediate stiffening response after muscular activation. However, the relevance of these findings to the knee musculature is not known. Furthermore, these studies evaluated muscular response characteristics under voluntary conditions with the muscle at rest before the stimulus. These conditions are not representative of the dynamic and reflexive responses that may occur with joint perturbations or during sport activity, where the muscle may already be contracting. Research models assessing sex differences in reflexive stiffening and EMD at the knee under dynamic conditions and after unexpected joint perturbations are needed.

**DIRECTIONS FOR FUTURE RESEARCH**

From the limited research available, it appears that males and females may differ in some aspects of neuromuscular responses. However, more research is needed to draw firm conclusions regarding these differences and their potential roles as possible predisposing factors to the higher incidence of ACL injury in females.

When considering previous studies that have measured reflexive activation patterns after unanticipated joint loading or perturbation, the response stimulus has been typically applied in an open chain or partially loaded lower extremity under resting conditions. Unfortunately, these conditions do not mimic the environment of the joint during the activities when these injuries are likely to occur. Research indicates that hamstring activation patterns and their ability to stabilize the knee can vary substantially depending on weight-bearing status, joint angle, and trunk position. Furthermore, whether a muscle is actively contracting before the perturbation may greatly influence immediate stiffening responses and reflexive activity patterns. Therefore, there is a need to assess neuromuscular responses using functional, full weightbearing activities and perturbation models. Studies by Gauffin and Troup and Branch et al assessing dynamic activation patterns in ACL-deficient subjects during jumping and cutting activities may provide potential models to assess sex differences during similar activities.

Research should also address sex differences in intrinsic stiffening responses and delays in force production not accounted for in EMG measures alone. In order for the neuromuscular system to be effective in preventing ligament strain, muscular tension must be developed in a timely fashion to limit joint deformation. Measures of intrinsic stiffening before reflexive muscular activation, as well as the EMD after myoelectric activation, provide essential information regarding the adequacy (or inadequacy) of protective neuromuscular response mechanisms. Furthermore, given recent evidence suggesting that estrogen levels may affect collagen metabolism and tissue compliance, the influence of this hormone on intrinsic and electromechanical response characteristics in females deserves attention.

Future studies should also consider assessing sex differences while controlling for skill level and training across subjects. Both specificity of training and level of conditioning may significantly impact muscle reaction time and coactivity patterns, and thus the ability to provide dynamic stability and adequate joint protection. While the study by Huston and Wojtys appears to be the first to specifically address potential sex differences at the knee, it should be noted that the female and male athlete groups participated in different sports. The different skill and training backgrounds required for various sport activities could potentially confound results, making it difficult to determine whether differences were due to sex or training. Therefore, training variables should be considered when developing future research models to explore potential sex differences in neuromuscular response characteristics.

Finally, it is apparent from the literature that the manner in which sEMG has been used to assess neuromuscular response characteristics has been quite varied and has been, at times, inadequately reported. Given the multiple factors that can influence the detection and interpretation of the EMG signal, lack of standardization and reporting make it difficult to interpret the findings and compare results between studies. Moreover, given the inherent variability in EMG data, including reliability estimates and reporting the standard error of measurement would seem prudent and would provide the reader with the information needed to critically evaluate the clinical versus statistical significance of a study’s results. In order to detect true differences between the sexes, any statistically significant difference must reasonably exceed the expected variability in scores that can be evaluated only with repeat testing and reliability studies. Of the studies discussed previously, only Winter and Brookes reported test-retest measurement variance with their data. However, Huston and Wojtys did report expected measurement variability in previous work and stated that this variation was accounted for in their statistical analysis. Future investigators should subject their data to the scrutiny of this measurement analysis if truly valid and clinically relevant conclusions are to be made. Shroot and Fleiss and Denegar and Ball provide excellent discussions on the issues and computation methods associated with measurement reliability and standard error of measurement.

**CONCLUSIONS**

The speed at which muscular activation can be generated may be an important determinant in providing dynamic stability and potential injury prevention. Whether or not a difference in muscular response characteristics exists between the sexes
may be a significant finding in assessing ACL injury risk in females. However, more research is clearly needed in this area. Future studies should address sex differences at the knee under functional, weightbearing conditions while controlling for training and other confounding variables. Other associated factors, such as hormone levels and their influence on muscular mechanics and activation patterns in females, should also be addressed.

To that end, sEMG can provide a useful tool to assess potential sex differences in the timing, recruitment order, and coactivity patterns of the knee musculature in response to an imposed perturbation. However, the appropriate application, as well as limitations, of this instrument must be fully realized if quality research is to be conducted and if valid and reliable results are to be obtained. Although this review is far from exhaustive regarding the many technical aspects of sEMG, our hope is that the information presented here will enhance the reader’s appreciation for the use of this evaluative tool and generate further interest in and research on this timely topic.

REFERENCES


Rehabilitation After Anterior Cruciate Ligament Reconstruction in the Female Athlete

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Objective: To discuss the rehabilitation program after anterior cruciate ligament (ACL) reconstruction in the female athlete. In addition, we will discuss 8 unique characteristics identified in the female athlete and specific training drills to address and correct the potentially deleterious effects of these unique characteristics.

Background: The female athlete appears to be more susceptible to noncontact ACL injuries than the male athlete. There seem to be many differences between the female and male athlete that may contribute to the increased injury rate in the female athlete. These variations include anatomical and neuromuscular considerations and differences.

Description: Based on the unique characteristics of the female athlete and the anatomical and neuromuscular dissimilarities, a specially designed rehabilitation program has been established for the female athlete after ACL surgery.

Clinical Advantages: The rehabilitation drills discussed in this article challenge the neuromuscular system through proprioception, kinesthesia, dynamic joint stability, neuromuscular control, and perturbation training activities. Improving the female athlete’s neuromuscular system will, we believe, expedite the injured athlete’s recovery after ACL injury or surgery. Although the concepts discussed are part of a postoperative rehabilitation program after ACL surgery, these concepts may also be implemented as a preventive program to assist in reducing the incidence of ACL injuries in the female athlete.

Key Words: neuromuscular control, perturbation training, dynamic stability

Anterior cruciate ligament (ACL) injuries are the most common severe ligamentous injuries incurred by athletes. The typical mechanism of injury is deceleration with twisting, pivoting, or a change of direction. In our clinical experience, at least 60% of all ACL injuries sustained by athletes are due to a noncontact mechanism of injury. The female athlete appears to be more susceptible to noncontact ACL injuries than her male counterpart.1-5

An increasing number of female athletes seem to be sustaining ACL injuries. Malone et al reported that collegiate female basketball players were 8 times more likely to sustain ACL injuries compared with collegiate male basketball players. During the 1989–1990 intercollegiate basketball season, the NCAA Injury Surveillance System reported that female athletes injured their ACLs 7 to 8 times more frequently than male athletes. Lindenfeld et al reported that the injury rate for ACL injuries in female soccer players was 6 times greater than that of male soccer players. Other sports in which the female athlete appears to be more susceptible to ACL injuries include volleyball and gymnastics.4,5 Ferretti et al4 reported a 4-fold higher incidence of serious knee ligament injuries in female versus male elite volleyball players. Chandy and Grana,5 in a 3-year study, reported that female athletes were 4.6 times more likely to sustain a season-ending knee injury than male athletes. Specifically, female athletes in jumping sports had significantly more severe knee injuries.

Understanding the reasons for this increased injury rate is vital to the development of a postoperative rehabilitation program, and even more importantly, a preventive training program to decrease the incidence of severe ligamentous injury. According to our injury data, including high school and college athletes in all competitive and recreational sports, the female high school athlete appears to have a 1 in 100 chance of sustaining an ACL injury, whereas the male high school athlete appears to have a 1 in 500 chance of sustaining an ACL injury. The collegiate male athlete appears to exhibit a 1 in 50 chance, while the collegiate female athlete appears to have a 1 in 10 chance (K. E. Wilk et al, unpublished data, 1998).

Thus, with the increasing number of females participating in athletics and an increasing number of ACL injuries occurring, a specific postoperative rehabilitation program for the female athlete after ACL surgery is useful. In this article, we will discuss the rehabilitation program after ACL surgery. Additionally, specific exercises to address the unique characteristics...
of the female athlete will be discussed, along with suggestions regarding specific drills.

**UNIQUE CHARACTERISTICS OF THE FEMALE ATHLETE**

There are numerous sex differences that contribute to the increased rate of ACL injuries in the female athlete. These sex differences are both anatomical and neuromuscular (Table 1). The female usually exhibits a wider pelvis, increased flexibility, less-developed thigh musculature, increased genu valgum, and increased external tibial torsion when compared with the male. Although these differences are anatomical, suggesting structural variations in the body, several of these anatomical differences may be affected by specially designed training drills. Discussions with many patients who have torn their ACLs and review of videotapes documenting ACL injury reveal that a frequent mechanism for sustaining an ACL injury is a valgus stress with rotation at the knee joint. This mechanism of ACL injury is especially common when the athlete lands from a jump. Thus, preventive and rehabilitative training drills should be developed to control the valgus moment at the knee joints through hip and ankle movement strategies. Also, the female athlete exhibits increased flexibility and genu recurvatum. Therefore, the female athlete must be trained to control knee extension and hyperextension through quadriceps and hamstring muscle coactivation.

Specific neuromuscular and muscular performance differences exist between female and male athletes. Several authors have documented that females exhibit significantly less muscular strength than males. Hakkinen examined the force-production characteristics of the leg extensors and trunk flexors and extensors in male and female basketball players. The male players demonstrated greater absolute maximal strength values in all 3 muscle groups when compared with the females, even when the force values were related to body weight.

Explosive force production of the leg musculature is an important neuromuscular characteristic among athletes. Electromechanical response time refers to the interval between a stimulus and a change in electrical activity in skeletal muscle and the delay between the change in electrical activity and actual force generation by the muscle. females appear to generate muscular force at a slower rate than males. Komi and Karlsson reported that female subjects required about twice as much time as males to attain 70% of a maximal voluntary contraction. Bell and Jacobs demonstrated a shorter electromechanical response time in males compared with females. Several investigations have documented similar results. Bell and Jacobs postulated that the shorter electromechanical response time in males is due to stiffer muscles. The elastic component in males' muscles is more resistant to stretching than in females due to inherent flexibility differences, thereby shortening the electromechanical delay. This finding has significant rehabilitation and training implications. A critical component to dynamic joint stability is the time required to generate muscular torque once the protective muscle contraction has been initiated. The time interval required to reach maximum muscular capacity appears to be an important parameter in injury prevention. Therefore, it would appear that the enhancement of dynamic joint stability in the female athlete depends in part on neuromuscular response times. High-speed muscle training seems to be an important way to address this parameter.

Furthermore, it appears that muscular fatigue significantly affects the rate of force development and muscle contraction velocity. Hakkinen and Komi examined the effects of fatigue produced by a maintained isometric contraction of the knee extensors at 50% of a maximum effort in 14 males. The continual contraction caused a significant increase in integrated electromyogram (EMG) activity and a decrease in mean power. Additionally, the investigators noted that fatigue occurred in the contractile element of the muscle and that the muscle spindle sensitivity was increased during fatigue loading. Zhou et al noted a significant increase (147%) in the electromechanical delay of the knee extensors after muscular fatigue. Thus, it appears that muscular endurance training should be an integral component of a well-structured rehabilitation program after ACL injury.

Recently, Huston and Wojtys examined the neuromuscular performance differences between male and female collegiate athletes and nonathletes. Significant findings were numerous; however, a few key points stand out. The order of muscular recruitment to produce dynamic joint stability in response to anterior tibial translation in female athletes was significantly different than that of male athletes or female nonathletes. The male athletes and nonathletes recruited their hamstring and gastrocnemius muscles to resist anterior tibial translation, whereas the female athletes relied more on the quadriceps muscles. Thus, the female athlete appears to exhibit a less effective protective reflex to stabilize the knee joint than either

<table>
<thead>
<tr>
<th>Anatomical Differences</th>
<th>Muscular and Neuromuscular Differences</th>
<th>Laxity and Range of Motion</th>
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</thead>
<tbody>
<tr>
<td>Wider pelvis</td>
<td>Diminished muscular force</td>
<td>Greater range of motion</td>
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<tr>
<td>Increased flexibility</td>
<td>Dependence on quadriceps muscle for stability</td>
<td>Genu recurvatum</td>
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<tr>
<td>Less-developed thigh musculature</td>
<td>Longer time to develop force</td>
<td>Increased knee laxity</td>
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<tr>
<td>Narrower femoral notch</td>
<td>Longer electromechanical response time</td>
<td>Increased hip rotation</td>
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<td>Smaller ACL</td>
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<tr>
<td>Increased genu valgum</td>
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<td>Increased external tibial torsion</td>
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</table>
the male athlete or the female nonathlete. In fact, using the quadriceps to stabilize the knee joint may render the ligament more susceptible to injury by increasing ACL strain. Hewitt et al reported a significant imbalance between the hamstrings and quadriceps muscles in a group of high school volleyball players. The investigators noted that the female athletes’ unilateral hamstrings to quadriceps muscle ratio was 47%, while the males’ was 67%. The authors stated that the female athletes’ unilateral muscle ratio was less efficient in stabilizing the knee joint. Hence, the rehabilitation program must incorporate drills to train the female athlete to better use the knee-flexor musculature in providing dynamic joint stability.

