The American Journal of Sports Medicine

http://ajs.sagepub.com/

Identification of Athletes at Future Risk of Anterior Cruciate Ligament Ruptures by Neuromuscular Screening

Mette K. Zebis, Lars L. Andersen, Jesper Bencke, Michael Kjær and Per Aagaard

Am J Sports Med 2009 37: 1967 originally published online July 2, 2009
DOI: 10.1177/0363546509335000

Identification of Athletes at Future Risk of Anterior Cruciate Ligament Ruptures by Neuromuscular Screening

Mette K. Zebis,*† PhD, Lars L. Andersen,† PhD, Jesper Bencke,‡ PhD,
Michael Kjær,§ MD, DMsci, and Per Aagaard,‖ PhD
From the †National Research Centre for the Working Environment, Copenhagen, Denmark, ‡Gait Analysis Laboratory, Hvidovre University Hospital, Copenhagen, Denmark, §Institute of Sports Medicine Copenhagen, Bispebjerg Hospital, Copenhagen, Denmark, and ‖Institute of Sports Sciences and Clinical Biomechanics, University of Southern Denmark, Odense, Denmark

Background: A high percentage of female athletes who sustain an anterior cruciate ligament (ACL) rupture suffer serious long-term consequences such as osteoarthritis and disability. Thus, identification of risk factors has high clinical relevance in the prevention of ACL rupture.

Hypothesis: Noninjured athletes with low knee flexor electromyography (EMG) preactivity and high knee extensor EMG preactivity during sidecutting are at increased risk of future ACL rupture.

Study Design: Cohort study (prognosis); Level of evidence, 2.

Methods: Fifty-five elite female athletes (team handball and soccer) aged 24 ± 5 years with no history of ACL injury were tested for EMG preactivity of vastus lateralis and medialis, rectus femoris, semitendinosus, and biceps femoris during a standardized side-cutting maneuver. The incidence of ACL ruptures was registered in the following 2 match seasons.

Results: During the subsequent 2 match seasons, 5 athletes sustained a confirmed noncontact ACL rupture. Before injury, all 5 players displayed a neuromuscular pattern that differed from the noninjured players, characterized by reduced EMG preactivity for the semitendinosus (ST) and elevated EMG preactivity for the vastus lateralis (VL) ($P < .01$). On the basis of these findings, a high-risk zone was defined as one standard deviation above the mean VL-ST difference. In our population, 5 of 10 subjects with a VL-ST difference in this zone sustained an ACL injury during the study period.

Conclusion: In the present study, currently noninjured female athletes with reduced EMG preactivity of the ST and increased EMG preactivity of the VL during side cutting were at increased risk of future noncontact ACL rupture. Our data indicate that a high-risk zone can be used to identify noninjured players at high risk of future ACL rupture. Consequently, individual preventive efforts can be introduced in time. However, large prospective studies are needed to confirm this finding before definitive clinical recommendations can be made.

Keywords: side-cutting maneuver; electromyography; high-risk zone; semitendinosus; knee joint; injury; prophylactic

An unacceptably high number of noncontact anterior cruciate ligament (ACL) ruptures are observed in female soccer and handball players. A 4- to 8-fold higher incidence of ACL injuries has been reported for female athletes compared with male athletes.[20,31] One potential long-term consequence of ACL injury, whether the treatment has been operative or nonoperative, is osteoarthritis of the knee. This serious consequence occurs despite surgical correction of the instability. Studies have shown that an ACL injury results in osteoarthritic changes in 50% to 90% of patients 7 to 20 years after the injury.[18,24,28,29,32]

In recent years, increased focus has been directed on prevention of ACL injury, where a pivotal issue has been identification of critical biomechanical and physiological risk factors. It is well established that most noncontact ACL injuries in sports and exercise occur in situations like landing, side cutting, or deceleration, which involve substantial eccentric muscle force of the knee extensors.[33] Consequently, substantial anterior-directed shear of the

*Address correspondence to Mette K. Zebis, PhD, National Research Centre for the Working Environment, Lersø Parkallé 105, DK-2100 Copenhagen, Denmark (e-mail: mettezebis@hotmail.com).

No potential conflict of interest declared.

