American Journal of Sports Medicine

http://ajs.sagepub.com

Deficits in Neuromuscular Control of the Trunk Predict Knee Injury Risk: A Prospective Biomechanical-Epidemiologic Study

Bohdanna T. Zazulak, Timothy E. Hewett, N. Peter Reeves, Barry Goldberg and Jacek Cholewicki

Am. J. Sports Med. 2007; 35; 1123 originally published online Apr 27, 2007;
DOI: 10.1177/0363546507301585

Deficits in Neuromuscular Control of the Trunk Predict Knee Injury Risk

A Prospective Biomechanical-Epidemiologic Study

Bohdanna T. Zazulak,*[†‡§] DPT, MS, OCS, Timothy E. Hewett,[‖¶] PhD, FACSM, N. Peter Reeves,[§#] MSc, Barry Goldberg,[**] MD, and Jacek Cholewicki,[§#] PhD
*From [†]Department of Rehabilitation Services, Yale-New Haven Hospital, New Haven, Connecticut, [‡]Department of Physical Therapy, Quinnipiac University, New Haven, Connecticut, the [§]Department of Orthopaedics & Rehabilitation, Biomechanics Research Laboratory, Yale University School of Medicine, New Haven, Connecticut, the [‖]Sports Medicine Biodynamics Center and Human Performance Laboratory, Cincinnati Children's Hospital Research Foundation, Cincinnati, Ohio, the [¶]Departments of Pediatrics, Orthopaedic Surgery, Biomedical Engineering, and Rehabilitation Sciences, University of Cincinnati College of Medicine, Cincinnati, Ohio, the [#]Department of Biomedical Engineering, Yale University, New Haven, Connecticut, and **Yale University Health Services, New Haven, Connecticut*

Background: Female athletes are at significantly greater risk of anterior cruciate ligament (ACL) injury than male athletes in the same high-risk sports. Decreased trunk (core) neuromuscular control may compromise dynamic knee stability.

Hypotheses: (1) Increased trunk displacement after sudden force release would be associated with increased knee injury risk; (2) coronal (lateral), not sagittal, plane displacement would be the strongest predictor of knee ligament injury; (3) logistic regression of factors related to core stability would accurately predict knee, ligament, and ACL injury risk; and (4) the predictive value of these models would differ between genders.

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

Methods: In this study, 277 collegiate athletes (140 female and 137 male) were prospectively tested for trunk displacement after a sudden force release. Analysis of variance and multivariate logistic regression identified predictors of risk in athletes who sustained knee injury.

Results: Twenty-five athletes (11 female and 14 male) sustained knee injuries over a 3-year period. Trunk displacement was greater in athletes with knee, ligament, and ACL injuries than in uninjured athletes ($P < .05$). Lateral displacement was the strongest predictor of ligament injury ($P = .009$). A logistic regression model, consisting of trunk displacements, proprioception, and history of low back pain, predicted knee ligament injury with 91% sensitivity and 68% specificity ($P = .001$). This model predicted knee, ligament, and ACL injury risk in female athletes with 84%, 89%, and 91% accuracy, but only history of low back pain was a significant predictor of knee ligament injury risk in male athletes.

Conclusions: Factors related to core stability predicted risk of athletic knee, ligament, and ACL injuries with high sensitivity and moderate specificity in female, but not male, athletes.

Keywords: anterior cruciate ligament (ACL); trunk or core stability; gender; knee injury prevention

*Address correspondence to Bohdanna T. Zazulak, DPT, MS, OCS, Yale Physicians Building, 800 Howard Avenue, New Haven, CT 06510 (e-mail: bohdanna.zazulak@ynhh.org).

No potential conflict of interest declared.

The American Journal of Sports Medicine, Vol. 35, No. 7
DOI: 10.1177/0363546507301585

Female athletes are at significantly greater risk of anterior cruciate ligament (ACL) injury than male athletes in the same high-risk sports.[29] The mechanism of ACL injury is likely a combination of factors: valgus positioning of the lower extremity; relative extension with unbalanced weight distribution; and the plantar surface of the foot being fixed in position, away from the center of mass of the body.[13] The mechanism of ACL injury may differ in female and male athletes, especially with respect to the dynamic positioning of the knee, as female athletes demonstrate increased valgus collapse of the lower extremity in the coronal plane.[21] Dynamic stability of an athlete's knee depends on accurate sensory input and appropriate motor responses to meet the demands of rapid changes in trunk position during cutting, stopping, and landing movements.[14,16] Dynamic stability may be operationally defined as the ability of the knee joint to maintain position (static stability) or intended trajectory (dynamic stability) after internal or external disturbance. Inadequate neuromuscular control of the body's trunk or "core" may compromise dynamic stability of the lower extremity and result in increased abduction torque at the knee, which may increase strain on the knee ligaments and lead to injury.[2,16,24,39]