Female athletes also exhibit greater laxity and range of motion than male athletes. Huston and Wojtys have demonstrated that the knees of women exhibit greater laxity than those of men. The female athlete group showed significantly more anterior tibial displacement (4.5 mm) when compared with the male athlete group (3.5 mm). It should also be noted that changes in knee laxity have been reported during the menstrual cycle. Huston and Wojtys reported a statistically significant difference in knee laxity during one menstrual cycle. The greatest laxity was noted on day 1 of the cycle. In addition, females tend to exhibit greater genu recurvatum than males. In a recent study conducted at our center, we compared tibiofemoral displacement measurements in female athletes with significant hyperextension (more than 7°) and female athletes who exhibited less than 5° of hyperextension. We found a tendency, but no statistically significant difference, toward greater total tibiofemoral displacement in individuals who exhibited more hyperextension compared with individuals with only a few degrees of hyperextension (K. E. Wilk et al, unpublished data, 1998). Another protective mechanism in preventing ACL injuries is the ability to actively contract the knee musculature to increase the stiffness of the knee joint. Recently, Wojtys et al reported that male athletes were able to increase knee stiffness by 473%, whereas females were able to increase knee stiffness by only 217%.

The increased incidence of ACL injuries in the female athlete appears to be multifactorial. To our minds, it seems to be caused by a combination of both anatomical and neuromuscular differences. Based on these differences, we have developed 8 key factors to consider when developing an ACL rehabilitation program for the female athlete (Table 2).

<table>
<thead>
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<th>Table 2. Factors to Consider in ACL Rehabilitation of the Female Athlete</th>
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<tbody>
<tr>
<td>Factor</td>
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<tr>
<td>Females exhibit a wider pelvis and increased genu valgum</td>
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<tr>
<td>Female athletes recruit quadriceps muscle to stabilize the knee</td>
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<tr>
<td>Females generate muscular force more slowly than males</td>
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<tr>
<td>Jumping athletes lose hip control upon landing</td>
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<tr>
<td>Less-developed thigh musculature</td>
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<tr>
<td>Genu recurvatum and increased knee laxity</td>
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<tr>
<td>Exhibit less-effective dynamic stabilization</td>
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<td>Poorer muscular endurance rates</td>
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</table>

CURRENT CONCEPTS IN ACL REHABILITATION

Before discussing the specific factors to consider in the female athlete, we will briefly discuss our philosophy and our current rehabilitation program after ACL reconstruction. Our current rehabilitation program is an adaptation of our previously published program and represents an evolution in rehabilitation to a greater emphasis on functional rehabilitation drills and a reflection of the importance of proprioception and neuromuscular control. We currently use 2 ACL rehabilitation programs. The accelerated ACL rehabilitation program is used for competitive or serious recreational athletes. This program is more aggressive and demanding because of the increased demands placed on the knee joint by the athlete. In contrast, the other rehabilitation program is designed for the less-serious recreational athlete. This program is slightly slower than the accelerated program because these patients are generally less conditioned and their lifestyle prohibits any aggressive rehabilitation program.

The female athlete who undergoes an ACL reconstructive procedure is initiated on the accelerated rehabilitation program unless specific circumstances exist (eg, meniscus repair, osteochondral procedures, concomitant lateral collateral ligament or posterior cruciate ligament surgery). Hardin et al have suggested a decelerated rehabilitation program after ACL reconstruction for an adolescent female athlete who exhibits hyperelasticity. While we agree with the authors that overaggressive rehabilitation may result in excessive capsular mobility or graft stretch-out, or both, we strongly support immediate muscular training and early restoration of proprioception and neuromuscular control in the female athlete. We base this point of view on the neuromuscular differences exhibited by the female athlete.

The accelerated 6-phase ACL rehabilitation program outlined in Table 3 is designed to return the athlete to sport as quickly and safely as possible. We use a criterion-based approach, where the patient must accomplish specific objectives before advancing to the next phase of the rehabilitation program. Also, the specific time frames are based on healing constraints. We will briefly discuss the program.

The rehabilitation program begins immediately after the ACL injury. The goals of the preoperative phase are to diminish inflammation, swelling, and pain and to restore normal range of motion. Before surgery, emphasis is placed on...
Table 3. Accelerated Rehabilitation for ACL PTG* Reconstruction (Isolated)

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<th>Phase</th>
<th>Goals</th>
<th>Exercises</th>
<th>Brace</th>
<th>Weightbearing</th>
<th>Range of motion</th>
<th>Ice and elevation</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Preoperative Phase</td>
<td>Goals: Diminish inflammation, swelling, and pain</td>
<td>Ankle pumps</td>
<td>EZ Wrap or knee sleeve to reduce swelling</td>
<td>2 crutches</td>
<td>4 to 6 times</td>
<td>Ice 20 min of every hour and elevate leg with knee in full extension</td>
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<td></td>
<td>Restore normal range of motion (especially knee extension)</td>
<td>Overpressure into full, passive knee extension</td>
<td>or immobilizer applied to knee, locked in full knee extension during</td>
<td>as tolerated</td>
<td>per day</td>
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<td></td>
<td>Restore voluntary muscle activation</td>
<td>Active and passive knee flexion (90° by day 5)</td>
<td>ambulation</td>
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<td></td>
<td>Provide patient education to prepare patient for surgery</td>
<td>Straight-leg raises</td>
<td>KT-2000 test: 6.75-kg anterior-posterior test only</td>
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<td></td>
<td>Goals: Maintain full passive knee extension</td>
<td>Quadriceps isometric setting</td>
<td>Exercises: Muscle stimulation to quadriceps during quadriceps</td>
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<tr>
<td>II. Immediate Postoperative</td>
<td>Gradually improve knee flexion</td>
<td>Hip abduction and adduction raises</td>
<td>exercises (4 to 6 h/d)</td>
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<td>Phase (Day 1 through Day 7)</td>
<td>Reestablish quadriceps control</td>
<td>Hamstring stretches</td>
<td>Muscle stimulation: Apply to quadriceps</td>
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<td></td>
<td>Restore independent ambulation</td>
<td>Closed kinetic chain exercises: minisquats, weight shifts</td>
<td>during active muscle exercises</td>
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<td>Postoperative Day 1:</td>
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<td>Brace: EZ Wrap Brace</td>
<td>Brace: Discontinue brace or immobilizer at 2 to 3 wk</td>
<td>Continuous passive motion: as needed, 0° to 45° to 50° (as tolerated and</td>
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<td>or immobilizer applied to</td>
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<td>and as directed by physician)</td>
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<td>extension during ambulation</td>
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<td>Weightbearing: 2 crutches,</td>
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<td>weightbearing as tolerated</td>
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<td>Exercises: Ankle pumps</td>
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<td>Overpressure into full, passive</td>
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<td>Active and passive knee flexion</td>
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<td>Straight-leg raises</td>
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<td>Quadriceps isometric setting</td>
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<td>Hip abduction and adduction</td>
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<td>Hamstring stretches</td>
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<td>Closed kinetic chain exercises:</td>
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<td>Minisquats, weight shifts</td>
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<td>Continuous passive motion:</td>
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<td>As needed, 0° to 45° to 50°</td>
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<td>III. Early Rehabilitation</td>
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<td>Phase (Week 2 through Week 4)</td>
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<td>Goals: Maintain full passive</td>
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<td>knee extension</td>
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<td>Gradually increase knee flexion</td>
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<td>Diminish swelling and pain</td>
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<td>Muscle training</td>
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<td>Patellar mobility</td>
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<td>Minimal joint effusion</td>
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<td>Independent ambulation</td>
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<td>Week 2:</td>
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<td>Brace: Discontinue brace or</td>
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<td>immobilizer at 2 to 3 wk</td>
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<td>Weightbearing: As tolerated</td>
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<td>crutches at 10 d</td>
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<td>Range of motion: Self-ROM</td>
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<td>progression (4 to 8 times a day), emphasis on maintaining full, passive range of motion</td>
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<td>KT-2000 test: 6.75-kg</td>
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<td>anterior-posterior test only</td>
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<td>Exercises: Muscle stimulation to</td>
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<td>quadriceps during quadriceps</td>
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<td>exercises</td>
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<td>Isometric quadriceps sets</td>
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<td>Straight-leg raises (4 planes)</td>
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<td>Leg press</td>
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<td>Knee extension 90° to 40°</td>
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<td>Half-squats 0° to 40°</td>
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<td>Weight shifts</td>
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<td>Front and side lunges</td>
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<td>Hamstring curls</td>
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<td>Bicycle</td>
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<td>Proprioception training</td>
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<td>Overpressure into extension</td>
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<td>Passive range of motion from 0° to 50°</td>
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<td>Patellar mobilization</td>
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<td>Well-leg exercises</td>
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<td>Progressive resistance</td>
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<td>exercise program (begin with .45 kg, increase by .45 kg per wk)</td>
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<td>Week 3:</td>
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<td>Brace: Discontinue</td>
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<td>Range of motion: Continue</td>
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<td>range-of-motion stretching and</td>
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<td>overpressure into extension</td>
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<tr>
<td>Exercises: Continue all</td>
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<tr>
<td>exercises as in wk 2</td>
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<tr>
<td>Passive range-of-motion</td>
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<tr>
<td>exercises from 0° to 115°</td>
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<tr>
<td>Bicycle for range-of-motion</td>
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<tr>
<td>progression</td>
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<tr>
<td>Pool-walking program (if incision is closed)</td>
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<tr>
<td>Eccentric quadriceps program</td>
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<tr>
<td>Lateral lunges</td>
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<tr>
<td>Lateral step-ups</td>
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</tbody>
</table>

Table 3. Continued

*ACL PTG*: Patellar Tendon Gracilis
Table 3. Continued

<table>
<thead>
<tr>
<th>Exercises:</th>
<th>Continue all exercises listed in wks 6, 8, and 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plyometric training drills</td>
<td>Continue stretching drills</td>
</tr>
</tbody>
</table>

**V. Advanced Activity Phase (Week 10 through Week 16)**

Goals:  
- Normalize lower extremity strength  
- Enhance muscular power and endurance  
- Improve neuromuscular control  
- Perform selected sport-specific drills  

Criteria to enter phase V:  
- Active range of motion from 0° to 125° or greater  
- Quadriceps strength 70% of contralateral side, knee flexor/extensor ratio of 70% to 75%  
- No change in KT values (comparable with contralateral side, within 2 mm)  
- No pain or effusion  
- Satisfactory clinical examination  
- Satisfactory isokinetic test (values for females at 180 degrees)  
  - Quadriceps bilateral comparison 75%  
  - Hamstrings equal bilateral  
  - Quadriceps peak torque/body weight ratio 66% to 75%  
  - Hamstrings/quadriceps ratio 66% to 75%  
- Hop test (80% of contralateral leg)  
- Subjective knee scoring (modified Noyes System): 80 points or better  

Continue all exercises listed in wks 10–12

**VI. Return-to-Activity Phase (Week 16 through Week 22)**

Goals:  
- Gradual return to full unrestricted sports  
- Achieve maximal strength and endurance  
- Normalize neuromuscular control  
- Progress skill training  

Criteria to enter phase VI:  
- Full range of motion  
- Unchanged KT-2000 test (within 2.5 mm of opposite side)  
- Isokinetic test that fulfills criteria  
- Quadriceps bilateral comparison (80% or greater)  
- Hamstrings bilateral comparison (110% or greater)  
- Quadriceps torque/body weight ratio (55% or greater)  
- Hamstrings/quadriceps ratio 70% or greater  
- Proprioceptive test 100% of contralateral leg  
- Functional test 85% or greater of contralateral side  
- Satisfactory clinical examination  
- Subjective knee scoring (modified Noyes System: 90 points or better)  

Tests: KT-2000, isokinetic, and functional tests before return  

Exercises:  
- Continue strengthening program  
- Continue neuromuscular control drills  
- Continue plyometric drills  
- Progress running and agility program  
- Progress sport-specific training  

6-month follow-up:  
- Isokinetic test  
- KT-2000 test  
- Functional test  

12-month follow-up:  
- Isokinetic test  
- KT-2000 test  
- Functional test  

* PTG = patellar tendon graft.

restoring full passive knee extension to decrease postoperative complications such as arthrofibrosis. Additionally, muscle-training exercises are performed to prevent muscular atrophy.
The primary goal of the muscle-strengthening exercises is muscle activation. It has been reported that, once an individual has torn the ACL, one of the protective mechanisms is a reflex inhibition of the quadriceps and facilitation of the hamstring muscles. This protective reflex mechanism, in the opinion of author KEW, is the primary reason for quadriceps muscle atrophy after ACL injury or surgery. Thus, a critical aspect of the rehabilitation program before and after surgery is reestablishing voluntary muscular activation of the quadriceps muscles. The patient is encouraged to recruit as much of the quadriceps muscle as possible. Often, electrical muscle stimulation or biofeedback, or both, are used to facilitate greater muscle activation.

Additionally, closed and open kinetic chain exercises are performed to activate muscular patterns and to restore proprioception. Specific drills to improve balance, proprioception, kinesthesia, and neuromuscular control are initiated immediately postinjury to prevent deafferentation. Another key component of the preoperative phase is patient education and counseling. The patient is instructed in the postoperative program as part of the mental preparation for the surgery and the rehabilitation program. During this preoperative phase, an appropriate date for surgery is determined. We have found a great deal of variability as to when an athlete is ready for surgery. Instead of delaying surgery set amount of time, the clinician should consider the following preoperative conditions: full range of motion, minimal swelling, active muscle recruitment, and mental preparedness. Shelbourne et al reported that delaying surgery until motion had been restored decreased the incidence of arthrofibrosis. Also, Shelbourne and Foulk have noted that quadriceps muscle strength returned more quickly when surgery was delayed longer than 21 days.

The postoperative rehabilitation program is initiated immediately after surgery. The goals of this phase are listed in Table 3. Patients remain in the hospital after surgery for 23 hours’ observation. This overnight stay allows control of the patient’s activity level, pain, and swelling and ensures the consistent and accurate start of the prescribed rehabilitation program. A commercial cold wrap is applied to the knee immediately after surgery (Figure 1). Continuous passive motion via machine is initiated from 0° to 45° when the patient goes to the hospital room. Quadriceps muscle contractions and full, passive knee-extension exercises are emphasized during the first week to prevent the development of knee-flexion and patellar contractions. The patient is permitted to weightbear as tolerated with 2 crutches, and the postoperative brace is locked in full knee extension. The patient’s knee flexion range of motion is gradually increased. By postoperative day 5, the patient should exhibit 90° of knee flexion and, by day 7, approximately 100°. Additionally, closed kinetic chain functional training is begun during the first week. These drills include mini-squats (0° to 45°), weight shifts, balance drills, and proprioceptive training activities. The rehabilitation specialist and the patient perform patellar mobilizations to restore normal patellar mobility. The primary goals of the first week of rehabilitation are restoring full passive knee extension, diminishing swelling and pain, restoring patellar mobility, gradually restoring knee flexion, reestablishing voluntary quadriceps control, and controlling the patient’s activity level.

