Female athletes have a greater susceptibility to knee injury than male athletes. The combination of this greater susceptibility and a 10-fold increase in the female sports population since the inception of Title IX has resulted in a dramatic increase in the number of knee injuries in women. In the United States, women and girls sustain more than 30,000 anterior cruciate ligament (ACL) injuries a year, with costs that may exceed $650 million annually. The mechanism of ACL injury may include a combination of the following components: valgus positioning of the lower extremity; relative extension with unbalanced weight distribution; and the center of the mass of the body displaced away from the plantar surface of the

---

**Background:** In sports involving pivoting and landing, female athletes suffer knee injury at a greater rate than male athletes.

**Hypotheses:** Proprioceptive deficits in control of the body’s core may affect dynamic stability of the knee. Female, but not male, athletes who suffered a knee injury during a 3-year follow-up period would demonstrate decreased core proprioception at baseline testing as compared with uninjured athletes.

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

**Methods:** Study subjects were 277 collegiate athletes (140 female, 137 male) who were prospectively tested for core proprioception by active proprioceptive repositioning and passive proprioceptive repositioning. Athletes were monitored for injury for 3 years. An ANOVA and multivariate logistic regression were used to test whether core proprioception was related to knee injuries in athletes.

**Results:** Twenty-five athletes sustained knee injuries (11 women, 14 men). Deficits in active proprioceptive repositioning were observed in women with knee injuries (2.2°) and ligament/meniscal injuries (2.4°) compared with uninjured women (1.5°, P ≤ .05). There were no differences in average active proprioceptive repositioning error between injured men and uninjured men (P ≥ .05). Uninjured women demonstrated significantly less average error in active proprioceptive repositioning than uninjured men (1.5° vs 1.7°, P ≤ .05). For each degree increase in average active proprioceptive repositioning error, a 2.9-fold increase in the odds ratio of knee injury was observed, and a 3.3-fold increase in odds ratio of ligament/meniscal injury was observed (P ≤ .01). Active proprioceptive repositioning predicted knee injury status with 90% sensitivity and 56% specificity in female athletes.

**Conclusions:** Impaired core proprioception, measured by active proprioceptive repositioning of the trunk, predicted knee injury risk in female, but not male, athletes.

**Keywords:** neuromuscular control; proprioception; ACL injury; gender sex differences; injury prevention
Proprioceptive deficits in the body's core may contribute to decreased active neuromuscular control of the lower extremity, which may lead to valgus angulation and increased strain on the ligaments of the knee.\textsuperscript{12,22} The core of the body includes the passive structures of the thoracolumbar spine and pelvis and the active contributions of the trunk musculature.\textsuperscript{35} The stability of the body's core is contingent on neuromuscular control of the trunk in response to internal and external forces, including the forces generated from distal body parts and from expected or unexpected perturbations. Core stability, as generally defined in 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.\textsuperscript{30} For the purposes of this study, a more precise operational definition was developed. Core stability was defined as the body's capacity to maintain or resume a relative position of the trunk after perturbation.

Deficits in core neuromuscular control may contribute to unstable behavior and injury throughout all segments of the kinetic chain.\textsuperscript{13} For example, abdominal muscle fatigue appears to contribute to hamstring injuries.\textsuperscript{10} In agreement with these findings, retrospective studies of subjects with prior ankle sprains demonstrated a delay in the onset of muscle activation of the gluteus maximus\textsuperscript{6} and the gluteus medius.\textsuperscript{2} Cholewicki et al\textsuperscript{8} observed prospectively that delayed trunk muscle reflex responses predicted low-back injuries in collegiate athletes. A recent large prospective cohort study reported that female athletes who subsequently suffered an ankle injury demonstrated significantly greater body sway than uninjured athletes.\textsuperscript{4} In contrast, predictors of injury in male athletes were related to ankle range of motion and not measures of proprioception.\textsuperscript{4} To date, no study has established a correlation between core neuromuscular control and knee injury.

Many athletic maneuvers, such as running, jumping, and cutting, are inherently unstable and require neuromuscular control to maintain stability and improve performance.\textsuperscript{25,26} Neuromuscular control of the trunk is based on feedback control. The information concerning the state of the system, such as position of each segment, is fed back and used to modify the descending movement commands. A host of sensory information is used to track the system over time.\textsuperscript{11} Because control is driven by the estimated state and not the true state, accuracy in representation becomes an issue. A poorly represented system cannot be controlled properly and at some point will become unstable. Consequently, impaired core proprioception may lead to impaired control of the core, which in turn affects control of the knee and may lead to knee injury.

The purpose of this study is to identify potential factors related to neuromuscular control of the trunk that predispose athletes to knee injuries. We hypothesize that core proprioception may play a role in dynamic stability of the lower extremity and subsequent knee injuries. The first hypothesis is that decreased proprioception will increase knee injury risk. The second hypothesis is that proprioceptive deficits will predict knee injury risk in female athletes but not in male athletes. Measurable deficiencies in core proprioception could identify modifiable neuromuscular risk factors that predispose athletes to knee injury.