The dynamic stability of the body, or any specific joint such as the knee, is contingent on neuromuscular control of the displacement of all contributing body segments during movement.[16] Core stability is related to the body's ability to control the trunk in response to internal and external disturbances, including the forces generated from distal body segments as well as from expected or unexpected perturbations. Core stability, as generally defined in the sports medicine literature, is a foundation of trunk dynamic control that allows production, transfer, and control of force and motion to distal segments of the kinetic chain.[20] For the purposes of the present study, a more precise operational definition was developed. Core stability was defined as the body's ability to maintain or resume an equilibrium position of the trunk after perturbation. Deficits in neuromuscular control of the body's core may lead to uncontrolled trunk displacement during athletic movement, which in turn may place the lower extremity in a valgus position, increase knee abduction motion and torque, and result in high knee ligament strain and ACL injury.[13,16]

Core muscle activity precedes lower extremity muscle activity in the temporal sequence of many athletic tasks. Hodges and Richardson[17,18] demonstrated that trunk muscle activity often occurs before the activity of the lower extremity musculature. They concluded that the central nervous system creates a stable foundation for movement of the lower extremities through cocontraction of the transversus abdominis and multifidus muscles.[17] Cholewicki and Van Vliet[8] reported that all of the musculature of the trunk, including abdominal as well as back musculature, contributes to core stability. The relative contributions of each muscle group continually change throughout an athletic task.[6]

Deficient core neuromuscular control of motion during athletic tasks may predispose athletes to low back injuries as well as injuries of the lower extremity. Delayed reflex response of trunk muscles increases the risk of low back injury in athletes and appears to be a preexisting risk factor.[7] Similarly, abdominal muscle fatigue may be a contributing factor to hamstring injuries.[9] Retrospective examination of patients with ankle sprains shows a delay in the onset of muscle activation of the gluteal muscles compared with uninjured control subjects.[1,4] In a recent prospective study of over 900 athletes, female athletes who subsequently suffered ankle injury demonstrated significantly greater body sway than those athletes who were not injured, while predictors of injury in male athletes were related to ankle range of motion and not to measures of trunk sway.[3]

TABLE 1
Subject Demographics[a]

	Female	Male
	n = 140	n = 137
Height (m)	1.70 ± 0.08[b]	1.83 ± 0.08[b]
Weight (kg)	65.6 ± 8.7[b]	79.9 ± 11.9[b]
BMI (kg/m^2)	22.6 ± 2.2[b]	23.8 ± 2.8[b]
Age (y)	19.4 ± 1.0	19.3 ± 1.8

[a]All values are mean ± standard deviation. BMI, body mass index.
[b]Significant differences between groups.

The purpose of the present study was to identify potential neuromuscular factors related to core stability that predispose athletes to knee injuries. We hypothesized that motor control of the core may play an important role in dynamic stability of the lower extremity and subsequent injury to the knee. Specifically, we examined whether there was a relationship between factors related to core stability and increased risk of knee, knee ligament, and/or ACL injury. The 4 hypotheses tested were (1) increased trunk displacement after sudden force release would be associated with increased knee injury risk; (2) lateral angular displacement of the trunk in the coronal plane would be the best predictor of ligament injury; (3) logistic regression models of combined factors related to core stability would predict knee, ligament, and ACL injury with high sensitivity and moderate specificity; and (4) the predictive value of these models differs in male and female athletes. The development of sensitive measures related to core stability in athletes could lead to the identification of neuromuscular risk factors that predispose specific athletes to knee injury, and interventions could be developed to modify these factors in these individuals to decrease injury risk. There is strong evidence that neuromuscular control of the trunk and lower extremity can be improved with neuromuscular training.[15,26,27,36,37]

METHODS

Subjects

A total of 277 athletes volunteered for the study. Table 1 provides subject demographics for female and male volunteers. Athletes were tested at baseline and then followed for 3 years to track all knee injuries sustained during that period. Before experimental testing, every subject completed a detailed, 45-item questionnaire pertaining to personal demographic data (height, weight, and age), athletic experience, varsity level, sport(s) affiliation, and history of injury. For the purposes of this study, an injury was defined as any injury that resulted in a visit to a sports physician, and a knee injury was defined as ligament, meniscal, or patellofemoral injury to the knee joint. None of the athletes enrolled in the study had any history of knee injury. Fractures and contusions were excluded in the knee-injured athlete