The next phase, the early rehabilitative phase, includes weeks 2 through 4. The goals of this specific phase are listed in Table 3. Additionally, the patient must fulfill specific criteria before progressing into phase III. One of the critical goals of this phase is restoring full passive knee extension. Females usually exhibit hyperextension of the knee joint. A rehabilitation dilemma has been whether or not to restore hyperextension in the female’s knee after an ACL reconstruction. Rubenstein et al have reported that restoring full hyperextension does not adversely affect ligamentous stability. However, we suggest restoring only approximately 5° of hyperextension in the female athlete through stretching techniques in the training room or clinic (Figure 2). If the athlete exhibits more than 5° of hyperextension in the contralateral knee, the authors prefer...
the athlete to gradually regain the additional hyperextension of the involved knee through functional activities. The purpose of restricting hyperextension is the effect it has on dynamic joint stability. When the knee is in a fully extended or hyperextended position, the knee flexors are at a mechanical disadvantage to be recruited to produce forceful knee flexion (Figure 3). Several studies\textsuperscript{40-43} have documented that the hamstring muscles are more efficient at 30° of knee flexion than at 0° or 5° of hyperextension, which is due to moment arms and muscle fiber lengths.

During phase III, the patient's knee flexion is gradually increased. The rate of progression is based on the patient's response to the surgery (eg, joint swelling and pain). If significant joint effusion exists, we progress the knee flexion motion slightly more slowly until the swelling is reduced. The rate of knee flexion motion is progressed based on the patient's ligamentous endfeel. A firm endfeel indicates aggressive stretching and progression of motion. Conversely, a capsular endfeel or one with give to it would suggest the need for a more gradual rate of stretching. Muscle-training drills and exercises are progressed with closed and open chain exercises. Electrical muscle stimulation is applied to the quadriceps to facilitate active quadriceps contraction, to reeducate the muscle, and to prevent muscle inhibition due to pain or swelling.\textsuperscript{42-46} It is essential to reestablish muscle activation early in the rehabilitation program to prevent quadriceps atrophy and promote quadriceps muscular training. In addition, drills to enhance proprioception and weight distribution are initiated (Figures 4 and 5). A vital goal during the second week is to train the patient to assume full-body weight on the involved leg. A NeuroCom Balance System (NeuroCom International, Clackamas, OR) is used to assess the percentage of body weight the patient is assuming on the involved leg and to provide biofeedback training. Additionally, selected open kinetic chain exercises are permitted, such as resisted knee flexion (unless a meniscus repair was performed), hip abduction and adduction, and knee-extension exercises from 100° to 40°. Many investigators have reported that ACL strain increases significantly during the last 30° of knee extension.\textsuperscript{47-53} Recently, Beynnon et al\textsuperscript{54} studied the strain behavior of the anteromedial bundle of the ACL during rehabilitation exercises in vivo. During an open kinetic chain isometric quadriceps contraction at 15° of knee flexion against 30 Nm of torque, the peak strain was 4.4%, whereas at 30° of knee flexion against the same resistance, the peak strain was approximately 2.7%. At 60° of knee flexion, there was no strain on the ACL. Because of the increasing strain on the ACL at terminal extension, we initially restrict active resisted knee extensions to 40°. Placement of the resistance and speed of the exercise can also influence the
magnitude of tibiofemoral shear forces. Wilk and Andrews studied the effects of pad placement during isokinetic exercise in ACL-deficient patients. The investigators noted significantly less tibial displacement when the resistance pad was positioned proximally as compared with the conventional distal pad placement. Furthermore, a greater magnitude of anterior tibial displacement was noted during knee extensions at slower speed (60°/s) compared with faster isokinetic speeds (180°/s and 300°/s). Beynnon et al have documented an ACL strain during closed kinetic chain exercises, such as a vertical squat. They demonstrated the greatest strain on the ACL from 40° of flexion to full extension. The strain behavior of the ACL during a closed kinetic chain exercise (eg, squats) was extremely similar to that during open kinetic chain knee extension.

Exercise drills, which are functional and emphasize weight-bearing activities to strengthen the lower extremity, are implemented in this phase. Functional strengthening exercises are used during this phase, including vertical squats, lateral step-ups, front step-downs, lateral lunges, and lateral step-overs. The patient is encouraged to ride a stationary bicycle to facilitate range of motion. Lastly, a pool program is initiated (once the incision has healed adequately) to facilitate proper gait training and to provide a safe environment for other functional exercise drills.

The intermediate phase usually is started at week 4 and progresses to week 10. The patient is progressed into this phase based on specific criteria (Table 3); therefore, the actual time frame may vary slightly. The goals of this phase are to restore full motion (0° to 125°); improve lower extremity strength; enhance proprioception, balance, and neuromuscular control; and restore limb confidence and function. The exercises and drills performed in this phase should be functional, effective, and safe. The isotonic strengthening program should be progressed in weight and number of repetitions and sets. During this phase, proprioception and functional exercises are performed to enhance dynamic joint stability. Thus, balance drills such as squats on an unstable platform (eg, the Biodex Stability System [Biodex Corp, Shirley, NY]) (Figure 6) are performed. The pool program is progressed to incorporate forward and backward running, agility drills, and eventually jumping drills in the pool. The lateral lunges and front lunges are advanced from straight planes to multiple planes, and ball catches and throws are incorporated to remove the patient’s conscious awareness (Figure 7). Hence, proprioceptive and dynamic stability drills are performed in conjunction with upper extremity skills.

At 10 weeks, isokinetic and knee arthrometer tests are performed to determine muscular performance and static knee stability, respectfully. The muscular performance characteristics of an ACL-reconstructed knee at 10 to 12 weeks postsurgery have been documented by the authors. At this time, the patient typically exhibits a 30% deficit in the quadriceps, as indicated by bilateral peak torque comparisons, and minimal to no deficit demonstrated in the knee-flexor muscle group. Additionally, the patient torque-to-body weight ratio and unilateral muscle ratios are also evaluated. The knee arthrometer score should be comparable with the uninvolved knee (usually within 2 mm).

The advanced activity phase is usually initiated at week 10 and progresses until week 16. The emphasis of the phase is on advanced strengthening drills, neuromuscular control drills, and posture training.
and early return to sport-specific training drills. Before the patient enters this phase of the rehabilitation program, specific criteria must have been achieved (Table 3). Once these predetermined criteria are achieved, advanced drills can be initiated. During this phase, strengthening exercises are progressed to high-weight, low-repetition sets to emphasize muscular hypertrophy. Plyometric drills are used to enhance dynamic joint stability and neuromuscular control. Additionally, perturbation training is emphasized to enhance neuromuscular control. A running program is also initiated, including agility drills such as side shuffles, carioca spreads, and backward running. At 14 to 16 weeks postsurgery, a series of tests is performed to determine whether the athlete can gradually return to sport activities (eg, team practice). We routinely perform knee arthrometer, isokinetics,59,60 proprioceptive, and hop tests.51-63 In addition, the patient completes a subjective knee function questionnaire. The specific criteria can be found in Table 3. Once these criteria have been met and the clinical examination is satisfactory, the athlete enters the return-to-activity phase.

The return-to-activity phase usually begins at approximately 16 weeks after surgery but can vary based on the patient’s rate of progression. During this phase, the patient is strongly encouraged to perform specific strengthening exercises (selected to correct deficits), plyometrics, and neuromuscular control drills and to accelerate sport-specific training drills. Functional motor patterns through skill activities are progressed and closely monitored. Once the patient has achieved normal movement patterns and the criteria have been satisfactorily achieved, the athlete may resume team practice.

### SPECIAL CONSIDERATIONS FOR THE FEMALE ATHLETE

We have identified 8 factors that we feel are important to consider when rehabilitating a female athlete after ACL recon-

**Table 4. Female ACL Rehabilitation: 8 Special Considerations and Specific Exercise Drills**

<table>
<thead>
<tr>
<th>Exercise Drills</th>
<th>Hip musculature to stabilize knee</th>
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</thead>
<tbody>
<tr>
<td>Lateral step-overs (regular, fast, very slow)</td>
<td>Lateral step-overs with ball catches</td>
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<tr>
<td>Step-overs with rotation</td>
<td>Step-overs with rotation</td>
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<tr>
<td>Lateral step-ups on foam</td>
<td>Lateral step-ups on foam</td>
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<tr>
<td>Dip walk</td>
<td>Dip walk</td>
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<tr>
<td>Squats (foam) (Balance Master)</td>
<td>Squats unstable pattern</td>
</tr>
<tr>
<td>Front diagonal lunges onto foam</td>
<td>Lateral lunges jumping</td>
</tr>
<tr>
<td>Retrain neuromuscular pattern hamstring control</td>
<td>Lateral unstable pattern</td>
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<tr>
<td>Lateral lunges straight</td>
<td>Coactivation balance through biofeedback</td>
</tr>
<tr>
<td>Lateral lunges with rotation</td>
<td>Slide board</td>
</tr>
<tr>
<td>Lateral lunges onto foam</td>
<td>Fitter (Fitter International, Calgary, Alberta, Canada)</td>
</tr>
<tr>
<td>Lateral lunges with ball catches</td>
<td>Control valgus moment</td>
</tr>
<tr>
<td>Squats unstable pattern</td>
<td>Front step-downs</td>
</tr>
<tr>
<td>Lateral lunges jumping</td>
<td>Lateral step-ups with Thera-Band (The Hygienic Corporation, Akron, OH)</td>
</tr>
<tr>
<td>Lateral unstable pattern</td>
<td>Tilt board balance throws</td>
</tr>
<tr>
<td>Coactivation balance through biofeedback</td>
<td>Control hyperextension</td>
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<tr>
<td>Slide board</td>
<td>Plyometric leg press</td>
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<tr>
<td>Fitter (Fitter International, Calgary, Alberta, Canada)</td>
<td>Plyometric leg press with 4 corners</td>
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<tr>
<td>Control hyperextension</td>
<td>Plyometric jumps</td>
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<tr>
<td>Plyometric jumps</td>
<td>1 box</td>
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<tr>
<td>2 boxes</td>
<td>2 boxes</td>
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<tr>
<td>4 boxes</td>
<td>2 boxes rotation</td>
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<tr>
<td>2 boxes with catches</td>
<td>2 boxes with catches</td>
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<tr>
<td>Bounding drills</td>
<td>Bounding drills</td>
</tr>
<tr>
<td>Forward and backward step-over drills</td>
<td>High-speed training, especially hamstrings</td>
</tr>
<tr>
<td>Isokinetics</td>
<td>Isokinetics</td>
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<tr>
<td>Backward lunging</td>
<td>Backward lunging</td>
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<td>Shuttle</td>
<td>Shuttle</td>
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<td>Lateral lunges (fast jumps)</td>
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<tr>
<td>Resistance tubing for hamstring</td>
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<td>Backward running</td>
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<td>Neuromuscular reaction</td>
<td>Neuromuscular reaction</td>
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<tr>
<td>Squats on tilt board</td>
<td>Squats on tilt board</td>
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<tr>
<td>Balance beam with cords</td>
<td>Balance beam with cords</td>
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<tr>
<td>Dip walk with cords</td>
<td>Dip walk</td>
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<tr>
<td>Balance throws</td>
<td>Balance throws</td>
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<td>Balance throws perturbations</td>
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<tr>
<td>Lateral lunges with perturbations onto tilt board</td>
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<tr>
<td>Less-developed thigh musculature</td>
<td>Knee-extensor and -flexor strengthening exercises</td>
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<td>Squats</td>
<td>Squats</td>
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<td>Leg press</td>
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<td>Wall squats</td>
<td>Bicycling</td>
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<tr>
<td>Bicycling</td>
<td>Poorer muscular endurance</td>
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<tr>
<td>Stair climbing</td>
<td>Stair climbing</td>
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<tr>
<td>Bicycling</td>
<td>Weight training (low weights, high repetitions)</td>
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<tr>
<td>Weight training (low weights, high repetitions)</td>
<td>Cardiovascular training</td>
</tr>
<tr>
<td>Balance drills for longer durations</td>
<td>Balance drills for longer durations</td>
</tr>
</tbody>
</table>

Figure 7. Lateral lunges performed in a single plane of motion. The patient is instructed to lunge, land, and maintain knee flexion to 25° to 30° during the drill.
struction (Tables 2 and 4). These factors take into consideration the unique anatomical and neuromuscular characteristics of the female athlete. We have developed rehabilitation considerations and specific exercises and neuromuscular drills based on each of these 8 characteristics. We will briefly discuss and illustrate these rehabilitation considerations.

**Dynamic Control of the Valgus Moment**

First, an anatomical characteristic unique to the female athlete is the wider pelvis and increased genu valgum compared with the male athlete. The rehabilitation goal is dynamic control of the valgus moment at the knee joint. We have observed that valgus stress at the knee joint combined with femoral external rotation is a common mechanism of noncontact ACL injuries in the female athlete, especially when landing after a jump (Figure 8). Thus, through specific neuromuscular training drills, the athlete must learn to dynamically control this type of valgus moment. Markolf et al. have shown that muscular contraction can decrease both varus and valgus laxity of the knee 3-fold. Specific neuromuscular control drills designed to dynamically control valgus and varus moments at the knee joint include front step-downs, lateral step-ups with resistance, and balance on a tilt board while performing a throw. While performing the front step-down, the athlete is instructed to control the knee to prevent it from going into a valgus position (Figure 9). Lateral step-ups can be performed with a resistance band placed around the knee, forcing the knee into a valgus moment and requiring the athlete to resist that movement (Figure 10). An additional drill to control the valgus moment at the knee is performed with the athlete standing on a tilt board, maintaining a fixed posture, while performing a throw and catch with a ball (Figure 11).