METHODS

Subjects

Subjects were 277 Yale varsity athletes who volunteered for the study. The participants comprised 140 women (mean age, 19.4 yrs ± 1.0; mean height, 1.70 m ± 0.08; mean body mass, 65.6 kg ± 8.7; mean body mass index, 22.6 kg/m\(^2\) ± 2.2) and 137 men (mean age, 19.3 yrs ± 1.8; mean height, 1.83 m ± 0.08; mean body mass, 79.9 kg ± 11.9; mean body mass index, 23.8 kg/m\(^2\) ± 2.8). Athletes were tested at baseline and then followed for 3 years (38 months) to track any knee injuries sustained during that period. Before experimental testing, every subject completed a detailed, 45-item questionnaire pertaining to personal data (height, weight, and age), athletic experience, varsity level sport(s) affiliation, and history of injury. None of the athletes enrolled in the study had any history of knee injury. Knee injury was defined as any ligament, meniscal, or patellofemoral injury diagnosed by the university sports medicine physician. Fractures and contusions were excluded from the knee-injured athlete group. Knee injuries were further subclassified as only ligament and/or meniscal, and then only ACL injuries. Athletes were not injured at the time of the test. All ligament and meniscal injuries were confirmed by magnetic resonance imaging (MRI). All subjects understood the experimental protocol and signed the consent form, both of which were approved by the Human Investigation Committee.

Proprioception Experiment

Core proprioception was evaluated using a previously validated apparatus as described by Taimela et al (Figure 1).\textsuperscript{23,24,33} The apparatus was designed to produce passive motion of the lumbar spine in the transverse plane. Subjects were positioned on this apparatus so that the vertical pivot axis extended through the L4/L5 vertebrae. The seat was driven by a stepper motor at a steady, slow rate to minimize tactile cueing. The contribution of a vestibular system was eliminated since the upper body remained fixed to the backrest with a 4-point seatbelt and the lower body moved in the plane parallel to the ground. Care was taken to eliminate visual and auditory cues of the apparatus motion. Therefore, this proprioception test focused mainly on the feedback from muscular and articular mechanoreceptors of the trunk.

Subjects were initially rotated 20° away from the neutral spine posture (at 2° per second) and briefly held in that position for 3 seconds. In the passive test, the subjects were slowly rotated toward the original position by the motor (at 1° per second). In the active test, the subject rotated himself or herself after the clutch was disengaged from the motor drive. In both tests, the subjects stopped the apparatus by pressing a switch when they perceived they...
were in the original, neutral position. Each subject performed 4 practice trials before each test, 2 in each direction. Subsequently, 5 randomized trials in each direction for each test were performed.

Statistical Analysis

The average absolute repositioning errors from all 10 trials were calculated. To determine the most appropriate set of parameters for regression analysis, a 2-factor ANOVA with Tukey’s post-hoc test was used to identify the measures that differed significantly between the injured and uninjured athletes ($P \leq .05$). The 2 factors were as follows: knee injury versus no knee injury during the follow-up, and male versus female. The dependent measures were the average absolute error in active proprioceptive repositioning (APR) and passive proprioceptive repositioning (PPR). A prior analysis determined that 21 injuries were required to achieve an adequate power of 0.8.

The reproducibility of both measures was tested by computing intraclass correlation coefficients (ICC) ($2, k$) between the averages of the first 5 trials and the last 5 trials for each of the 277 subjects. The reproducibility of APR and PPR was good as indicated by the ICC of 0.61 and 0.58, respectively.

RESULTS

During the 3-year posttest follow-up period, 25 of the 277 athletes sustained knee injuries; 11 occurred in female subjects and 14 in male subjects (Table 1). There were 14 ligament and/or meniscal injuries; 6 occurred in women and 8 in men. Of these, 11 were ligament injuries. Six subjects sustained ACL rupture, 4 females and 2 males. All ACL injuries were confirmed by MRI.

The ANOVA returned a significant interaction between sex and knee injuries. Deficits in APR were observed in female subjects with knee (2.2°) and ligament/meniscal injuries (2.4°) compared with uninjured female subjects (1.5°, $P \leq .05$) (Figure 2). There was no significant difference in average error in APR between injured male subjects compared with uninjured male subjects ($P \geq .05$) (Figure 2). Interestingly, uninjured female subjects demonstrated significantly less average error in APR than uninjured male subjects (1.5° vs 1.7°, $P \leq .05$) (Figure 2). No difference in the average error in PPR was observed in knee injured versus uninjured athletes ($P \geq .05$).

Figure 2. Average absolute error in active proprioceptive repositioning in female and male athletes who sustained or did not sustain knee, ligament/meniscal, or anterior cruciate ligament injury during the follow-up period (*$P < .05$). Error bars designate standard error of the mean.
For each degree increase in average APR error, a 2.9-fold increase in the odds ratio of knee injury \((P = .005)\) and 3.3-fold increase in the odds ratio of ligament/meniscal injury were observed \((P = .007)\). Active proprioceptive repositioning predicted knee injury status with 90% sensitivity and 56% specificity, and ligament/meniscal injuries with 86% and 61% specificity in female athletes (Table 2).