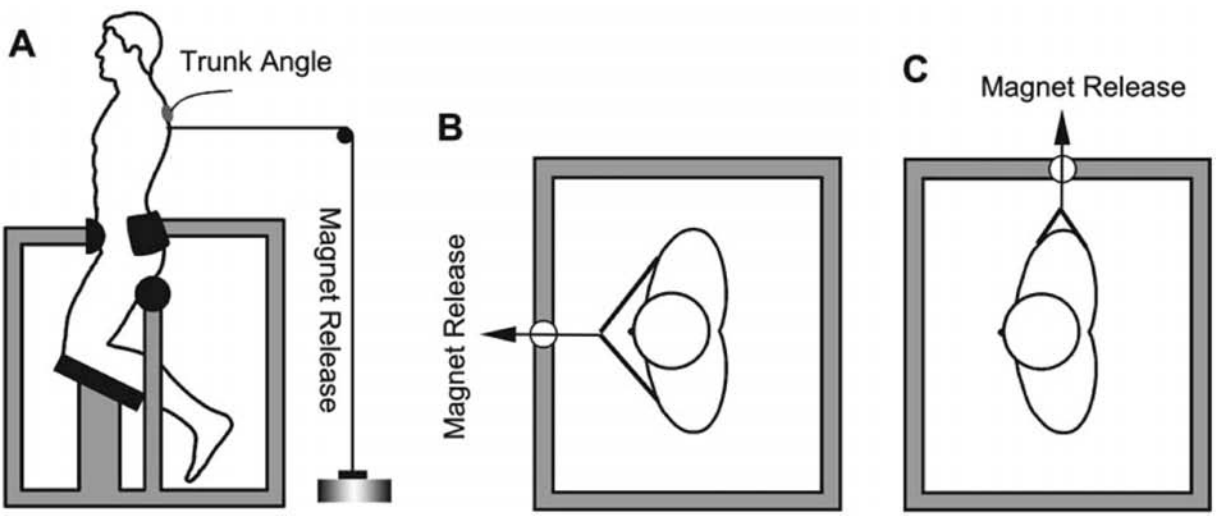

Figure 1. A subject positioned in a multidirectional, sudden force release apparatus. Flexion (A), extension (B), and lateral bending (C) loads were applied via a system of pulleys.

group. All ligament and meniscal injuries were confirmed by magnetic resonance imaging. All subjects understood the experimental protocol and signed the consent form, both of which were approved by the Human Investigation Committee.

Trunk Displacement Measure After Sudden Force Release

A quick force release in 3 directions of isometric trunk exertions was used for assessing the trunk response to sudden unloading. Subjects were placed in a wooden apparatus that was designed for isometric exertions in trunk flexion, extension, and lateral bending (Figure 1). The apparatus restrained pelvic motion but allowed the upper body to move freely in any direction. The restraint excluded any postural adjustments through joints other than the spine (ie, hip, knee, and ankle). Subjects sat in a semiseated position, which allowed the subjects to assume their most comfortable lumbar spine geometry before their pelvis was restrained. A cable attached to a chest harness at approximately the fifth thoracic vertebra was held with an electromagnet and served as a resisting force for isometric exertions. Each subject performed 5 trials at a constant force level corresponding to 30% of the maximal isometric trunk exertion for an average healthy man (108 N) or woman (72 N), established empirically in a preliminary study. Thirty percent of the maximum isometric exertion was selected, as lower forces would not produce appreciable perturbation and higher forces become uncomfortable when released. This was also determined by a prior empirical study. The force level was displayed on an oscilloscope to provide visual feedback to the athlete helping them to reach and maintain the target force. The resisted force was suddenly released when the electromagnet was deactivated. Deactivation occurred at random time intervals after the target force was reached.

A Flock of Birds electromagnetic device (Ascension Technologies, Burlington, Vt) was used to record trunk motion after the force release. The sensor was placed on the back at approximately the T5 level. The receiver was within 3 ft of the transmitter according to the device specifications. Care was taken that no metal parts were in the vicinity of the setup. The data were recorded at 123 Hz and then digitally filtered at 8.5 Hz (fourth order, dual pass, Butterworth filter). Angular trunk displacements 150 milliseconds after the release and maximum displacements were selected and averaged across 5 trials in each direction.

Statistical Analysis

The sudden force release test generated 6 parameters: flexion, extension, and lateral flexion angular displacement both at 150 milliseconds and maximum displacement. First, a 3-factor (force release direction, gender, and injury) analysis of variance and Tukey post hoc test were used to identify displacement parameters that were significantly different between the injured and uninjured athletes. These parameters served as input into a backward stepwise binary logistic regression model (Minitab, State College, Pa) for predicting knee injury. Initially, all parameters that were related to core stability were entered into the regression model. These included active proprioceptive repositioning (APR) error of the trunk,[38] 6 trunk displacement parameters (lateral flexion, extension, and flexion both at maximum displacement and at 150 milliseconds), and history of low back pain (LBP). Active proprioceptive repositioning was measured in a parallel study with an apparatus designed to quantify trunk proprioception. In this apparatus, subjects were initially rotated 20° away from the neutral spine posture (at 2 deg/s), briefly held in that position for 3 seconds and then actively rotated back toward the original position. The subjects stopped the apparatus by pressing a switch