**Muscular Coactivation for Dynamic Stabilization**

Next, as discussed previously, the female athlete recruits the quadriceps muscle to stabilize the knee joint instead of the more efficient hamstring muscle group. Therefore, the rehabilitation goal is to train the athlete to use the coactivation pattern of the quadriceps and hamstrings to stabilize the knee joint. Barratta et al. noted the increased risk of ligamentous injury in athletes with quadriceps to hamstring muscle strength imbalances and reduced hamstring-quadriceps muscle contraction patterns. They observed an increased coactivation of...
hamstring muscles in athletes after muscle-training exercises. We use various specific exercises such as lateral lunges, vertical squats with stabilization, and balance drills with biofeedback applied to hamstring muscles to encourage activation. The lateral lunge is performed with a resistance cord applied to the athlete’s waist with a belt. As the athletes lunge laterally, they are instructed to land with the knees flexed to approximately 25° to 30°. Having been trained to land with flexed knees, athletes learn to cocontract the quadriceps and hamstring muscles. We refer to this position as the “position of stability.” Additionally, by encouraging knee flexion to 30°, quadriceps muscle activation is enhanced. Perry et al. reported the EMG activity of quadriceps muscles during exercise: 15° of flexion resulted in 15% maximum voluntary isometric contraction of the quadriceps, whereas, at 30°, the quadriceps EMG activity increased to 51%. We use a functional progression for the lateral lunges: straight-plane lateral lunges, multiple-plane lateral lunges (3 directions), lateral lunges with rotation, lateral lunges onto foam, lateral lunges with rotation and ball catches, and finally, lateral jump lunges (Figure 12). Another drill performed to enhance cocontraction and hamstring activation involves squats performed on an unstable platform (Figure 13). The athlete is instructed to perform the squat to 25° to 30° and to dynamically stabilize the platform to prevent platform movement. Wilk et al. have shown that vertical squats to 30° produce the greatest hamstrings-quadriceps muscle coactivation. In addition, once the athlete has mastered this drill, perturbations can be introduced to increase the challenge. Lastly, biofeedback applied to the hamstrings or gastrocnemius muscles, or both, during balance drills, such as balancing on a tilt board while catching and throwing (Figure 14), can also train the athlete to activate the hamstring muscles to stabilize the knee joint.

Muscular Training for Fast Reaction Times

The third factor to consider in the rehabilitation program is that females generate muscular force more slowly than males; therefore, we must train the female at fast speeds for quicker reaction times. This need is especially important for the stabilizing muscles of the knee joint, the hamstrings, and the
gastrocnemius. Specific rehabilitation drills performed to promote high-speed hamstring contractions are high-speed isokinetics (Biodex) (180° to 450°/s), backward running (maintaining a flexed-knee posture), high-speed knee flexions with a resistance cord, high-speed lateral jumping lunges, and alternating-leg rapid step-ups, and side shuffles.

Learn To Control the Hip and Pelvis

The next factor to consider is the loss of hip and trunk control when the athlete lands after a jump. A frequently seen mechanism is hip adduction with internal rotation and knee valgus, with the body falling laterally over the lower extremity (Figure 15). We refer to this as “the point of no return,” a common mechanism of ACL injury in the female athlete. The goal of the rehabilitation training drills in this instance is to teach the athlete to control the hip and the trunk. By controlling the hip and trunk, we believe the athlete may be able to reduce adduction and abduction of the knee joint. Specific training drills to fulfill this goal are lateral step-overs, balance beam drills, neuromuscular control lateral step-ups, and squats on foam. The lateral step-over drill is performed over cones or cups (Figure 16). The athlete is instructed to raise the thighs as high as the hip while flexing and laterally stepping over the cones. The functional progression we use clinically is to have the athlete perform the first set at a comfortable speed, then the second as fast as possible, and the third as slowly as possible. Incorporating a skill, such as ball catches and throws, during the step-over enhances the neuromuscular control. The step-overs can be progressed to step-overs with...
rotation and step-overs onto foam. Another hip and trunk neuromuscular control drill is the dip walk (Figure 17). The dip walk is performed on a balance beam, and the athlete executes a lateral step-up and then forward steps the entire length of the beam as slowly as possible. A traditional lateral step-up can be performed with the foot on a piece of circular foam to enhance neuromuscular control (Figure 18). Lastly, the vertical squat or front lunge can be performed onto foam to stimulate and challenge the neuromuscular system and the hip and knee musculature.

Hip Joint and Trunk Stabilization Enhances Knee Stability

The female athlete generally exhibits a less-developed thigh musculature compared with the male athlete. Thus, the female athlete must incorporate the hip musculature to assist in dynamic stabilization of the knee joint. The exercise drills to enhance hip musculature control include lateral step-overs, lateral lunges, dip walk, and balance beam drills.

Train Athlete to Control Knee Extension

The sixth unique characteristic is that females exhibit greater genu recurvatum and knee laxity compared with male athletes. The rehabilitation goal is to train the athlete to control knee extension and to learn to maintain the “position of stability.” The position of stability is knee flexion between 25° and 30°, with coactivation of the quadriceps, the hamstrings, and the gastrocnemius muscle groups. The specific drills we use to train the athlete to control knee extension are plyometric jumping, bounding drills, and forward and backward step-over drills. The plyometric jumping drills are initiated on a leg press first, then progressed to the flat ground or onto boxes. We usually begin the plyometric jumping with 2-leg jumps progressing to single-leg jumps. The athlete is instructed to land with the knee flexed (Figure 19). If the athlete lands with the knee in extension, the drill is stopped, and the athlete is instructed in proper landing technique. By landing in full knee extension, the stabilizing muscles are less efficient, and the athlete is at risk for an ACL injury. Jump training programs have been advocated to increase performance and decrease injury risk in competitive athletes in jumping sports. Several high school, collegiate, and Olympic sports teams have developed jump training programs.

Hewitt et al reported that male athletes demonstrate 3-fold greater knee-extension movements (hamstring muscle activity) than female athletes when landing from a vertical jump. Additionally, the investigators noted a 22% decrease in peak landing forces in female athletes after an 8-week jump-training program. When performing plyometric training, we strongly encourage the athlete to work on landing techniques. Athletes are instructed to land lightly and softly. The athlete should flex the knees to increase shock absorption when landing. Several authors have stated that a high percentage of ACL injuries

Figure 18. The lateral step-up exercise performed on a proprioceptive device.

Figure 19. A and B, Plyometric jumping drills. B, Note the patient’s knee-flexion position.
occur in jumping sports upon landing.\textsuperscript{72,73} Thus, when performing a plyometric jump training program, proper technique and execution are crucial. Other drills to enhance knee extension control are bounding drills and forward and backward step-over drills. The rehabilitation specialist should carefully analyze the jumping and landing technique for each athlete when performing these drills.

Enhance Neuromuscular Control of the Lower Extremity

The next unique characteristic for the female athlete, and one of the most important, is that the female athlete exhibits less-effective dynamic stabilization patterns. Some authors\textsuperscript{68,74,75} believe the protective mechanisms may not have been developed during the early developmental years in the female athlete compared with the male athlete because of fewer opportunities for the young female athlete. The goals of the training drills are to enhance neuromuscular control of the entire lower extremity and to improve the protective reflexes. The specific rehabilitation drills we use are designed to enhance neuromuscular reaction with perturbation training. The specific drills we employ are squats on a tilt board, walking and side shuffles on a balance beam with resistance cords fixed to the athlete’s waist (Figure 20), and single-leg balancing on a tilt board in the stability position while throwing a ball (Figure 21). Specific perturbation training is performed with the athlete balancing on a tilt board and throwing a ball...
while the clinician rocks the tilt board, creating a perturbation. The athlete must react and restabilize the platform as quickly as possible (Figures 22 and 23). We believe this is one of the best drills to train and enhance muscular reaction and neuromuscular control.

Train to Enhance Muscular Endurance

The eighth and final unique characteristic is the fact that female athletes have been shown to exhibit poorer muscular endurance ratios than male athletes. Once muscular fatigue occurs, proprioception and neuromuscular control diminish significantly. Lattanzio et al. have demonstrated a significant decline in proprioception (joint angle reproduction) function after exercise bouts that resulted in muscular fatigue. Therefore, the female athlete must perform endurance training throughout the rehabilitation program. Exercises such as stair climbing and bicycling performed for long durations are preferred. Weight training using lower weights and higher repetitions should also be implemented. Specific exercises, such as the lateral step-up, front step-down, and front lunge, can be performed using higher repetitions and lower weights to promote muscular endurance. Exercises including knee extensions, leg presses, and vertical squats can be performed with lower weights and higher repetitions to enhance muscular strength. Additionally, we frequently recommend neuromuscular control drills, such as perturbations, at the end of a treatment session, after cardiovascular training. This type of training is performed to challenge the neuromuscular control of the knee joint complex when the dynamic stabilizers have been adequately fatigued.

SUMMARY

The female athlete appears to be more susceptible to ACL injuries than the male athlete. There are many reasons for this increased injury rate. Anatomical differences are obvious, but the subtle neuromuscular differences may be more important when rehabilitating an athlete after ACL surgery. Because of these differences, we have developed 8 special considerations for the female athlete. We recommend that these 8 considerations be taken into account when rehabilitating a female athlete. The goal is to enhance the outcome of the rehabilitation program, but also to provide a preventive program to reduce the incidence of noncontact ACL injuries in the female athlete. We have used the specific rehabilitation drills discussed in this article with early clinical success. We strongly encourage research and critical analyses of these techniques to assist in the development of a program to rehabilitate the female athlete successfully after ACL surgery, but perhaps more critically, to assist in a preventive program to reduce the incidence of noncontact ACL injuries.

REFERENCES

Reactive Neuromuscular Training for the Anterior Cruciate Ligament-Deficient Knee: A Case Report

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Objective: To demonstrate the response to a proprioceptive training model during a 1-week rehabilitation regime. The techniques were demonstrated on a college-aged female basketball player who had injured her anterior cruciate ligament (ACL) several weeks earlier. The athlete was tested, trained, and then retested during her semester break.

Background: The ACL injury has become a fairly common occurrence in the world of athletics. Knowing this, the athletic trainer is constantly searching for ways to improve the rehabilitative process. New research demonstrates that rehabilitation should be based on proprioception. The ACL not only serves a mechanical role by limiting passive knee mobility but also serves a sensory role through the mechanoreceptors deep in its tissue, which communicate with the neuromuscular system to provide proprioceptive feedback during training and competition.

Differential Diagnosis: Partial or complete tear of the ACL.

Treatment: The athlete was treated with a rehabilitation protocol based on proprioception, which uses reactive neuromuscular training.

Uniqueness: Our rehabilitation focused on the muscular imbalances about the hip, knee, and ankle. The athlete achieved dramatic decreases in muscular imbalances about the hip and knee in only 1 week of rehabilitation through reactive neuromuscular training.

Conclusions: The athlete had significant gains in strength over her brief period of therapy. However, these gains can be viewed only as neuromuscular changes and not strictly as gains in strength. The athlete returned to postseason competition under the supervision of her surgeon, who later recommended surgical reconstruction at the completion of the basketball season with rehabilitation during the offseason.

Key Words: oscillating technique for isometric stabilization, impulse technique for isometric stabilization

The anterior cruciate ligament (ACL) injury is commonly managed by orthopaedic surgeons, physical therapists, and athletic trainers. A variety of surgical techniques and rehabilitation protocols is used to treat the ACL injury. It is important to realize, however, that the partial or complete tear of the ACL is, in most cases, the symptom or result of underlying muscular or mechanical imbalances in the lower extremity. These imbalances can be created by traumatic or microtraumatic injuries and can occur with or without contact. Contact injuries, as the name implies, are the result of a collision with another individual or object. The contact injury has no warning signs and no history of symptoms. Noncontact injuries are sustained without contact or when the momentum or movement of the body exceeds muscular control and joint stability, thus exposing the ligament to stress without the coordinated muscular support of the knee. Many underlying problems may have contributing roles in noncontact ACL injuries and stresses, including muscular imbalances of the hip, poor foot mechanics, poor deceleration and plyometric (energy-storing) function, inefficient quadriceps/hamstring ratio, poor acclimation to playing surface, and poor proprioception.1-6 The underlying problem must be identified and addressed during rehabilitation if the athlete is to return to participation at the preinjury level.2-6 With this principle in mind, it is the job of the sports medicine team to find the safest and most efficient path for the athlete that will allow the athlete to return to competition, whether this path is surgical and rehabilitative or strictly rehabilitative. However, the focus must always remain on the cause, not just the symptom.

Remember that not only do structures around the knee joint need to be trained, but other structures in the lower extremity must be trained as well.1,2,5-6 These structures include the musculature about the hip and ankle joints. Damage to the ACL can affect the whole lower extremity as a result of the mechanical imbalances created by the knee.1,6,8-10 The mechanical imbalances, which may predate the noncontact injury and hinder the rehabilitation process, lead the body to make muscular compensations in order to function as normally as possible. These compensations will occur and recur since the body will always sacrifice quality of movement for quantity.1,5
Attention must be given equally in 2 areas that are sometimes overlooked: sport-specific function and motor learning. In order to understand sport-specific function, the clinician must identify the demands of the sport and the abilities of the athlete. Functional exercise programs allow the physical therapist and the athletic trainer to combine conditioning and rehabilitation with activities that increase motor pathway function and reaction time, thus restoring efficient movement through motor programs. An example of this is an exercise program known as reactive neuromuscular training (RNT), first introduced by Voight and Cook and the basis for our ACL exercise regime, which emphasizes kinesthetic or proprioceptive input and places less emphasis on verbal and visual input.