The American Journal of Sports Medicine, Vol. 37, No. 10
DOI: 10.1177/0363546509335000

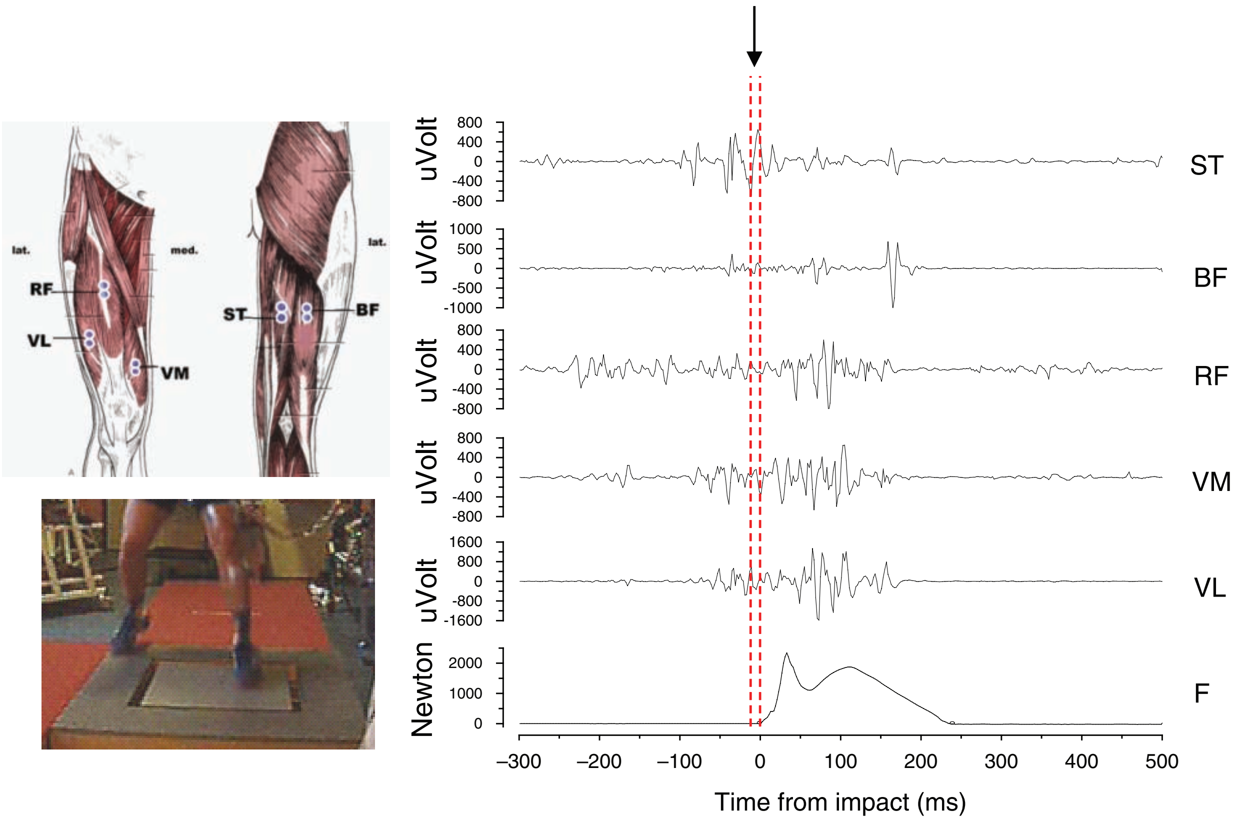

Figure 1. Top left: Illustration of the surface electromyography (EMG) electrode placement on the examined muscles (modified from Bojsen-Møller, F. "Bevægeapparatets anatomi," Munksgaard Danmark, 2002). Knee flexors: biceps femoris (BF) and semitendinosus (ST). Knee extensors: vastus medialis (VM), vastus lateralis (VL), and rectus femoris (RF). Bottom left: The side-cutting maneuver just prior to foot contact on a force plate. Right: An example of raw EMG activity and vertical ground reaction force (F) during side cutting in 1 subject. The dotted lines represent the examined 10-millisecond time interval just before landing on a force plate.

tibia relative to the femur occurs.[9,22] This shear can be counteracted not only by the ACL but also by appropriate coactivation of the knee flexor muscles.[10] During side cutting, injuries occur when the knee is near full extension and in valgus combined with external rotation of the tibia.[30] In this regard, the medial knee flexor muscles (semitendinosus and semimembranosus) become particularly important to counterbalance and protect against movement conditions with excess valgus.