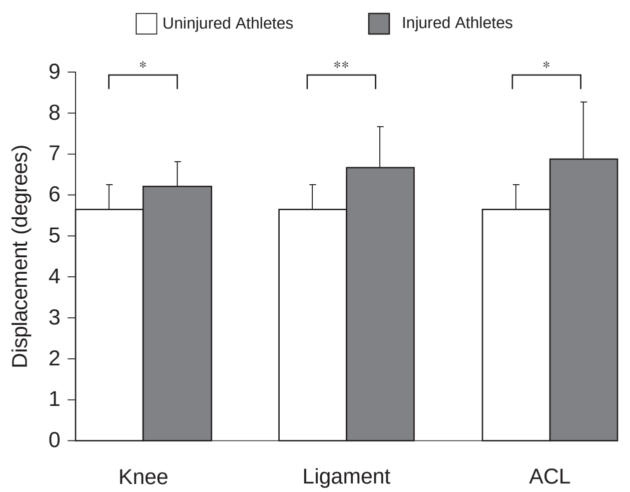

Figure 2. Displacement at 150 milliseconds in athletes (female and male combined) who subsequently sustained or did not sustain knee, ligament, or anterior cruciate ligament (ACL) injury. $^*P \leq .05$, $^{**}P \leq .01$. Error bars designate standard error of the mean.

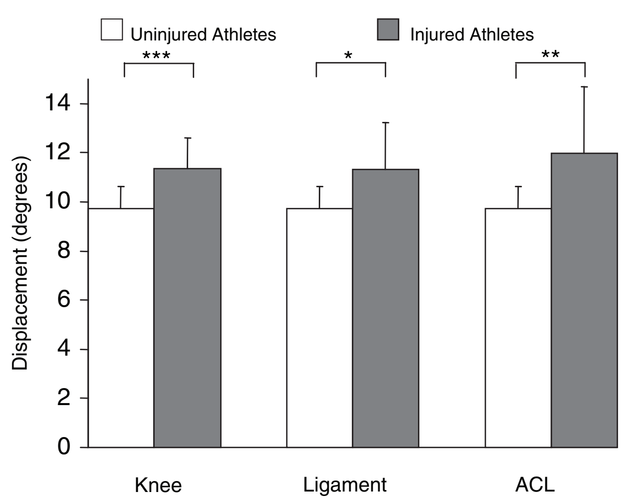

Figure 3. Maximum displacement in athletes (female and male combined) who subsequently sustained or did not sustain knee, ligament, or anterior cruciate ligament (ACL) injury. $^*P \leq .05$, $^{**}P \leq .01$, $^{***}P \leq .001$. Error bars designate standard error of the mean.

when they perceived being in the original, neutral position. Active proprioceptive repositioning error is the absolute difference (in degrees) between the original neutral position and the final position of the athlete in the apparatus. In addition, weight, height, body mass index (BMI), and gender were also included in the analysis. Next, the parameter contributing the least to the regression model was removed and the process repeated at each iteration until only the parameters with $P \leq .1$ remained. An a priori power analysis was performed, based on pilot testing, and it was determined that 21 injuries were needed to achieve power of .8.

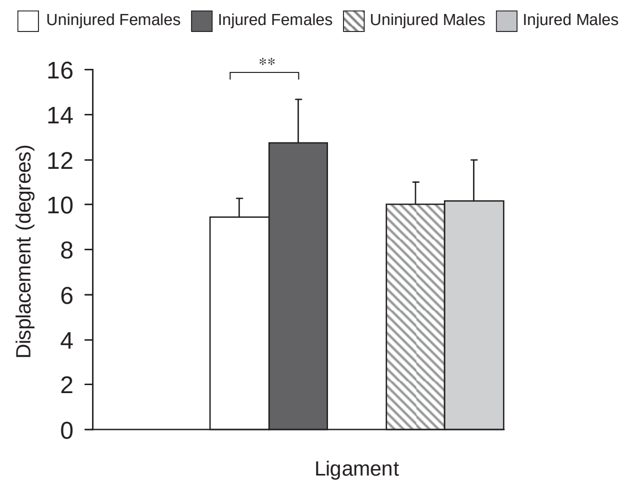

Figure 4. Maximum displacement in female and male athletes who subsequently sustained or did not sustain ligament injury. $^{**}P \leq .01$. Error bars designate standard error of the mean.

TABLE 2
P Values (*P*) and Odds Ratios (OR) for the Binary Logistic Regression Analysis for All Athletes[a]

	Knee		Ligament		ACL	
Variable	OR	*P*	OR	*P*	OR	*P*
Lateral displacement	2.14[b]	.001[b]	2.22[b]	.016[b]	2.32[b]	.02[b]
Extension displacement	1.25[b]	.025[b]	1.32	.055	1.61	.012
Flexion displacement	1.23	.062	1.48[b]	.017[b]	1.62[b]	.02[b]
APR	1.83[b]	.030[b]				
History of LBP	2.79[b]	.036[b]	6.75[b]	.006		
Overall *P*	< .0001[b]		.001[b]		.002[b]	
Concordance (%)	77.7[b]		84.5[b]		80.9[b]	
Sensitivity (%)	83[b]		91[b]		83[b]	
Specificity (%)	63[b]		68[b]		76[b]	

[a]ACL, anterior cruciate ligament; APR, active proprioceptive repositioning error of the trunk; LBP, low back pain.
[b]Significant predictors.