**REACTIVE NEUROMUSCULAR TRAINING**

The theory behind RNT is to emphasize activities designed to minimize the need for verbal and visual instruction from the physical therapist or athletic trainer. This type of training asks only that the athlete respond to a stimulus created by an outside force (eg, being pulled by elastic tubing). The initial emphasis is not on altering strength, but rather on dynamic stability and proprioception, which can be defined as awareness of posture, movement, and changes in equilibrium and the knowledge of position, weight, and resistance of objects in relation to the body, respectively. This type of training focuses on appropriate body positioning and posture to promote proper dynamic muscular stabilization during functional activities, thus allowing for the control of abnormal joint translation during functional activities. These activities are designed to emphasize quality of movement before quantity of movement.

The goal of phase I is to successfully stimulate a proprioceptive reaction for a certain number of repetitions. This should not be attempted until active range of motion is restored. If proprioception and stability training are attempted without a good mobility base, then compensations will be learned and motor programs will be altered. However, with a good mobility base, the correct movements will be learned and will become automatic.

**PRESENTATION OF THE CASE**

Our subject was an ACL-deficient, college-aged female basketball player. Her rehabilitative training regimen followed a progression adapted from the theory of RNT. The athlete began her rehabilitative program with her collegiate certified athletic trainer before her visit to our clinic. The collegiate athletic trainer had succeeded in helping her regain full, active range of motion and basic strength; however, her ballistic movements were awkward.

We were asked by her collegiate athletic trainer to evaluate and treat her over the semester break. The athlete already had a solid rehabilitation foundation before she began her work with us due to her program with her collegiate athletic trainer. We will focus only on the particular treatment we provided in our clinic and the results we achieved over the athlete's semester break.
The athlete was injured during a basketball game on November 7. She reported that her knee twisted and she felt a “pop.” The initial evaluation by the orthopaedist revealed substantial instability and a positive Lachman from a probable ACL tear. The athlete was braced and treated acutely, then allowed to return to activities as tolerated. The goals set by the athlete’s orthopaedic surgeon and collegiate athletic trainer were to have the athlete ready for postseason play with the possibility of reconstructive surgery afterward. We were informed that we would have approximately 5 visits to work with the athlete over the holiday season.

The athlete’s initial rehabilitation program from her collegiate athletic trainer included a variety of strengthening and conditioning activities. On odd days, her workouts consisted of bilateral leg presses, short-arc extensions, lunges, step-ups, eyes-closed unilateral squats, Fitter (Fitter International, Inc, Calgary, AB, Canada) or slide, tubing, and lazy-S running. On even days, the workouts consisted of squats, leg extensions and curls (including isokinetics), walking lunges, step-ups, and lazy-circle running. In addition she was biking, stair climbing, and jogging for cardiorespiratory conditioning.

EVALUATION AND TESTING

On the first visit, we performed a complete evaluation and assessment, including computerized eccentric contraction break tests (J-Tech Power Tracker, Heber City, UT) bilaterally to identify any strength imbalances (Figure 1). We found no point tenderness or lack of range of motion but did find 1 cm of joint effusion when compared bilaterally at the joint lines. The Lachman and anterior drawer sign revealed moderate visible joint laxity. A modified Thomas test was performed bilaterally to evaluate hip mobility (Figure 2). This test is performed by having the athlete sit on the edge of a table; with the support of the athletic trainer or physical therapist, the athlete lies back with both knees drawn up to the chest. One knee is held to the chest (locking out the pelvis and lumbar spine), and the other leg is relaxed off the table edge. If the knee range of motion is less than 90°, the rectus femoris muscle is tight; if the thigh remains elevated (<0° hip extension) above the table, then the iliopsoas muscle is tight. If the thigh and lower leg fall or turn out laterally (external rotation of the tibia or abduction of the femur), the iliotibial band may be tight. If the thigh and lower leg fall or turn out laterally (external rotation of the tibia or abduction of the femur), the iliotibial band may be tight. As confirmed by a computer manual muscle test, this athlete was found to have a tight iliotibial band on the involved side, which is usually indicative of adductor weakness.

Functional testing was performed by means of resisted medial-lateral weight-shift running. The ability to load and unload the extremities was compared bilaterally. This test was
done in order to simulate change-of-direction movements on the court without having to actually perform the movement on a gymnasium floor. Foot contacts were counted over a 15-second period and compared medially and laterally. Closed chain kinesthetic awareness was assessed through a timed, unilateral stance with eyes open and then with eyes closed. Isometric endurance was assessed by a timed, unilateral 90-degree isometric wall squat. A single-leg hop test was used to test strength and power; the distance jumped by each leg was measured.

These functional tests revealed no significant deficits between the involved and the uninvolved sides. We used 10% as the cutoff point for a significant difference between the extremities. This percentage is commonly used, because it allows for unilateral limb dominance.13,14 The fact that functional tests revealed no significant deficits with bilateral comparison was interesting, considering the results of the computer dynamometer test (Table 1). This test confirms the body’s ability, by sacrificing quality movements in order to perform effectively, to make muscular compensations. If we had not analyzed the individual components through the computerized dynamometry, we would have overlooked some of the areas that could have been serving as weak links and could have led to microtraumatic changes over time.

The computer dynamometer test involved hip medial and lateral rotation, hip abduction and adduction, hip flexion and extension, and knee flexion (laterally rotated) and extension. These movements were tested by performing an eccentric break test on the muscle or muscle group. Many muscles in the lower extremity contract eccentrically to help stabilize the knee and hip. The purpose of this type of muscle testing is to isolate these muscles eccentrically, while also providing a comparison between the strength of the muscles surrounding the knee and those surrounding the hip. If the hip movements had not been tested, major weaknesses and muscular imbalances that can increase stress on the knee might have been overlooked. The athlete might have returned to competition with significant hip weaknesses.

The computer dynamometer results revealed significant weakness (>10%) when compared bilaterally in hip medial rotation, hip adduction, and knee flexion (laterally rotated) and knee extension (Table 1). Thus, there was a strength imbalance with regard to medial and lateral stability. (The other muscles tested revealed no significant weaknesses.)

**REHABILITATION AND TRAINING**

Our main focus was to resolve the noted deficits about the involved extremity, while improving knee joint stability, since full mobility had already been obtained. The athlete had also been training mostly in an anterior-posterior plane using isokinetics. Our goal was to now advance her training, gearing it toward multiplanar and functional activities, while continu-
ing to focus on the deficits at hand. We sought to accomplish this through a progression of RNT. It was imperative that our exercises be specific enough to address the imbalances at hand, yet effective during the limited time allotted. We decided that an interval program would accommodate both the athlete’s functional needs and her conditioning concerns. In addition to the clinic program, a complementary home exercise program was established (Table 2).

Our first task was to promote isometric stabilization for static control and posture with the goal of advancing to dynamic stabilization. This was done to decrease the body’s need to compensate for quality movements. Two types of stability techniques, described by Voight and Cook, were chosen to stimulate mechanoreceptor and muscle spindle function in a closed chain situation. The first technique, oscillating technique for isometric stabilization (OTIS), incorporates short, rapid oscillatory movements of an uninvolved body part to promote isometric stabilization of the involved body part. This technique is accomplished by having the arms pull elastic tubing fixed to the wall (Figure 3). This is helpful because the involved leg does not initiate any movement, but has only to react to weight shifting generated by arm movements, thus emphasizing the proprioceptive role of the lower extremity.

A complementary technique, impulse technique for isometric stabilization (ITIS), was performed with a plyoback training aid. ITIS provides for quick and repetitive loading and unloading or impulses within a short arc of movement (Figure 4). The same principle could be applied by throwing a medicine ball with a partner. The correct posture and positioning are imperative so that the involved mechanoreceptors are appropriately stimulated for joint proprioception.

OTIS and ITIS techniques may be applied in different directions to elicit involvement from various muscle groups. For our athlete, based on the imbalances found on the tests, we felt that directional emphasis would accommodate strengthening of the hip medial rotators, hip adductors, tibial medial rotators, and knee extensors. The applicable directions for the OTIS and ITIS techniques place the involved extremity away from the wall or rebounder with the foot at a 45-degree angle. The athlete must overcome rotational forces in this position while focusing on the muscle weaknesses in order to maintain proper posture and position. A foam roll added under the heel further increased musculature involvement in
order to maintain ankle, knee, and hip stability during the exercise (Figure 5).

We then implemented exercises that were progressively dynamic in nature to strengthen the hip and knee musculature while maintaining the athlete’s cardiorespiratory endurance. She was able to immediately begin resistance activities, such as running, bounding, and scissored running, due to the performance scores established on the functional tests. She performed these activities with medial-lateral resistance and anterior-posterior resistance (Figures 6-9). These types of resistance focused on hip medial rotation, hip adduction, knee flexion, and knee extension. We, however, focused more on medial resistance activities in order to emphasize hip medial rotation and adduction, due to the computer dynamometry results.

The third aspect of her training incorporated progressive plyometrics. These movements use the neuromuscular stretch reflex and require greater degrees of dynamic stability than the previously mentioned activities. Activities within this phase also simulate the forces encountered during sport participation. They include plyometric demands, kinesthetic forces, and energy systems demands. The athlete performed plyotaps, or jumping with a graded resistance (Figure 10). This exercise emphasizes eccentric loading and vertical plyometrics. The athlete’s day-to-day training regimen is outlined in Tables 3–6 (Figures 11 and 12).

The fifth visit included the same activities as the fourth visit. The last visit was scheduled solely to retest and review an ongoing home exercise program.

Upon completion of our brief rehabilitation, the manual computer dynamometer muscle tests were repeated. No functional tests were performed because there were no functional deficits during the pretest. The dynamometry posttest revealed some astonishing results: hip medial rotation on the involved side went from being 40% deficient to only 13% deficient, and the knee extension, knee flexion laterally rotated, and hip adduction deficits had resolved (Table 7).

DISCUSSION

We know from past research that improvements in true strength may take several weeks to occur; however, there is some evidence to support substantial gains in what appears to be strength by our subject. These gains often occur within the first 6 weeks with various forms of weight training. The reason for these changes is most often attributed to neuromuscular changes, including better coordination and im-

![Figure 9. Athlete performing resisted bounding with a lateral weight shift.](image)

![Figure 10. Athlete performing plyotaps on Shuttle 2000 (Contemporary Design Co, Glacier, WA).](image)

Table 3. Training Regime for Day 1

<table>
<thead>
<tr>
<th>Exercise</th>
<th>Sets</th>
<th>Repetitions or Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Walking: warm-up to 2.46 m/s jog on treadmill</td>
<td>1</td>
<td>5 min</td>
</tr>
<tr>
<td>2) Flexibility routine on BackSystem3</td>
<td>1</td>
<td>10 repetitions each</td>
</tr>
<tr>
<td>3) Review of home program</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
proved recruitment. The human body has the inherent ability to recognize and react to movements that it identifies as familiar or patterned, which may be stored in muscle memory. The stability exercises that we chose for rehabilitation use similar movement patterns and allow the body to react appropriately with little compensatory activity. By implementing appropriate purpose, posture, positioning, and patterning, we can more efficiently affect the athlete’s state of functioning. Since we treated the athlete only over an 8-day period, her progress and testing results would seem to

Table 4. Training Regime for Day 2

<table>
<thead>
<tr>
<th>Exercise</th>
<th>Sets</th>
<th>Repetitions or Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Walking: warm-up to 2.46 m/s jog (interval jog between activities)</td>
<td>1</td>
<td>5 min</td>
</tr>
<tr>
<td>2) Flexibility routine on BackSystem3</td>
<td>1</td>
<td>10 repetitions each</td>
</tr>
<tr>
<td>3) ITIS unilateral in plantar flexion</td>
<td>3 (4 directions)</td>
<td>30 repetitions</td>
</tr>
<tr>
<td>4) OTIS unilateral in plantar flexion</td>
<td>3 (4 directions)</td>
<td>30 repetitions</td>
</tr>
<tr>
<td>5) Resisted running</td>
<td>3</td>
<td>15 s</td>
</tr>
<tr>
<td>6) Leg press bilaterally, 8 cords</td>
<td>3</td>
<td>20 repetitions</td>
</tr>
<tr>
<td>7) Plyotaps (eccentric loading) bilaterally, 8 cords</td>
<td>3</td>
<td>20 repetitions</td>
</tr>
<tr>
<td>8) Cool-down after 2.46 m/s jog</td>
<td>1</td>
<td>5 min</td>
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</table>

Table 5. Training Regime for Day 3

<table>
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<tr>
<th>Exercise</th>
<th>Sets</th>
<th>Repetitions or Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Walking warm-up to 2.46 m/s jog (interval jog between each activity)</td>
<td>1</td>
<td>5 min</td>
</tr>
<tr>
<td>2) Flexibility routine on BackSystem3</td>
<td>1</td>
<td>10 repetitions each</td>
</tr>
<tr>
<td>3) ITIS unilateral in plantar flexion</td>
<td>3 (4 directions)</td>
<td>30 repetitions</td>
</tr>
<tr>
<td>4) OTIS unilateral in plantar flexion</td>
<td>3 (4 directions)</td>
<td>30 repetitions</td>
</tr>
<tr>
<td>5) Resisted bounding</td>
<td>3</td>
<td>15 s</td>
</tr>
<tr>
<td>6) Plyotaps (eccentric loading) bilaterally, 8 cords</td>
<td>3</td>
<td>20 repetitions</td>
</tr>
<tr>
<td>7) Unilateral wall squats, 90° knee flexion</td>
<td>3</td>
<td>20 repetitions</td>
</tr>
<tr>
<td>8) Cool-down after 2.46 m/s jog</td>
<td>1</td>
<td>5 min</td>
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Table 6. Training Regime for Day 4