A recent study has indicated that the timing of noncontact ACL injury ranges between 17 to 50 milliseconds after initial ground contact,[14] leaving no time for mechanosensory feedback mechanisms to prevent injury. Thus, during fast movements like side cutting, substantial neural preactivation of the knee flexor muscles just before ground contact seems essential.

The objective of the present study was to investigate the efficacy of neuromuscular screening to predict future ACL rupture in currently noninjured athletes. We hypothesized that currently noninjured athletes with low preactivity of their knee flexor and high preactivity of their knee extensor muscles during side-cutting maneuvers are at increased risk of future noncontact ACL rupture.

MATERIALS AND METHODS

Subjects

This investigation was conducted as a prospective cohort study. Before the match season, 55 elite female team handball and soccer players (age, 24 ± 5 years; height, 169 ± 6 cm; weight, 69 ± 7 kg) were screened for the pattern and magnitude of neuromuscular preactivity in relevant leg muscles during side cutting (Figure 1). The incidence of ACL ruptures was registered in the following 2 match seasons.

The players were recruited from 3 handball and 2 soccer teams, and only players with no history of knee injury were included. Further, only players who were uninjured at the time of testing and above 18 years of age were included. Each player was recruited on a voluntary basis; that is, the coach did not make the decision. Ethical approval was obtained from the local ethics committee (KF 01 259540), and informed consent was obtained from all players before testing.

Side-cutting Maneuver

The side-cutting maneuver is a movement that the player is able to perform in match situations when time for decision

Figure 2. Sequential steps of the examined side-cutting maneuver (modified from www.klokavskade.no). Reprinted with permission from Grethe Myklebust of the Oslo Sports Trauma Research Centre, Norwegian School of Sports Sciences, Oslo, Norway.

making about posture correction is extremely limited. The purpose of the side-cutting maneuver is to fake the defense player in one direction and then move in the opposite direction (Figure 2). A previous study has demonstrated high test-retest reproducibility for magnitude and timing of the EMG activity during side cutting,[36] showing that this maneuver is executed by a consistent motor program. The side-cutting maneuver is a highly consistent motor program and has been found to remain unchanged during a regular season with training and match playing.[36]

The standardized side-cutting maneuver was performed with a fixed distance of 2 m to a force plate. Instructions were given to the subjects to perform the side cutting as fast and forceful as possible to simulate a match situation.

Neuromuscular Screening

The skin of the subject was shaved with a hand razor and carefully cleaned with ethanol before electrode placement on the preferred push-off leg during a standardized side-cutting maneuver. Bipolar surface EMG electrodes (Medicotest M-00-S, Ølstykke, Denmark) with a 2.0-cm interelectrode distance were placed on the medial portion of the vastus lateralis (VL), vastus medialis (VM), and rectus femoris (RF) muscles of the quadriceps femoris muscle, and the biceps femoris caput longus (BFcl) and semitendinosus (ST) muscles representing the lateral and medial hamstring muscle groups, respectively. The EMG electrodes were connected directly to small preamplifiers, and the signals were led through shielded wires to custom-built differential instrumentation amplifiers, with a bandwidth of 10 to 10 000 Hz and a common mode rejection ratio >100 dB.[2] It has previously been documented with this experimental set-up that the amount of EMG cross-talk is negligible (2%-6%).[2] Knee and hip joint positions were measured during side cutting with flexible electrogoniometers (Penny & Giles G180, Christchurch, Dorset, UK) positioned laterally over the knee and hip joint.[7] Calibration of the goniometer signal was performed at anatomical knee and hip joint angles of 0° and 90° using a geometric retractor. Knee and hip joint angles, ground-reaction forces, and EMG during side cutting have previously been documented to be highly reliable using the present method.[36] The EMG and goniometer position signals were sampled synchronously at 1000 Hz using an external A/D-converter (dt2801-A, Data Translation Inc, Marlborough, Massachusetts) and stored on a personal computer for later analysis. A sampling frequency of 1000 Hz was used[3,6,27,34] because most of the surface EMG signal energy is concentrated in the band between 20 and 200 Hz, and only negligible content occurs beyond 500 Hz.[35]

During later off-line analysis, all EMG signals were high-pass filtered at a 5-Hz cutoff frequency (4th order zero-lag Butterworth filter) and subsequently smoothed by a symmetrical moving root mean square (RMS) filter of 30 milliseconds.[1]

The RMS EMG amplitude was obtained instantly before ground contact, defined as 10 milliseconds before foot strike on the force plate, and subsequently normalized to the peak RMS EMG amplitude recorded during the side-cutting maneuver.[36] The average of 5 trials was calculated for each player.