RESULTS

During the 3-year follow-up period, the cohort of 277 athletes sustained 25 knee injuries; 11 were sustained by female athletes and 14 by male athletes. Eleven of these knee injuries were ligament injuries (5 women and 6 men), and 6 were ACL ruptures confirmed by MRI (4 women and 2 men). Both displacement at 150 milliseconds and maximum displacement were significantly greater in knee-injured, knee ligament–injured, and ACL-injured athletes compared with uninjured athletes (Figures 2 and 3). In addition, ligament-injured female athletes demonstrated greater maximum displacement than uninjured female athletes (P = .005) (Figure 4). No significant differences were observed in maximal displacement between the male injured/uninjured groups.

TABLE 3
Binary Logistic Regression Analysis of the 3 Displacements on Knee, Ligament, and ACL Injury Risk in All Athletes and by Gender[a]

	All Injured Athletes			Injured Female Athletes			Injured Male Athletes		
Variable	Knee	Lig	ACL	Knee	Lig	ACL	Knee	Lig	ACL
Lateral displacement	.001[b]	.009[b]	.014[b]	.024[b]	.024[b]	.09	.016[b]	.152	.058
Overall *P*	.001[b]	.011[b]	.020[b]	.027[b]	.030[b]	.117	.013[b]	.156	.540
OR	1.91[b]	1.99[b]	2.24[b]	1.89[b]	2.28[b]	1.96	1.91[b]	1.71	3.24
Concordance (%)	70.7[b]	73.0[b]	78.8[b]	73.5[b]	85.8[b]	83.2	67.7[b]	62.7	76.4
Extension displacement	.506	.794	.354	.379	.384	.127	.773	.807	.682
Overall *P*	.501	.793	.335	.360	.406	.108	.774	.808	.684
OR	1.05	1.03	1.16	1.14	1.19	1.47	1.03	0.97	0.91
Concordance (%)	48.7	42.9	52.3	50.5	48.1	58.1	46.9	46.6	55.4
Flexion displacement	.056	.042	.045	.209	.098	.172	.146	.234	.138
Overall *P*	.061	.051	.061	.222	.080	.200	.139	.217	.165
OR	1.17	1.26	1.33	1.19	1.37	1.32	1.17	1.20	1.38
Concordance (%)	59.5	65.5	67.9	63.8	80.3	78.4	57.0	54.3	52.9

[a]ACL, anterior cruciate ligament; Lig, ligament; OR, odds ratio.
[b]Significant predictors.

TABLE 4
P Values (*P*) and Odds Ratios (OR) for the Binary Logistic Regression Analysis by Gender[a]

	Female Athletes						Male Athletes					
	Knee		Ligament		ACL		Knee		Ligament		ACL	
Variable	OR	*P*	OR	*P*	OR	*P*	OR	*P*	OR	*P*	OR	*P*
Lateral displacement	2.33[b]	.024[b]	3.48[b]	.033[b]	2.53	.099		.014		.208		.126
Extension displacement	1.35[b]	.084[b]	1.85[b]	.011[b]	1.85[b]	.014[b]		.195		.613		.599
Flexion displacement	—	.131	2.31[b]	.016[b]	1.97[b]	.036[b]		.251		.213		.322
APR	4.62[b]	.002[b]						.787				
History of LBP	6.19[b]	.024[b]		.116				.290	9.94[b]	.015[b]		
Overall *P*	< .0001[b]		.005[b]		.012[b]		.063		.046[b]		.18	
Concordance (%)	84.5[b]		90.6[b]		89.2[b]		74.3		83.1[b]		70.2	

[a]ACL, anterior cruciate ligament; APR, active proprioceptive repositioning error of the trunk; LBP, low back pain.
[b]Significant predictors.

A multiple logistic regression model that included all athletes predicted knee injury, ligament injury, and ACL injury with high sensitivity and moderate specificity (Table 2). The variables in the final model (those with $P \le .1$) included lateral, extension, and flexion angular trunk displacements at 150 milliseconds, APR error of the trunk, and history of LBP. Maximum displacements were eliminated from all regression models ($P \ge .1$) because of their correlation with displacements at 150 milliseconds, which better predicted injury. The combination of factors related to core stability (increased displacement at 150 milliseconds in all 3 measured directions, absolute error in APR, and history of LBP) predicted knee injury with 83% sensitivity and 63% specificity ($P < .0001$). Displacements at 150 milliseconds in all 3 directions and history of LBP predicted ligament injury with 91% sensitivity and 68% specificity ($P = .001$). Lateral, extension, and flexion displacements were the sole predictors of ACL injury, with 83% sensitivity and 76% specificity ($P = .002$).