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<th>Exercise</th>
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<td>1) Walking warm-up to 2.46 m/s jog (interval jog between each activity)</td>
<td>1</td>
<td>5 min</td>
</tr>
<tr>
<td>2) Flexibility routine on BackSystem3</td>
<td>1</td>
<td>10 repetitions each</td>
</tr>
<tr>
<td>3) ITIS unilateral in plantar flexion</td>
<td>3 (4 directions)</td>
<td>30 repetitions</td>
</tr>
<tr>
<td>4) OTIS unilateral in plantar flexion</td>
<td>3 (4 directions)</td>
<td>30 repetitions</td>
</tr>
<tr>
<td>5) Resisted scissored running</td>
<td>3</td>
<td>15 s</td>
</tr>
<tr>
<td>6) Plyotaps (eccentric loading) bilaterally, 8 cords</td>
<td>3</td>
<td>20 repetitions</td>
</tr>
<tr>
<td>7) Unilateral wall squats, 90° knee flexion</td>
<td>3</td>
<td>20 s</td>
</tr>
<tr>
<td>8) Cool-down after 2.46 m/s jog</td>
<td>1</td>
<td>5 min</td>
</tr>
</tbody>
</table>

Table 7. Computer Dynamometer Test Comparing Right and Left Lower Extremities, December 27 (Refer to Table 1)

<table>
<thead>
<tr>
<th>Exercise</th>
<th>Left (kg)</th>
<th>Right (kg)</th>
<th>Deficit (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip medial rotation</td>
<td>12.70</td>
<td>10.89</td>
<td>-13 R*</td>
</tr>
<tr>
<td>Hip adduction</td>
<td>26.31</td>
<td>25.85</td>
<td>-3 R</td>
</tr>
<tr>
<td>Knee flexion (lateral rotation)</td>
<td>21.32</td>
<td>21.32</td>
<td>0</td>
</tr>
<tr>
<td>Knee extension</td>
<td>31.75</td>
<td>29.03</td>
<td>-9 R</td>
</tr>
</tbody>
</table>

* R, right leg (the involved side).
indicate neuromuscular adaptations and not just improved strength. The athlete already had a well-established rehabilitation program, focusing on uniplanar movements, such as flexion-extension isokinetics and leg presses. Our focus was on multiplanar movements, focusing on the hip musculature imbalances. We felt that by shifting our focus to more medial-lateral and rotational-type activities, we could place the athlete in a more functional position while addressing the noted deficits.

The ability to identify the hip muscular imbalances and then use a more multiplanar and sport-specific training model provided the athlete with a more solid foundation for postseason competition. If these imbalances had not been identified, she would have continued to sacrifice knee stability to compensate for hip muscular imbalances. This might have led to more knee and hip problems and a longer rehabilitation after surgery.

The athlete did return to competition and completed a successful season. She continued to train throughout the remainder of the season using her home exercise program. At the end of the season, she underwent reconstruction and was then rehabilitated by her collegiate athletic trainer. The athlete had an excellent recovery after surgery with a continuation of her previous rehabilitation protocol. We believe that the RNT techniques applied before surgery helped to eliminate some of the primary imbalances that could have led to a more complicated and less active recovery. Also, the athlete’s diligent work ethic should be given credit in collaboration with our training program. She did everything we asked of her and was extremely compliant with her independent home program.

REFERENCES


**Abstracts**

**Background and Purpose:** The purpose of this case report is to describe the evaluation, treatment, and short-term outcome for an individual with chronic, progressively worsening instability of the knee during gait associated with anterior cruciate ligament (ACL) insufficiency. Case Description: The patient was a 34-year-old man who sustained bilateral ACL injuries. Subsequently, an autograft reconstruction of the left knee ACL was performed. Eight months post-reconstruction, the left knee was unstable despite bracing. Gait analysis and tests to determine the presence of muscle inhibition were performed before and after 12 weeks of training. Isometric torque of the knee extensors and flexors was measured with the knee in 90° of flexion. A training program primarily consisted of electromyographic biofeedback during thigh muscle exercises, balance exercises, and gait. Outcomes: Muscle inhibition decreased and maximal isometric knee flexion and extension torques increased during the 12-week training period. Gait analysis demonstrated a 50% decrease in the maximum knee extensor moment and an increase in walking speed. Discussion: Selected gait variables, torque production, and muscle inhibition may change in a person with an unstable knee. The measurement of variables that have previously been documented as mechanisms of knee instability during walking allows for the selection of a specific treatment approach.

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There is a dearth of reliable and valid instrumentation that measures disability following injury and/or surgery of the knee joint that is responsive to clinically significant changes over time. The purpose of this investigation was to determine whether performance-based or patient-reported measures of function are more effective in estimating disability in individuals with an anterior-cruciate-ligament (ACL)-deficient knee. Subjective rating of knee function was used as the criterion measure for disability, and selected performance-based and patient-reported measures were used as estimation variables. Twenty-nine individuals with an ACL-deficient knee participated in this investigation. Step-wise regression analysis revealed that the Cincinnati Knee Scale, Lysholm Knee Scale, and hop index were the most effective estimates of disability. The results demonstrate that patient-reported measures are more related to the patient’s level of disability in individuals with an ACL-deficient knee. More research is necessary to substantiate these findings.

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Loss of motion and knee extension weakness are recognized as significant complications following anterior cruciate ligament (ACL) reconstruction. The purpose of this study was to determine 1) what degree of preoperative motion loss represents a risk for postoperative motion problems and 2) if preoperative weakness (deficit ≥ 20%) affects return of strength following surgery. Measurements of range of motion and strength were made on 102 patients (56 men, 46 women; age = 31 ± 1 years) within 2 weeks before ACL reconstruction (preop) and repeated 6 months following surgery (postop). Thirteen of 40 patients (33%) lacking ≥ 5° preop, 8 of 20 patients (40%) lacking 1°–4° preop, and 3 of 42 (7%) patients with full extension preop had ≥ 5° loss 6 months postop (*P < .001*). Thirty-two of 39 (82%) patients with normal strength preop had weakness 6 months postop. Forty of 51 (78%) patients with preop knee extension weakness still had weakness 6 months postop. Preop strength was not a good predictor of residual weakness following ACL reconstruction. The magnitude of the preop extension loss appears not to be a risk factor. It is the presence or absence of full extension equal to the contralateral leg that identifies risk for postop problems regaining extension.

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Efforts to minimize the morbidity of anterior cruciate ligament (ACL) reconstruction include the use of cryotherapy and/or compressive dressings in the immediate postoperative period. We undertook our study to determine if the alleged benefits of the Cryo/Cuff, which combines these modalities, are more attributable to its compressive effect rather than cold application. Seventy-eight patients admitted for primary endoscopic ACL reconstruction using a bone-patella tendon-bone autograft were randomized to receive Cryo/Cuff compressive dressings postoperatively. Forty subjects (Group 1)
had the cuff applied with continuous circulating ice water using the Autochill device, while 38 others (Group 2) received the cuff with room temperature water. Cases were performed as inpatients, and all subjects were administered intravenous morphine postoperatively via a patient-controlled infusion pump for the first 24 postoperative hours. At baseline, the groups were well matched in age, sex, duration of symptoms, operative time, and associated meniscal surgery. No significant difference between groups was detected with respect to length of hospitalization, Hemovac knee drainage, oral and intravenous narcotic requirement, or subjective pain as measured by a visual analog scale. No apparent complications related to the use of the Cryo/Cuff dressings were noted. The clinical effect of the Cryo/Cuff in this study was not influenced by the use of continuous ice water versus room temperature water. Further study should focus on variations in compression to evaluate the clinical impact of this device.


Rehabilitation following anterior cruciate ligament (ACL) reconstruction is varied. Patients are usually prescribed an independent home exercise program, although some patients may attend physical therapy for additional supervised exercise. It is not known whether additional supervised exercise provides any further benefit. The purpose of this study was to compare efficacy for two types of rehabilitation following ACL reconstruction. A randomized controlled trial of 31 ACL-reconstructed patients was used to test the hypothesis that a home program plus supervised rehabilitation (Group S) is more effective than a home program (Group H) alone. Function, activity level, anterior tibial translation, and muscle strength were measured preoperatively and at 3 and 6 months postoperatively. Improvement of function, activity level, muscle strength, and anterior tibial translation was evident in both groups, but no significant differences were found between groups even though the sample size was sufficient to detect small treatment effects. It was concluded that supervised exercise, in addition to a home program, has minimal extra benefit for patients who have undergone ACL reconstruction.


Health care reform will quite possibly change the delivery of physical therapy by demanding physical therapists to be more accountable for providing appropriate, yet cost-effective treatment. The purpose of this study was to retrospectively compare the results after anterior cruciate ligament (ACL) reconstruction between two groups of patients with different numbers and frequencies of physical therapy visits postoperatively. Two random samples of 100 patients from a total of 1345 patients identified as undergoing ACL reconstruction from 1990 through 1993 were included. Group A patients attended physical therapy regularly and participated in a home exercise program, while patients in Group B attended limited physical therapy visits and also performed a prescribed home exercise program. Both groups followed the same postoperative rehabilitation program for early range of motion, early weight bearing, and muscle control. The outcome variables measured 1, 6, and 12 months postoperatively included the number of structured visits to physical therapy, range of motion, isokinetic strength testing, and subjective rating. There was a significant difference for hyperextension (Group A, 2°; Group B, 6°). The results of this investigation indicated that, following a structured physical therapy program postoperatively, it is possible for patients to achieve a successful outcome with a limited number of routine physical therapy visits.


Anterior displacement of the tibia during knee extension movement has been identified as a possible factor in anterior cruciate ligament (ACL) reconstruction failure due to the increased stress placed on the graft, leading to a creep response in the healing graft. Nineteen healthy subjects with a unilateral ACL deficiency were evaluated in an open and closed kinetic chain. A KT-1000 was used to measure anterior displacement of the tibia on the femur during isometric open and closed kinetic chain exercise at 30° and 60°. An analysis of variance for repeated measures followed by Newman-Keuls multiple comparison tests were performed to determine the differences between the open and closed kinetic chain for the involved and uninvolved knee. Statistically significant differences were found when comparing the amount of anterior displacement between the open and closed kinetic chain for the involved and uninvolved knee at 30° and 60°. Clinicians utilizing isometric exercise in rehabilitation of the anterior-cruciate-deficient and the anterior-cruciate-reconstructed patient should be aware of the increased amount of anterior tibial displacement when comparing open and closed kinetic chain exercise.


Study Design: Single group repeated measures following anterior cruciate ligament (ACL) reconstruction. Objectives: The purpose of this study was to evaluate the intrarater reliability of selected clinical outcome measures in patients having ACL reconstruction. Background: Several investigations have reported the reliability of isokinetic testing and knee ligament arthrometry. Fewer studies have examined the reliability of lower extremity functional tests, with most of these studies evaluating normal subjects. Methods and Measures: Fifteen physically active males with unilateral ACL-reconstructed knees were evaluated with the KT-1000, Biodex isokinetic dynamometer, and 3 functional hop tests on 5 occasions. Results: Intraclass correlation coefficients (ICCs) revealed good to high intrarater reliability (ICC > 0.80) of the functional hop tests and isokinetic peak torque values. ICCs were higher for the involved limb than the uninvolved limb using the scores from the KT-1000 Manual Maximum Test. Conclusions: The outcome measures examined in this investigation have been shown to be reliable in patients with ACL reconstructions and support previous investigations in nonimpaired populations. Further research is needed to examine the validity of these postoperative outcome measures in patients with ACL reconstructions.


Study Design: Single group repeated measures with multiple raters. Objectives: To determine the intrarater reliability of KT-1000 measurements of novice and experienced raters and to provide error estimates for these raters. Background: The KT-1000 arthrometer is often used clinically to quantify anterior tibial displacement. Few data have been documented, however, about the relative reliability of KT-1000 measurements obtained by novice compared with experienced users. Methods and Measures: Two novice and two experienced KT-1000 users performed measurements on 29 knees of 25 patients after anterior cruciate ligament (ACL) reconstruction or with a diagnosis of ACL deficiency. Measurements were performed at 131 N. Interrater and intrarater reliability coefficients (interclass correlation coefficient; ICC) and the standard error of measurement were calculated for expert and novice raters. Results: The interrater ICC for novices was 0.65 and the interrater error was ±3.52 mm (90% confidence interval [CI]). The interrater ICC for experts was 0.79 and the interrater error was ±2.94 mm (90% CI). Conclusions: These results suggest that experience in using the KT-1000 is related to the interrater error of measurements and that training is an important consideration when using the KT-1000 arthrometer.


Purpose: The purpose of this study was to determine the relationship among laxity, quadriceps strength, instability, and function in subjects with complete rupture of the anterior cruciate ligament (ACL) who compensate well for the injury (copers) and those who require surgical stabilization (noncopers). Methods: Forty-five patients with unilateral ACL rupture (confirmed via arthroscopy or magnetic resonance imaging [MRI] and arthrometer measurements) participated in this study. Subjects were divided into two groups: copers (n = 12), and subacute noncopers (n = 18) and chronic noncopers (n = 15). All copers had returned to all preinjury activity (including index sport) without limitation. Maximum manual anterior tibiofemoral laxity measurements, quadriceps femorius muscle strength measurements, and a series of hop tests were performed. Lysholm Scale, Knee Outcome Survey (KOS), global rating of knee function, and the International Knee Documentation Committee (IKDC) form were completed. Results: There was no significant difference in laxity between copers (avg = 5.5 ± 2.7 mm) and noncopers (chronic, avg = 5.1 ± 2.8 mm and subacute, avg = 4.2 ± 2.2 mm) or in IKDC scores among the groups. The copers, however, scored significantly better than the chronic and subacute ACL-deficient subsets on all other measures. Measurements of laxity were not correlated to any functional outcome measure or to episodes of instability. Conclusions: Copers were not different in any meaningful way from noncopers before injury, had equal or greater side-to-side laxity differences, and functioned normally. A battery of tests was identified that accurately discriminated noncopers from copers even early after injury. Thus, measurements of laxity alone are insufficient for determining functional status after ACL injury.