Statistical Analyses

Mean preactivity between subsequently injured (n = 5) and noninjured players (n = 50) was compared with Friedman 2-way analysis of variance (ANOVA). Factors included in the model were group (injured or noninjured) and muscle (vastus lateralis and medialis, rectus femoris, semitendinosus, biceps femoris). Mean knee and hip joint angles between subsequently injured and noninjured players were compared with an unpaired Student *t* test. An α level of 5% was accepted as statistically significant, and all values are presented as mean ± SD.

RESULTS

Five confirmed ACL ruptures occurred in the following 2 match seasons. All 5 players (3 handball and 2 soccer players) injured the preferred push-off leg. A priori hypothesis testing of main effects showed a significant group by muscle effect ($P < .001$). Post hoc tests showed lower preactivity of the ST (21% ± 6% vs 40% ± 17%; $P < .001$) and higher preactivity of the VL (69% ± 12% vs 35% ± 15%; $P < .01$) in the subsequently injured compared with the noninjured players (Figure 3A and B). No significant difference between subsequently injured and noninjured players was observed for any of the other muscles examined (Figure 4). The difference between VL and ST EMG preactivity (ΔVL-ST) was 47% ± 14% in the subsequently injured players and 2% ± 25% in the noninjured players ($P = .0006$) (Figure 3C). On the basis of the present findings, a high-risk zone was defined as one standard deviation above the mean VL-ST difference. The probability of sustaining ACL injury was 50% (5 of 10) for players in the presently defined high-risk zone (Figure 3C).

No significant differences in hip (53° ± 21° vs 46° ± 19°; $P = .553$) and knee (35° ± 16° vs 27° ± 11°; $P = .292$) joint angle were observed during the side-cutting maneuver when comparing the 5 subsequently ACL-injured players with the average of the noninjured players.

DISCUSSION

The main finding of this study is that currently noninjured female athletes with reduced and elevated preactivity of their ST and VL muscles, respectively, during side cutting are at increased risk of future noncontact ACL rupture.

The present study is the first to provide a solid neuromuscular screening method and to document the mechanism of future injury by showing a specific muscle activation pattern predisposing for future ACL rupture. In a recent study by Hewett et al,[13] dynamic knee joint valgus moment during drop jump was calculated by use of 3-dimensional video analysis and identified to predispose for ACL injury. The present study supports the theoretical considerations of ST activity being important to compress the medial knee joint. Speculatively, this may limit the risk of excessive dynamic valgus and external rotation of the knee joint and thereby reduce stress on the ACL. Thus, the ST plays a key role as the most important neuromuscular ACL agonist. In contrast, preactivity for the lateral hamstring (BFcl) was not different between subsequently injured and noninjured players, emphasizing the importance of the medial hamstring.

The present study has high clinical relevance for preventive sports medicine. Whereas it is well established that neuromuscular training can reduce the incidence of ACL injuries in female sports,[12,21,23] the efficacy of specific elements as well as the underlying mechanism for prevention has previously been unknown. The present study shows that preventive exercises should be focused on selective upregulation of the medial hamstring. In this regard, we have recently shown selective upregulation of ST activity through targeted neuromuscular training.[36] Although a high quadriceps activity also seems to predispose for future ACL rupture, high knee extensor activity is essential to gain power and speed in explosive movements as the side-cutting maneuver. Thus, upregulation of ST activity should be the essence of preventive neuromuscular training.