A binary logistic regression analysis was performed to determine the relative predictive value of the 3 displacements on knee, ligament, and ACL injury risk in all athletes combined and in the 2 genders separately (Table 3). Of the 3 displacements, lateral displacement was the strongest single predictor of knee, ligament, and ACL injury in all athletes (odds ratios, 1.9, 2.0, and 2.2, respectively). When split by gender, lateral displacement was the sole significant predictor of ligament injury risk in female athletes but was not a predictor in male athletes. Lateral displacement predicted ligament injury with 100% sensitivity and 72% specificity in female athletes ($P = .024$) but did not predict injury in male athletes.

The relative predictive value of each of the variables differed when the regression model was analyzed by gender (Table 4). The model of core stability parameters predicted injury in the knee, ligament, and ACL-injured groups for female athletes with 85%, 91%, and 89% accuracy (concordant observations), respectively ($P < .0001$, $P < .005$, and

$P < .012$, respectively). The strongest predictors of injury in the female athletes were the displacement variables. Active proprioceptive repositioning error and history of LBP were also predictors of knee injury in female athletes. In the male injured group, the model only reached statistical significance for the ligament-injured subjects, for whom history of LBP was the strongest predictor of injury, with 83% concordant observations ($P = .015$).

DISCUSSION

The current study demonstrates that factors related to core stability predict knee, ligament, and ACL injury risk in athletes. The findings support the first hypothesis, that increased trunk displacement in response to sudden trunk force release is associated with increased knee injury risk. Increased displacement was consistently observed in knee, ligament, and ACL-injured athletes versus uninjured athletes at both 150 milliseconds and maximum displacement. The increased trunk displacement observed in both of these measures in injured athletes likely indicates a potential neuromuscular impairment in the control of the body's core. Decreased neuromuscular control of the trunk appears to influence dynamic stability of the knee joint and to increase knee injury risk during high-speed athletic maneuvers. High ground-reaction forces directed toward the body's center of mass, coupled with decreased trunk neuromuscular control, may compromise dynamic stability of the knee.

Measurable deficits in trunk control may identify female and male athletes at increased risk of injury. Deficits in peak hip abduction and external rotation strength (albeit measured with handheld dynamometers) were observed in female athletes with patellofemoral pain. The authors of that study suggested that these strength deficits of the proximal musculature may contribute to the knee positioned of adduction and internal rotation, which is associated with high lateral retropatellar contact pressure.[19] A prospective study reported that decreased hip external rotation strength, again measured with handheld dynamometers, was the only significant predictor of combined back and lower extremity injury risk.[22] In addition, female athletes demonstrated significantly decreased femoral abduction and external rotation strength and significantly decreased quadratus lumborum endurance compared with male athletes.[22] However, there are several limitations to this prior study. It was underpowered, used handheld dynamometer measures of hip strength, which are questionable measures of core stability, and may have had overly liberal inclusionary criteria for injuries as all back and lower extremity injuries were pooled together. Further prospective study using state-of-the-art measures of core neuromuscular control was required to better ascertain the association between core stability and knee injury risk and to validate the use of core stability measures for identification of potentially high-risk individuals. Therefore, this prospective study provides evidence for the treatment of these individuals with neuromuscular training programs, designed to prevent knee injury, that incorporate core stability exercises.

Decreased core neuromuscular control may contribute to increased valgus positioning of the lower extremity, while training of the trunk musculature may increase control of hip adduction and internal rotation during weightbearing functional activities and decrease the tendency toward valgus collapse.[11,25,39] Neuromuscular training studies that incorporate core stability exercises decrease knee injury risk, which further supports the theory that neuromuscular control of the core is related to dynamic knee stability.[12,23,28] In a prospective cohort study, Hewett et al[13] reported that female athletes who participated in a neuromuscular training program that included core stability exercises demonstrated a 72% decrease in the incidence of knee ligament (including ACL) injuries compared with female athletes who did not participate in the program. Neuromuscular training reduces hip adduction and knee abduction torques during landing,[15,26] which are associated with increased knee and ACL injury risk.[13]

The finding of excessive lateral displacement in the coronal plane exhibited in injured athletes supported our second hypothesis, that lateral angular displacement of the trunk would be the single best predictor of knee ligament injury. These results are consistent with the findings of Paterno et al,[30] who reported that core proprioceptive neuromuscular training improved body sway in the anterior-posterior but not medial-lateral plane in female athletes. They hypothesized that emphasis should be placed on proprioceptive training in the coronal plane, as the coronal plane is associated with valgus collapse and subsequent ligament injury in this high-risk population.[13]

Measures of core stability, specifically trunk displacement, active trunk proprioception, and history of LBP, were significant predictors of knee, ligament, and ACL injury risk in female athletes. These findings supported our third and fourth hypotheses, as these parameters were not strong predictors of injury risk in male athletes. History of LBP was a significant predictor of knee injury in female athletes and ligament injury in male athletes, independent of other measured factors related to core stability. History of LBP can result in long-lasting alterations in trunk motor control.[31,33] Subjects with LBP were reported to demonstrate impaired postural control,[32] delayed muscle reflex latencies in response to sudden trunk unloading,[31,33] and abnormalities in trunk muscle recruitment patterns.[35] More specifically, athletes with a history of LBP, even after clinical recovery and return to their prior level of competition, continued to demonstrate motor control deficits of the trunk.[5,34] These athletes have a 3-fold greater risk of sustaining a low back injury than athletes without a history of LBP, which may be indicative of persistent deficits in neuromuscular control of the body's core.[10] Therefore, the current study has identified significant predictors of knee, ligament, and ACL injury. It is notable that all of these predictors are related to core stability.