Purpose: Accelerated rehabilitation for anterior cruciate ligament (ACL) injury and reconstruction surgery is designed to return injured people to athletic activities in approximately 6 months. The small amount of empirical data on this population suggests, however, that the torque at the knee joint may not return until 22 months after surgery during walking and even longer during running. Although the rehabilitation has ended and individuals have returned to preinjury activities, gait mechanics ap-
jury, 5.8 ± 5.3 years) performed an and the other at an intensity above LT constant load 20-minute tests, one at an intensity below lactate threshold (bLT),

ters during treadmill running. Methods: Eight ACL-injured and 22 healthy subjects were tested. Injured subjects were tested 3 weeks and 6 months (the end of rehabilitation) after surgery. Ground reaction force and kinematic data were combined with inverse dynamics to predict sagittal plane joint torques and powers from which angular impulse and work were derived. Results: The
differences between the two tests for the ACL group averaged 38% (all P < .05). The
matics were not different between the ACL group after rehabilitation and healthy subjects. Angular impulses and work averaged 100% difference for all joints (all P < .05) between tests for the ACL group. After rehabilitation, the differences between injured and healthy groups in angular impulse and work at both the hip and knee remained large and averaged 52% (all P < .05). Conclusions: Results indicated that after reconstruction surgery and accelerated rehabilitation for ACL injury, humans walk with normal kinematic patterns but continue to use altered joint torque and power patterns.

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Purpose: To assess the effects of a functional knee brace (FKB) for anterior cruciate ligament insufficiency (ACL) on physiological and perceptual parameters during treadmill running. Methods: Thirteen ACL injured subjects (time since injury, 5.8 ± 5.3 years) performed an incremental test to exhaustion and two constant load 20-minute tests, one at an intensity below lactate threshold (bLT), and the other at an intensity above LT (aLT) each with and without their FKB. Results: Bracing had no effect on peak variables except for higher ratings of perceived exertion at the legs (RPE-L) at the velocities associated with a blood lactate concentration [HLa] of 4.0 mm and at peak. Bracing had no effect when exercising at bLT but did significantly alter the metabolic profile developed during the performance of the aLT tests (83 ± 0.03% VO2peak). In particular, FKB resulted in elevated blood [HLa] (23%), VO2 (4%), VE (12%), VCO2 [corrected](7%), and VE/VO2 (7%). HR and slow component VO2 did not differ between the brace and no brace aLT tests. RPE-L and RPE-knee were significantly elevated during aLT when the brace was worn. Suspected mechanisms include alterations in muscle recruitment patterns and/or occlusion. Conclusions: When ACL injured individuals wear a FKB during high intensity straight-ahead running exercise of long duration, physiological parameters are affected.

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Static anterior-posterior (AP) laxity is one of the commonly used criteria in selecting patients for cruciate ligament reconstructions, but, in reality, dynamic AP laxity plays a more important role. The aim of this in vivo study was to compare the sagittal translation of the knee during active and passive motion, signifying dynamic AP laxity, with static AP laxity in healthy subjects (controls) and patients with anterior cruciate ligament deficiency. The sagittal plane knee translations were recorded and compared in both knees of nine healthy subjects (Controls) and seven patients with confirmed unilateral ACL deficiency during dynamic and static situations with an electrogoniometer system. In all groups during the ascents, the tibia moved anteriorly in relation to the femur, whereas, during the descents, it moved posteriorly. The static anterior-posterior translation was significantly smaller in the control knee than in both healthy and injured knees of the ACL-deficient group (P < .05). The injured knee showed the same laxity (92%) as the uninjured knee during dynamic activities, but it was 46% of static laxity. Also in the injured knees, the dynamic active laxity was larger during descents than ascents (P < .05). The results indicate that there is also a change in mechanics of the noninjured knee following injury to the contralateral knee and that this population of patients with ACL deficiency had good control over their abnormal anterior-posterior laxity.

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Gait analyses of rehabilitated individuals with anterior cruciate ligament (ACL) deficiency and reconstruction have identified the final adaptations of increased hip extensor torque and hamstring electromyography (EMG) and decreased knee extensor torque and quadriceps EMG during stance. The initial adaptations to injury and surgery are, however, unknown as are the factors that influence the development of the adaptations. Identification of the initial response to injury would provide a basis for determining whether the final adaptations are learned automatically or if they are the result of a lengthy training period in which various factors may affect their development. The purpose of the study was to evaluate the initial effects of ACL injury and reconstruction surgery on joint kinematics, kinetics, and energetics, during walking. Injured limbs from nine subjects with ACL injury were tested 2 weeks after injury, and 3 and 5 weeks after surgery. Ten healthy subjects were tested. Kinematic and ground reaction data were collected and combined with inverse dynamics to calculate the joint torques and powers. A knee exten-

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sor torque throughout most of stance was observed in the injured limbs at all test sessions. This result was in conflict with previous observations of reduced extensor torque or a flexor torque in rehabilitated patients with ACL reconstruction and patients with ACL deficiency. This result also differed from the typical midstance extensor then flexor torque in healthy control subjects. Trend analysis showed a significant ($P < .001$) change in average position at the hip and knee, extensor angular impulse at the hip, and positive work done at the hip 3 weeks after surgery followed by a partial rehabilitation at 5 weeks after surgery. Power and work produced at the knee were reduced 5-fold ($P < .001$) after 5 weeks of rehabilitation and did not recover to presurgical levels. The existence of a long-lasting knee extensor torque 2 weeks after injury indicated that the adaptation process to ACL deficiency is lengthy, requiring many gait cycles, and that numerous factors could be involved in learning the adaptations.

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Functional braces are often used as part of a comprehensive rehabilitation protocol following ligamentous injury of the knee. One of the common problems of a functional knee brace is distal migration. This study was undertaken to identify the migration tendencies of 14 commonly used functional knee braces and the design and measurement characteristics that contribute to migration. Two subjects performed 15 minutes of exercise (5 minutes each on a treadmill, slide board, and stair machine), and brace position was measured preexercise and postrereXercise. All 14 braces migrated somewhat. Nine of the braces had migration of less than 5 mm and were considered superior. The brace design (active or passive) had a significant effect ($P < .05$) on migration. No difference ($P > .05$) was noted for brace type (custom versus off the shelf) or fit method (cast versus measuring tool). Based upon this evaluation, an active brace design is recommended for functional knee braces.

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The records of 141 consecutive patients with confirmed complete anterior cruciate ligament injuries were reviewed retrospectively. One hundred and sixty-two associated injuries were divided into 25 injury complexes. Isolated injuries to the anterior cruciate ligament occurred in 40 cases (28.4%). Injuries of the medial meniscus occurred in 62 cases (38.2%), while injuries of the lateral meniscus occurred in 37 cases (22.8%). Injuries to the medial collateral ligament complex occurred in 42 cases (25.9%). Injuries to the lateral collateral ligament, posterior deep popliteus-arcuate ligament, and posterior cruciate ligament were found to be positively correlated ($\rho = 0.81, P = .001$, and $\rho = 0.77, P = .001$, respectively). Injuries to the medial collateral ligament and the posterior oblique ligament were likewise positively correlated ($\rho = 0.45, P = .001, n = 141$).

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Due to the likelihood of hamstring dysfunction associated with anterior cruciate ligament (ACL) injury, it is clinically significant to determine if a hamstring weakness exists preoperatively. The purpose of this study was to determine if a hamstring muscle deficit existed at the time of surgery and to determine the time necessary to achieve hamstring strength equal to preoperative measures of the uninvolved extremity during postoperative rehabilitation. Twelve patients who underwent ACL reconstruction using a patellar tendon autograft participated. Each subject underwent a preoperative isometric knee strength evaluation at 60° of knee flexion. Each subject underwent postoperative rehabilitation including hamstring muscle strengthening. Repeat isometric testing was performed on each subject at 21 and 42 days postoperative. There was no statistical difference in hamstring muscle strength, as measured by isometric peak torque, either preoperatively or postoperatively. Therefore, maintaining rather than increasing hamstring strength postoperatively should be emphasized as an integral part of rehabilitation.

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Athletes are particularly at risk for anterior cruciate ligament injury, and there is some evidence that female athletes are more at risk than males. The conflicting principles of stability and mobility are at odds within the knee, setting the stage for potentially serious injuries. Some investigators suggest that the size of the intercondylar notch should be used to identify athletes at risk for ACL damage, but more research is required before clinical decisions can be based on notch width measurements. Athletic shoe modifications and artificial playing surfaces may influence the incidence of ACL injuries. Functional knee braces appear to have beneficial strain shielding effect on the ACL for anterior directed loads and internal-external torques applied to the tibia, but this effect appears to decrease as the magnitude of these anterior directed loads and torques increases. Ski equipment is often pointed to as a contributing factor in ACL injuries, but there is no evidence that modifications in ski equipment will decrease ACL disruptions. An education program based on recognizing the events that lead to ACL injury in skiing may reduce knee injuries in the future.


The high rate of noncontact ACL injuries in female athletes has become a prominent and controversial subject. This article attempts to provide insight into this trend in athletic injuries. Anatomic, physiological, and biomechanical differences are discussed as possible causative factors. Epidemiological data regarding ACL injuries are reviewed, comparing the genders. The discussion also includes anecdotal findings that support current research. This review is intended to raise awareness of the problem and promote screening for risk factors and implementation of more thorough and aggressive preventive programs.

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Closed kinetic chain exercise has become popular in rehabilitation of the ACL patient. While many clinicians agree on the benefits of closed kinetic chain exercise, there is a great discrepancy as to which exercises fit this category. This discrepancy stems from the fact that the kinetic chain concept was originally developed using mechanical engineering concepts and not human kinesiology. In this paper, the kinetic chain concept is redefined in a continuum of lower extremity exercises from closed kinetic chain to open kinetic chain. The placement of an exercise in this continuum is based upon joint kinematics, quadriceps and hamstring muscle activity, cruciate ligament stress, and joint weight bearing load. An understanding of these factors can help the clinician design a comprehensive and effective rehabilitation program for the ACL patient.

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Rehabilitation following intra-articular anterior cruciate ligament (ACL) reconstruction has undergone a dramatic evolution during the last decade. This paper describes our accelerated rehabilitation program, which is divided into four phases. The preoperative phase begins immediately after injury and emphasizes control of swelling and restoration of full range of motion (ROM) and strength before surgery. Phase II, which includes the first 5 weeks after surgery, emphasizes helping the patient obtain full terminal knee extension and weight bearing. The final 2 phases focus on improving lower extremity strength and full return to daily and athletic activities. This accelerated program has resulted in an earlier return of ROM and strength as well as a decrease in postoperative procedures, without compromising ligamentous stability.

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This article provides the basis for development of an evaluation-based protocol of the anterior cruciate ligament (ACL). The historical background for ACL protocols is reviewed, and the foundation for protocol development is described. Crucial to the design of a rehabilitation protocol are basic science components, including surgical technique, biomechanics of exercise application, soft tissue healing response, articular cartilage response to injury and surgery, and evaluation fundamentals. The evaluation-based protocol was designed to account for patient variation through a hierarchy approach to exercise and functional levels. To assess the effectiveness of this approach, data are provided that support this protocol format. The outcome data are consistent with data found in the literature. It is concluded that rehabilitation must revolve around intrinsic patient variables, rather than the extrinsic independent variables.

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Anterior cruciate ligament (ACL) injury disrupts static and dynamic knee restraints, compromising functional stability. Deafferentation of ACL mechanoreceptors alters the spinal reflex pathways to motor nerves and muscle spindles in addition to the cortical pathways for conscious and unconscious appreciation of proprioception and kines-
thesis. The pathways are required by the feed-forward and feedback neuromuscular control systems to dynamically stabilize joints. Feed-forward motor control is responsible for preparatory muscle activity, while feedback motor control regulates reactive muscle activity. The level of muscle activation, preparatory or reactive, influences muscular stiffness, thereby providing dynamic restraint for the ACL-deficient athlete. Rehabilitation protocols should incorporate activities that enhance muscle stiffness while encouraging adaptations to peripheral afferents, spinal reflexes, and cortical motor patterns. Four elements crucial for reestablishing neuromuscular control and functional stability are proprioceptive and kinesthetic awareness, dynamic stability, preparatory and reactive muscle characteristics, and conscious and unconscious functional motor patterns.

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The purpose of this study was to determine the effects of preoperative, intraoperative, and postoperative intervention on the incidence of loss of motion (LOM) following ACL reconstruction. A retrospective review of patients undergoing ACL reconstruction between 1990 and 1991 was conducted to identify those with LOM. Factors potentially related to loss of motion were recorded. The results were compared with the findings of a similar group of patients who underwent ACL reconstruction between 1987 and 1989. From 1990 to 1991, less concomitant ligament surgery was performed, the incidence of loss of extension was significantly reduced, and the incidence of loss of flexion was significantly increased. It appears the risk for loss of extension can be minimized by delaying surgery following acute injury, performing less concomitant ligament surgery, paying meticulous attention to notch plasty and anatomical placement of the graft, and placing early emphasis on restoration of full extension following surgery.

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The purpose of our prospective, randomized, clinical trial was to evaluate the effect of knee bracing after anterior cruciate ligament reconstruction. Sixty patients were randomized into 1 of 2 groups: patients in the braced group wore rehabilitative braces for 2 weeks, followed by functional braces for 10 weeks, and patients in the nonbraced group did not wear braces. Data were recorded preoperatively and postoperatively at 6 weeks, 3 and 6 months, and 1 and 2 years. The following outcome measures were used: KT-1000 arthrometer, the Cincinnati knee score, goniometry to record range of motion, computed tomography to determine thigh atrophy, Cybex 6000 isokinetic testing to evaluate muscle strength, 3 functional knee tests, and a visual analog scale to evaluate pain. At all follow-up times, there were no significant differences between the 2 groups with regard to knee joint laxity, range of motion, muscle strength, functional knee tests, or pain. However, the Cincinnati knee score showed that patients in the braced group had significantly improved knee function compared with patients in the nonbraced group at the 3-month follow-up, even though the braced group showed significantly increased thigh atrophy compared with the nonbraced group at 3 months.