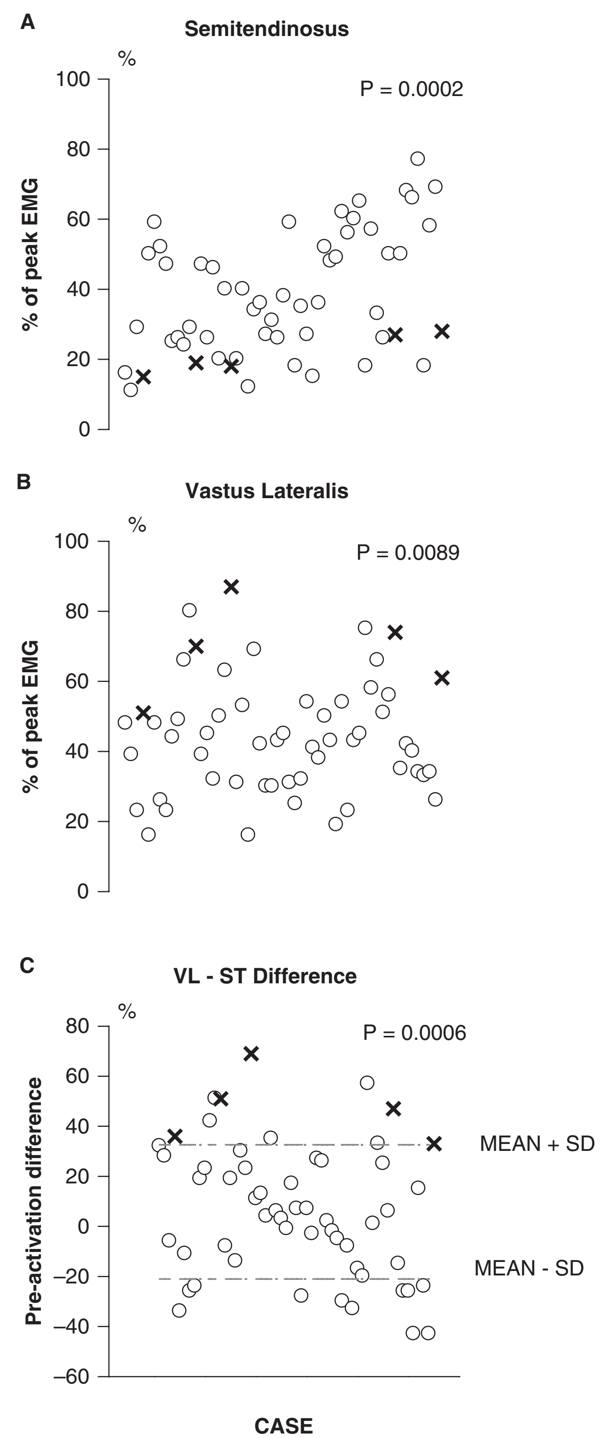

Figure 3. Electromyography (EMG) preactivity during side cutting recorded for the semitendinosus (ST) (A) vastus lateralis (VL) (B), and the VL-ST (C) preactivity difference. Circle: Players who remained uninjured. Cross: Players who subsequently had an anterior cruciate ligament (ACL) injury. The *P* value shows the significant difference level between the 2 groups.