Limitations of this study include a relatively low number of observed injuries, specifically ligament and ACL injuries. However, the power analysis was met since a total of 25 knee injuries occurred, whereas 21 were required for adequate power. Another limitation of this study was that the athletes may have varied in the type and amount of preparticipation neuromuscular training. Furthermore, the objective measures taken in the current study did not incorporate the entirety of the potential components of core stability. However, important components of core stability, including displacement after trunk force release, active proprioceptive repositioning, and history of LBP, were found to be highly predictive of knee injuries. The tests of displacement after sudden release were conducted under relatively artificial conditions and postures. The pelvis was restrained in the semiseated testing apparatus, which is not a functional athletic position; however, this position was chosen to control other potential neuromuscular response strategies mediated through movement of the hips, knees, and ankles.

CONCLUSIONS

Athletes with decreased neuromuscular control of the body's core, measured during sudden force release tasks and trunk repositioning, are at increased risk of knee injury. Athletes may be evaluated for deficits in core stability before competition and prophylactically treated with dynamic neuromuscular training targeted toward their specific deficits in core motor control. Both female and male athletes could be evaluated for trunk motion after perturbation or isometric force release, especially in the coronal plane. In addition, female athletes could also be monitored for their ability to actively reposition the trunk. The implementation of interventions that incorporate core stability training, including proprioceptive exercise, perturbation, and correction of body sway, has the potential to reduce knee, ligament, and ACL injury risk in both female and male athletes. Future research should focus on controlled, prospective longitudinal studies of defined populations of athletes who are followed through multiple sport seasons to correlate core stability profiles with injury risk. The efficacy of neuromuscular training interventions targeted toward the improvement of core stability measures is also a high priority for future studies.

ACKNOWLEDGMENT

This work was supported by National Institutes of Health (NIH) Grant R01-AR049735 (T.E.H.) and NIH Grant 5R01-AR46844 (J.C.), from the National Institute of Arthritis and Musculoskeletal and Skin Diseases.