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Twenty patients with anterior cruciate ligament-deficient knees were studied. Ten patients returned to all sports activities (compensators) and 10 patients were not improved with nonoperative management and required surgical stabilization (noncompensators). Joint laxity was measured using a KT-2000 arthrom-
eter (manual maximum Lachman). Subjects completed a Lysholm questionnaire and Knee Outcome Score. The International Knee Documentation Committee form was also completed. Patients also rated their knee function on a scale of 1 to 100. There was no difference in level and frequency of athletic activity between the 2 groups before their anterior cruciate ligament injuries as determined by the knee outcome score. The compensator group had a mean side-to-side difference of 3.25 mm at 89 N and the noncompensators had a mean difference of 3 mm preoperatively. Manual maximum tests gave side-to-side differences of 6.7 mm for the compensators and 6 mm for the noncompensators. There were no differences in laxity measures between groups. The correlation between knee outcome scores and side-to-side laxity measurements was not significant. Measurements of anterior laxity in anterior cruciate ligament-deficient patients were not correlated with measures of functional outcome used in this study. Functional outcome measurements that are partially based on joint laxity measures, such as the International Knee Documentation Committee form, may artificially overestimate the disability after anterior cruciate ligament rupture.

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We studied 6 adult male dogs to determine whether free patellar tendon grafts show evidence of reinnervation when used for anterior cruciate ligament reconstruction. Histologic return of neural elements and return of a somatosensory-evoked potential defined evidence of reinnervation. Before removal, the native anterior cruciate ligament was electrically stimulated with a bipolar electrode, and a somatosensory-evoked potential was recorded from a scalp electrode. The ligament was excised and reconstructed using an autogenous patellar tendon graft. Somatosensory-evoked potential was attempted immediately after reconstruction. Histology for nerve endings was performed on the native ligaments. Each animal underwent repeat arthroscopy 6 months later. The grafts were isolated and somatosensory-evoked potentials were attempted. An evoked potential was seen in all 6 dogs before reconstruction. No graft demonstrated a somatosensory-evoked potential acutely; however, 6 months postoperatively, the somatosensory-evoked potential returned in 2 cases. Histology of native ligaments showed that 25% of the 100 sections evaluated contained neural elements. Of the receptors present, 89% were mechanoreceptors and 11% were free nerve endings. Histologic examination of the graft tissue 6 months postoperatively revealed that all 6 grafts also contained neural elements. Mechanoreceptors and free nerve endings were present in approximately equal numbers in the grafts. The results of histology and somatosensory-evoked potential demonstrate that, in at least some cases, free patellar tendon grafts show evidence of reinnervation when used for anterior cruciate ligament reconstruction.

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We performed quantitative analysis of synovial fibrosis in the infrapatellar fat pad in 26 patients who underwent arthroscopically assisted anterior cruciate ligament reconstructions. Twelve patients underwent reconstruction with patellar tendon autografts, and 14 had reconstructions with semitendinosus and gracilis tendon autografts. Synovial samples were obtained at the time of reconstruction from 10 patients and at second-look arthroscopy from all 26 patients. Sections from quick-frozen samples were stained with either hematoxylin and eosin or Fast green and Sirius red. We used sodium hydroxide in absolute methanol to elute the Fast green and Sirius red stains, and the total collagen content of each section was estimated by measuring the optical density of the eluted solution. The volume of each section was determined on a computer using an imaging program, and collagen content per unit of tissue was calculated. Median collagen content was 15.3 µg/mm³ for the preoperative samples, 25.1 µg/mm³ for the group with patellar tendon autografts, and 27.1 µg/mm³ for the group with hamstring tendon autografts. Analysis of preoperative and postoperative paired samples revealed a significant increase in synovial collagen after anterior cruciate ligament reconstruction. We observed increased fibrosis in patients who had pain on exertion or stiffness in squatting after the reconstructive surgery.

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Restoring knee stability through reconstruction, while providing symptomatic relief, has not been shown to decrease the incidence of degenerative changes after rupture of the anterior cruciate ligament. This suggests that post-traumatic osteoarthritis may not be purely biomechanical in origin, but also biochemical. To test this, we measured the levels of 7 cytokine modulators of cartilage metabolism in knee joint synovial fluid after anterior cruciate ligament rupture. We also measured keratan sulfate, a product of articular cartilage metabolism. The sample population consisted of patients with uninjured knee joints (n = 10), and patients with acute (n = 60), subacute (n = 18), and chronic (n = 8) anterior cruciate ligament-deficient knees. Synovial fluid samples were analyzed by enzyme-linked immunosorbent assays. Normal synovial fluids contained high levels of the interleukin-1 receptor antagonist but low concentrations of other cytokines. Immediately
after ligament rupture, there were large increases in interleukins 6 and 8, tumor necrosis factor \( \alpha \), and keratan sulfate. Interleukin-1 levels remained low throughout the course. As the injury became subacute and then chronic, interleukin-6, tumor necrosis factor-\( \alpha \), and keratan sulfate levels fell but remained considerably elevated 3 months after injury. Concentrations of interleukin-1Ra fell dramatically. Granulocyte-macrophage colony-stimulating factor concentrations were normal acutely and subacutely but, by 3 months after injury, were elevated 10-fold. Our data reveal a persistent and evolving disturbance in cytokine and keratan sulfate profiles within the anterior cruciate ligament-deficient knee, suggesting an important biochemical dimension to the development of osteoarthritis there.

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We studied a group of 602 patients who had anterior cruciate ligament reconstructions between 1987 and 1992. An autogenous patellar tendon graft was used, regardless of pre-existing patellofemoral pain or chondromalacia. The surgeon and rehabilitation protocol were the same for all patients, with emphasis on obtaining full knee hyperextension postoperatively. All patients were evaluated by a questionnaire designed to determine the incidence and severity of anterior knee pain as it relates to sporting or daily living activities, prolonged sitting, stair climbing, and kneeling. Range of motion for the study group was recorded during physical examination. We compared the findings with those from a control group of 122 patients who had no previous knee injury. The study group reported a mean score of 89.5 ± 12.5, compared with 90.2 ± 12.3 in the control group. Both the operative and control groups reported few or no symptoms during sporting activities (94% and 92%, respectively). No differences were noted with respect to the other activities surveyed. These results demonstrate that anterior knee pain after anterior cruciate ligament reconstruction is not an inherent complication associated with patellar tendon harvesting. We suggest that the increased incidence of anterior knee pain with an autogenous patellar tendon graft can be prevented by obtaining full knee hyperextension postoperatively. This goal can be achieved through preoperative rehabilitation and a postoperative protocol emphasizing early restoration of full knee hyperextension.

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Patellofemoral pain may be associated with anterior cruciate ligament deficiency or may occur after anterior cruciate ligament reconstruction. We investigated the effects of the removal and reconstruction of the anterior cruciate ligament on the kinematics of the tibiofemoral and patellofemoral joints during physiologic levels of quadriceps muscle loads in seven cadaveric knees. A bone-patellar tendon-bone graft was used for intra-articular reconstruction of the anterior cruciate ligament. The spatial positions of the tibiofemoral and patellofemoral joints were measured between 0° and 90° of knee flexion in 15° increments with a 6 degree-of-freedom digitizing system. Excision of the anterior cruciate ligament resulted in statistically significant increases in anterior tibial translation between 0° and 90° and valgus tibial rotation between 30° and 90°; intra-articular reconstruction returned these to levels not significantly different from those of the intact knee. Excision of the anterior cruciate ligament resulted in significant increases in lateral patellar tilt, ranging from 6.3° to 9.0° between full extension and 90° of knee flexion, and in lateral patellar shift, ranging from 2.9 mm at 15° of knee flexion to 5.9 mm at 90°; intra-articular reconstruction returned these to levels not significantly different from those of the intact knee. Neither removal nor reconstruction of the anterior cruciate ligament significantly affected tibial internal-external rotation, patellar flexion, patellar mediolateral rotation, patellar anteroposterior translation, or patellar proximodistal translation.

We studied the effect of rehabilitation strength training and return to activities on anterior-posterior knee displacements after patellar tendon autogenous anterior cruciate ligament reconstruction. A total of 938 measurements were sequentially collected for 142 patients with the KT-2000 arthrometer. Rehabilitation included immediate knee motion and early weightbearing, light sports at 6 months, and competitive sports at 8 months or later. At a minimum of 2 years after surgery, 121 patients (85%) had normal displacements (less than 3 mm of increase at 134 N). 14 (10%) had 3 to 5.5 mm of increase (partial function), and 7 (5%) had more than 5.5 mm of increase (failed). There was no association found between the initial onset of the abnormal displacements in the 21 knees and either the amount of time after surgery or the rehabilitation program. Six of the 7 grafts that failed did so in the 1st postoperative year. Serial displacement measurements allow early detection of graft stretching and subsequent modification of rehabilitation or delay in return to strenuous activities. These measurements showed that the rehabilitation program used in this study was not itself injurious and resulted in an acceptable failure rate of 5%.

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DeVita P, Lassiter T Jr, Hortobagyi T, Torry M. Functional knee brace ef-

The purpose of this study was to compare lower extremity joint kinematics and kinetics during walking with and without a functional knee brace in patients with recent anterior cruciate ligament reconstructions. Seven volunteers walked at 1.26 m/s with and without one of two functional knee braces 3 weeks after surgery. Eleven uninjured subjects were also tested as a control group. Video and ground reaction data were collected and combined with inverse dynamics to estimate the joint positions, moments, and powers during the stance phase. Patients with ligament reconstructions were more erect with the brace, using 19% less knee flexion compared with walking without the brace. Areas under the internal extensor moment curve (angular impulse) and power curve (work) at the hip increased 40% and 44%, respectively, while walking with the brace. Extensor angular impulse decreased 41% at the knee while using the brace, and plantar flexor angular impulse and work increased 21% and 30%, respectively, at the ankle. While walking with the brace, the patients still had different kinematics, moments, and power than the control subjects. The reduced extensor moment at the knee in the braced condition indicated that the load on the recently reconstructed ligament was reduced and that the brace protected the ligament during the stance phase of walking. We concluded that functional knee braces may be one means of developing neuromuscular adaptations during gait after anterior cruciate ligament reconstruction surgery.

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With an electrogoniometer system, we made bilateral measurements of the maximal sagittal plane anterior-posterior knee translations in 15 healthy subjects (controls) and 14 patients with arthroscopically confirmed unilateral anterior cruciate ligament deficiency during 2 types of ascents and descents (straight and side). In both groups, during the ascent cycle, the tibia moved anteriorly in relation to the femur, whereas, during the descent cycle, it moved posteriorly. There was wide individual variation in maximal translation in both the control and anterior cruciate ligament-deficient groups (range, 10 to 12 mm; mean, 7 mm). The maximal translations were similar in both groups (*P* > .05), but they occurred at significantly smaller flexion angle in the injured knees (38°± 8°) than in the control and noninjured knees (44°± 8°) (*P* < .05). The translation during step ascent and descent did not differ between the injured and control knees. These findings indicate that patients with anterior cruciate ligament injuries are able to control abnormal anterior translation during normal activity.

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Anterior cruciate ligament injury rates are 4 to 8 times higher in women than in men. Because of estrogen's direct effect on collagen metabolism and behavior and because neuromuscular performance varies during the menstrual cycle, it is logical to question the menstrual cycle's effect on knee injury rates. Of 40 consecutive female athletes with acute anterior cruciate ligament injuries (less than 3 months), 28 (average age, 23 ± 11 years) met the study criteria of regular menstrual periods and noncontact injury. Details concerning mechanism of injury, menstrual cycle, contraceptive use, and previous injury history were collected. A *χ*² test was used to compute observed and expected frequencies of anterior cruciate ligament injury based on 3 different phases of the menstrual cycle: follicular (days 1 to 9), ovulatory (days 10 to 14), and luteal (day 15 to end of cycle). A significant statistical association was found between the stage of the menstrual cycle and the likelihood for an anterior cruciate ligament injury (*P* = .03). In particular, there were more injuries than expected in the ovulatory phase of the cycle. In contrast, significantly fewer injuries occurred in the follicular phase. These hormones may be a factor in the knee ligament injury dilemma in women.

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The CEU Quiz, formerly placed in the *Journal of Athletic Training*, now appears in the *NATA News*, a monthly magazine for NATA members. The quiz schedule for 1999 is:

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The CEU Quiz also is posted on the NATA Fax-on-Demand Service. Access the quiz by dialing toll-free (888) ASK-NATA or 214-353-6130 from a touch-tone telephone. Follow the automated instructions, requesting Document #1112. Deadlines for submitting each quiz are posted in the *NATA News*.

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current Literature

ACL DEFICIENCY


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FOLLOW-UP STUDIES


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IMAGING


Nakanishi K, Horibe S, Shiozaki Y, et al. MRI of normal anterior cruciate ligament (ACL) and
reconstructed ACL: comparison of when the knee is extended with when the knee is flexed. Eur Radiol, 1997;7:1020–1024.


INJURY


Soderberg GL, Ballantyne BT, Kestel LL. Reliability of lower extremity girth measurements.


Surgery


The mission of the Journal of Athletic Training is to enhance communication among professionals interested in the physically active through education and research in prevention, evaluation, management, and rehabilitation of injuries.

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complaint, history of present complaint (including symptoms), results of physical examination (example: "Physical findings relevant to the rehabilitation program were ..."), medical history (surgery, laboratory results, examination, etc.), diagnosis, treatment and clinical course (rehabilitation until and after return to competition), criteria for return to competition, and deviation from expectations (what makes this case unique).
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Percentages should be accompanied by the numbers used to calculate them.

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