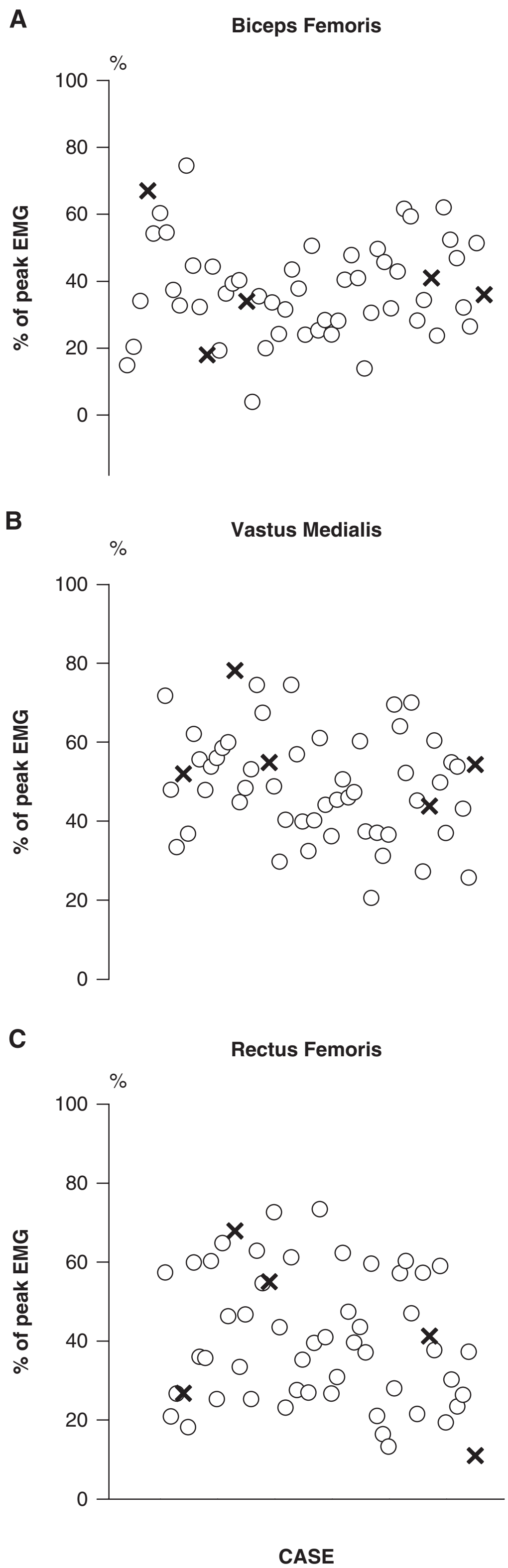

Figure 4. Electromyography (EMG) preactivity during side cutting recorded for the biceps femoris (A), vastus medialis (B), and rectus femoris (C). Circle: Players who remained uninjured. Cross: Players who subsequently had an anterior cruciate ligament (ACL) injury.

Five ACL injuries (~9%) were observed during 2 match seasons, which is in line with the incidence rate reported in the literature for female handball and soccer players. The injury rate for female elite handball players has been reported to be 0.14 to 0.31 ACL injuries per 1000 hours[23,25,26] (corresponding to ~1 to 2 ACL injuries per team per year) and 0.12 injuries per 1000 hours for female elite soccer players[16] (corresponding to ~1 ACL injury per team per year). Because more players may actually be at risk, difficulties arise in defining a clinically relevant cut point predisposing for ACL injury. However, based on the present findings, we propose a "high-risk" zone of one standard deviation above the mean VL to ST difference, theoretically corresponding to 16% of the players.[5] The lower limit of this high-risk zone corresponded to a VL-ST difference of 33%. Thus, special preventive efforts should be taken for players within this high-risk zone.

The present findings could also be relevant knowledge in respect to orthopaedic surgery because ruptured ACLs are commonly reconstructed by a graft harvested from the ST tendon[11,15,17,19] without considering the biomechanical consequences caused by reduced function of this particular muscle. Although it still is unknown whether harvest of hamstring tendon autograft increases risk of reinjury, the present findings suggest that ACL reconstruction with the ST tendon should be reconsidered. In support of this notion, ACL reconstruction using ST tendon has been shown to lower hamstring muscle power and the hamstring to quadriceps ratio for up to 3 years after surgery.[4] Further, it has been shown that female athletes who had this type of ACL reconstruction did not return to their preinjury activity level.[8] In the same study, it was found that the group of female athletes who underwent reconstruction with patellar tendon graft not only returned to their preinjury activity level but in some cases surpassed it postoperatively. Future studies should examine the effect of graft type on the neuromuscular function in this group of athletes.

Limitations

A limitation of the present study was the fact that we only measured the preferred push-off leg rather than both sides. However, the fact that all players who sustained an ACL injury actually injured the preferred push-off leg strengthens the present data. Another limitation may be that no clinical examination of the knee joint was performed before testing. However, only players with no history of knee injury were included.

Although EMG is a widely used screening tool, there are certain limitations associated with this method. Thus, the EMG amplitude varies between individuals because of differences in skin conductance, thickness of subcutaneous fat, muscle fiber pennation angle, muscle fiber size, and so on. Nevertheless, the present method of normalizing EMG amplitude to the peak EMG during sidecutting has previously been shown to result in a highly reproducible EMG pattern[36] and, in the present study, to predict future ACL ruptures.

The present study did not employ 3-dimensional kinematic analyses of dynamic valgus during side cutting. Thus, future studies may combine measurements of 3-dimensional kinematic and neuromuscular screening by EMG to determine the association between dynamic valgus and reduced ST activity.

Finally, although surface EMG measurements in the medial hamstring muscles can only be performed for the ST, the semimembranosus may play an equally important role.