REFERENCES

1. Beckman SM, Buchanan TS. Ankle inversion injury and hypermobility: effect on hip and ankle muscle electromyography onset latency. *Arch Phys Med Rehabil.* 1995;76:1138-1143.
2. Bendjaballah MZ, Shirazi-Adl A, Zukor DJ. Finite element analysis of human knee joint in varus-valgus. *Clin Biomech (Bristol, Avon).* 1997;12:139-148.
3. Beynnon B, Vacek PM, Abate JA III, Murphy D, Paller D. A prospective study of risk factors for first time ankle inversion ankle ligament trauma. Presented at the 32nd annual meeting of the American Orthopaedic Society for Sports Medicine; 2006; Hershey, Pa.
4. Bullock-Saxton JE, Janda V, Bullock MI. The influence of ankle sprain injury on muscle activation during hip extension. *Int J Sports Med.* 1994;15:330-334.
5. Cholewicki J, Greene HS, Polzhofer GK, Galloway MT, Shah RA, Radebold A. Neuromuscular function in athletes following recovery from a recent acute low back injury. *J Orthop Sports Phys Ther.* 2002;32:568-575.
6. Cholewicki J, McGill SM. Mechanical stability of the in vivo lumbar spine: implications for injury and chronic low back pain. *Clin Biomech (Bristol, Avon).* 1996;11:1-15.
7. Cholewicki J, Silfies SP, Shah RA, et al. Delayed trunk muscle reflex responses increase the risk of low back injuries. *Spine.* 2005;30:2614-2620.
8. Cholewicki J, VanVliet JJ. Relative contribution of trunk muscles to the stability of the lumbar spine during isometric exertions. *Clin Biomech (Bristol, Avon).* 2002;17:99-105.
9. Devlin L. Recurrent posterior thigh symptoms detrimental to performance in rugby union: predisposing factors. *Sports Med.* 2000;29:273-287.
10. Greene HS, Cholewicki J, Galloway MT, Nguyen CV, Radebold A. A history of low back injury is a risk factor for recurrent back injuries in varsity athletes. *Am J Sports Med.* 2001;29:795-800.
11. Hewett TE, Ford KR, Myer GD, Wanstrath K, Scheper M. Gender differences in hip adduction motion and torque during a single leg agility maneuver. *J Orthop Res.* 2006;24:416-421.
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;27:699-706.
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;33:492-501.
14. Hewett TE, Paterno MV, Myer GD. Strategies for enhancing proprioception and neuromuscular control of the knee. *Clin Orthop Relat Res.* 2002;402:76-94.
15. Hewett TE, Stroupe AL, Nance TA, Noyes FR. Plyometric training in female athletes: decreased impact forces and increased hamstring torques. *Am J Sports Med.* 1996;24:765-773.
16. Hewett TE, Zazulak BT, Myer GD, Ford KR. A review of electromyographic activation levels, timing differences, and increased anterior cruciate ligament injury incidence in female athletes. *Br J Sports Med.* 2005;39:347-350.
17. Hodges PW, Richardson CA. Contraction of the abdominal muscles associated with movement of the lower limb. *Phys Ther.* 1997;77:132-144.
18. Hodges PW, Richardson CA. Feedforward contraction of transversus abdominis is not influenced by the direction of arm movement. *Exp Brain Res.* 1997;114:362-370.
19. Ireland ML, Willson JD, Ballantyne BT, Davis IM. Hip strength in females with and without patellofemoral pain. *J Orthop Sports Phys Ther.* 2003;33:671-676.
20. Kibler WB, Press J, Sciascia A. The role of core stability in athletic function. *Sports Med.* 2006;36:189-198.
21. Krosshaug T, Nakame A, Boden B, et al. Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases. *Am J Sports Med.* 2007;35:359-367.
22. Leetun DT, Ireland ML, Willson JD, Ballantyne BT, Davis IM. Core stability measures as risk factors for lower extremity injury in athletes. *Med Sci Sports Exerc.* 2004;36:926-934.
23. 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;33:1003-1010.
24. Markolf KL, Burchfield DM, Shapiro MM, Shepard MF, Finerman GA, Slauterbeck JL. Combined knee loading states that generate high anterior cruciate ligament forces. *J Orthop Res.* 1995;13:930-935.
25. McConnell J. The physical therapist's approach to patellofemoral disorders. *Clin Sports Med.* 2002;21:363-387.
26. Myer GD, Ford KR, Brent JL, Hewett TE. The effects of plyometric versus dynamic balance training on power, balance and landing force in female athletes. *J Strength Cond Res.* 2006;20:345-353.
27. Myer GD, Ford KR, Palumbo JP, Hewett TE. Comprehensive neuromuscular training improves both performance and lower extremity

biomechanics in female athletes. *J Strength Cond Res.* 2005;19: 51-60.
28. 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;13:71-78.
29. National Collegiate Athletic Association. *NCAA Injury Surveillance System Summary.* Indianapolis, In: National Collegiate Athletic Association; 2002. Available at: http://www.ncaa.org.
30. Paterno MV, Myer GD, Ford KR, Hewett TE. Neuromuscular training improves single-limb stability in young female athletes. *J Orthop Sports Phys Ther.* 2004;34:305-317.
31. Radebold A, Cholewicki J, Panjabi MM, Patel TC. Muscle response pattern to sudden trunk loading in healthy individuals and in patients with chronic low back pain. *Spine.* 2000;25:947-954.
32. Radebold A, Cholewicki J, Polzhofer GK, Greene HS. Impaired postural control of the lumbar spine is associated with delayed muscle response times in patients with chronic idiopathic low back pain. *Spine.* 2001;26:724-730.
33. Reeves NP, Cholewicki J, Milner TE. Muscle reflex classification of low-back pain. *J Electromyogr Kinesiol.* 2005;15:53-60.
34. Reeves NP, Cholewicki J, Silfies SP. Muscle activation imbalance and low-back injury in varsity athletes. *J Electromyogr Kinesiol.* 2006;16: 264-272.
35. van Dieen JH, Selen LP, Cholewicki J. Trunk muscle activation in low-back pain patients: an analysis of the literature. *J Electromyogr Kinesiol.* 2003;13:333-351.
36. Wilder DG, Aleksiev AR, Magnusson ML, Pope MH, Spratt KF, Goel VK. Muscular response to sudden load: a tool to evaluate fatigue and rehabilitation. *Spine.* 1996;21:2628-2639.
37. Wojtys EM, Huston LJ, Taylor PD, Bastian SD. Neuromuscular adaptations in isokinetic, isotonic, and agility training programs. *Am J Sports Med.* 1996;24:187-192.
38. Zazulak BT, Hewett TE, Reeves NP, Goldberg B, Cholewicki J. The effects of core proprioception on knee injury: a prospective biomechanical-epidemiological study. *Am J Sports Med.* 2007;35:368-373.
39. Zazulak BT, Ponce PL, Straub SJ, Medvecky MJ, Avedisian LA, Hewett TE. The effect of gender on hip muscle activity during landing. *J Orthop Sports Phys Ther.* 2005;35:292-299.