CONCLUSION

Our data indicate that reduced preactivity of the ST in combination with elevated preactivity of the VL during side cutting predisposes for future noncontact ACL injury in female soccer and handball players. On the basis of the present findings, we propose a high-risk zone defined as one standard deviation above the mean VL-ST difference. Standardized screening of neuromuscular agonist-antagonist activity in potential risk situations like side cutting and jumping may hold a promising assessment tool in preventive sports science. However, large prospective studies are needed to confirm the present findings.

ACKNOWLEDGMENT

This study was supported by grants from The Danish Ministry of Culture Committee for Sports Research, The Team Denmark Elite Sports Association, and the Fédération Internationale de Football Association (FIFA).

REFERENCES

1. Aagaard P, Simonsen EB, Andersen JL, Magnusson P, Dyhre-Poulsen P. Increased rate of force development and neural drive of human skeletal muscle following resistance training. *J Appl Physiol.* 2002;93(4):1318-1326.
2. Aagaard P, Simonsen EB, Andersen JL, Magnusson SP, Bojsen-Moller F, Dyhre-Poulsen P. Antagonist muscle coactivation during isokinetic knee extension. *Scand J Med Sci Sports.* 2000;10(2):58-67.
3. Aagaard P, Simonsen EB, Andersen JL, Magnusson SP, Halkjaer-Kristensen J, Dyhre-Poulsen P. Neural inhibition during maximal eccentric and concentric quadriceps contraction: effects of resistance training. *J Appl Physiol.* 2000;89(6):2249-2257.
4. Ageberg E, Roos HP, Silbernagel KG, Thomee R, Roos EM. Knee extension and flexion muscle power after anterior cruciate ligament reconstruction with patellar tendon graft or hamstring tendons graft: a cross-sectional comparison 3 years post surgery. *Knee Surg Sports Traumatol Arthrosc.* Epub 2008 November 4.
5. Altman D. Theoretical distributions. In: *Practical Statistics for Medical Research.* London: Chapman & Hall; 1991: 48-73.
6. Andersen LL, Andersen JL, Magnusson SP, Aagaard P. Neuromuscular adaptations to detraining following resistance training in previously untrained subjects. *Eur J Appl Physiol.* 2005;93(5-6):511-518.
7. Andersen LL, Magnusson SP, Nielsen M, Haleem J, Poulsen K, Aagaard P. Neuromuscular activation in conventional therapeutic exercises and heavy resistance exercises: implications for rehabilitation. *Phys Ther.* 2006;86(5):683-697.
8. Barrett GR, Noojin FK, Hartzog CW, Nash CR. Reconstruction of the anterior cruciate ligament in females: a comparison of hamstring versus patellar tendon autograft. *Arthroscopy.* 2002;18(1):46-54.
9. Beynnon B, Howe JG, Pope MH, Johnson RJ, Fleming BC. The measurement of anterior cruciate ligament strain in vivo. *Int Orthop.* 1992;16(1):1-12.
10. Draganich LF, Vahey JW. An in vitro study of anterior cruciate ligament strain induced by quadriceps and hamstrings forces. *J Orthop Res.* 1990;8(1):57-63.
11. Harilainen A, Linko E, Sandelin J. Randomized prospective study of ACL reconstruction with interference screw fixation in patellar tendon autografts versus femoral metal plate suspension and tibial post fixation in hamstring tendon autografts: 5-year clinical and radiological follow-up results. *Knee Surg Sports Traumatol Arthrosc.* 2006;14(6):517-528.
12. Hewett TE, Lindenfeld TN, Riccobene JV, Noyes FR. The effect of neuromuscular training on the incidence of knee injury in female athletes: a prospective study. *Am J Sports Med.* 1999;27(6):699-706.
13. Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *Am J Sports Med.* 2005;33(4):492-501.
14. Krosshaug T, Nakamae A, Boden BP, et al. Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases. *Am J Sports Med.* 2007;35:359-367.
15. Laxdal G, Sernert N, Ejerhed L, Karlsson J, Kartus JT. A prospective comparison of bone-patellar tendon-bone and hamstring tendon grafts for anterior cruciate ligament reconstruction in male patients. *Knee Surg Sports Traumatol Arthrosc.* 2007;15(2):115-125.
16. Le Gall F, Carling C, Reilly T. Injuries in young elite female soccer players: an 8-season prospective study. *Am J Sports Med.* 2008;36(2):276-284.
17. Liden M, Ejerhed L, Sernert N, Laxdal G, Kartus J. Patellar tendon or semitendinosus tendon autografts for anterior cruciate ligament reconstruction: a prospective, randomized study with a 7-year follow-up. *Am J Sports Med.* 2007;35(5):740-748.
18. Lohmander LS, Ostenberg A, Englund M, Roos H. High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury. *Arthritis Rheum.* 2004;50(10):3145-3152.
19. Maletis GB, Cameron SL, Tengan JJ, Burchette RJ. A prospective randomized study of anterior cruciate ligament reconstruction: a comparison of patellar tendon and quadruple-strand semitendinosus/gracilis tendons fixed with bioabsorbable interference screws. *Am J Sports Med.* 2007;35(3):384-394.
20. Malinzak RA, Colby SM, Kirkendall DT, Yu B, Garrett WE. A comparison of knee joint motion patterns between men and women in selected athletic tasks. *Clin Biomech (Bristol, Avon).* 2001;16(5):438-445.
21. Mandelbaum BR, Silvers HJ, Watanabe DS, et al. Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. *Am J Sports Med.* 2005;33(7):1003-1010.
22. More RC, Karras BT, Neiman R, Fritschy D, Woo SL, Daniel DM. Hamstrings—an anterior cruciate ligament protagonist: an in vitro study. *Am J Sports Med.* 1993;21(2):231-237.
23. Myklebust G, Engebretsen L, Braekken IH, Skjolberg A, Olsen OE, Bahr R. Prevention of anterior cruciate ligament injuries in female team handball players: a prospective intervention study over three seasons. *Clin J Sport Med.* 2003;13(2):71-78.
24. Myklebust G, Holm I, Maehlum S, Engebretsen L, Bahr R. Clinical, functional, and radiologic outcome in team handball players 6 to 11 years after anterior cruciate ligament injury: a follow-up study. *Am J Sports Med.* 2003;31(6):981-989.
25. Myklebust G, Maehlum S, Engebretsen L, Strand T, Solheim E. Registration of cruciate ligament injuries in Norwegian top level team handball: a prospective study covering two seasons. *Scand J Med Sci Sports.* 1997;7(5):289-292.
26. Myklebust G, Maehlum S, Holm I, Bahr R. A prospective cohort study of anterior cruciate ligament injuries in elite Norwegian team handball. *Scand J Med Sci Sports.* 1998;8(3):149-153.

27. Narici MV, Hoppeler H, Kayser B, et al. Human quadriceps cross-sectional area, torque and neural activation during 6 months strength training. *Acta Physiol Scand.* 1996;157(2):175-186.
28. Neyret P, Donell ST, DeJour D, DeJour H. Partial meniscectomy and anterior cruciate ligament rupture in soccer players: a study with a minimum 20-year followup. *Am J Sports Med.* 1993;21(3):455-460.
29. Noyes FR, Mooar PA, Matthews DS, Butler DL. The symptomatic anterior cruciate-deficient knee. Part I: the long-term functional disability in athletically active individuals. *J Bone Joint Surg Am.* 1983;65(2):154-162.
30. Olsen OE, Myklebust G, Engebretsen L, Bahr R. Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. *Am J Sports Med.* 2004;32(4):1002-1012.
31. Ostenberg A, Roos H. Injury risk factors in female European football: a prospective study of 123 players during one season. *Scand J Med Sci Sports.* 2000;10(5):279-285.
32. Sherman MF, Warren RF, Marshall JL, Savatsky GJ. A clinical and radiographical analysis of 127 anterior cruciate insufficient knees. *Clin Orthop Relat Res.* 1988;227:229-237.
33. Simonsen EB, Magnusson SP, Bencke J, et al. Can the hamstring muscles protect the anterior cruciate ligament during a side-cutting maneuver? *Scand J Med Sci Sports.* 2000;10(2):78-84.
34. Suetta C, Aagaard P, Rosted A, et al. Training-induced changes in muscle CSA, muscle strength, EMG, and rate of force development in elderly subjects after long-term unilateral disuse. *J Appl Physiol.* 2004;97(5):1954-1961.
35. Winter DA. *Biomechanics and Motor Control of Human Movement.* 2nd ed. New York: John Wiley & Sons Inc; 1990.
36. Zebis MK, Bencke J, Andersen LL, et al. The effects of neuromuscular training on knee joint motor control during sidecutting in female elite soccer and handball players. *Clin J Sport Med.* 2008;18(4):329-337.