**DISCUSSION**

The findings of the current study demonstrate that increased error in trunk proprioception is associated with increased knee injury risk, which supports our first hypothesis. The poor APR of the trunk in those female athletes who subsequently suffered knee injuries supports our second hypothesis and indicates that decreased core proprioception could alter dynamic knee stability and may explain the increased risk of knee injury during sports activity in this high-risk population.

The proprioceptive deficits were observed in APR and not PPR in the injured female athletes. The active (APR) and passive (PPR) tests differ with respect to the relative contribution of the muscle receptor sensory input. In the active test, trunk muscles generate the movement and maintain fusimotor drive, therefore muscle spindle feedback is involved. However, during the passive test, when muscles are not active, fusimotor activity and the sensory feedback from muscle spindles are decreased. Therefore, input from joint and cutaneous receptors likely plays a greater role in sensory feedback. Hence, the level of input from the muscle spindles during reproduction of the trunk position likely differed between the active and passive tests. The observed deficits in active proprioception may have been translated to active athletic maneuvers associated with knee injuries.

The second hypothesis is that proprioceptive deficits would predict knee injury risk in female athletes. We hypothesized that this relationship would not be observed in male athletes for several reasons. First, male and female athletes have different ACL injury rates and potentially different underlying mechanisms of ACL injury. Second, our prior data demonstrated that body sway was significantly worse in female subjects who suffered ACL injury than in male subjects who sustained ACL injury. In agreement with these earlier findings, the female athletes who did not subsequently suffer knee injury had significantly better trunk proprioceptive ability than male athletes who did not go on to sustain knee injury. In addition, the findings of Beynnon et al related to ankle injury indicate that women and men have significantly different predictors of injury risk. Body sway was reported to be a strong predictor of ankle injury risk in female but not male

<table>
<thead>
<tr>
<th>Athlete</th>
<th>Sex</th>
<th>Injury</th>
<th>Knee</th>
<th>Lig/Men</th>
<th>ACL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>F</td>
<td>ACL</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>2</td>
<td>M</td>
<td>ACL/MCL</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>3</td>
<td>M</td>
<td>PF</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>4</td>
<td>M</td>
<td>MCL</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>5</td>
<td>F</td>
<td>ACL/MCL/MEN</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>6</td>
<td>F</td>
<td>PF</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>7</td>
<td>M</td>
<td>PF</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>8</td>
<td>M</td>
<td>LCL/MEN</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>9</td>
<td>M</td>
<td>PF</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>10</td>
<td>F</td>
<td>PF</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>11</td>
<td>F</td>
<td>PF</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>12</td>
<td>F</td>
<td>PF</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>13</td>
<td>F</td>
<td>MEN</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>14</td>
<td>M</td>
<td>PF</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>15</td>
<td>F</td>
<td>PF/MEN</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>16</td>
<td>M</td>
<td>PF/MEN</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>17</td>
<td>M</td>
<td>MEN</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>18</td>
<td>M</td>
<td>MCL/MEN</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>19</td>
<td>F</td>
<td>ACL/MEN</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>20</td>
<td>F</td>
<td>PF/MEN</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>21</td>
<td>M</td>
<td>PF</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>22</td>
<td>M</td>
<td>MEN</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>23</td>
<td>M</td>
<td>ACL/MEN</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>24</td>
<td>M</td>
<td>MCL</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>25</td>
<td>F</td>
<td>ACL/MEN</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

*Lig/men, ligament and meniscus; MEN, meniscus; ACL, anterior cruciate ligament; F, females; M, males; MCL, medial collateral ligament; PF, patellofemoral; LCL, lateral collateral ligament.*
There is no previously published literature to the authors’ knowledge supporting a relationship between decreased core proprioception and knee injury. Our prospective study lends greater credence to this association between decreased neuromuscular control of the body’s core and increased knee injury risk.

Hewett et al. suggested that dynamic neuromuscular training that enhances control of the body’s core would improve dynamic stability of the knee joint. Proprioceptive and neuromuscular control deficits are observed after ACL rupture and well into the postoperative rehabilitation period. Patients with ACL deficiency have impaired postural sway. Women with ACL-deficient knees and after ACL reconstruction possess greater deficits in proprioception and neuromuscular control, as measured by postural sway deficits, than their injured and reconstructed male counterparts.

The published literature referencing sex differences in postural sway is equivocal, as 2 other studies reported postural sway on stable force platforms in healthy subjects and observed no differences between sexes. In contrast, Hewett et al. examined single-leg balance of male control subjects compared with female control subjects on a dynamic unstable platform and reported that the female subjects performed significantly better than the male subjects. However, in the subjects with ACL deficiency, the men had significantly better preoperative performance than the women. The finding of proprioceptive differences between sexes raises important issues. First, women with intact knees have better single-leg balance than men with intact knees. This difference is presumed to be attributable to the lower center of gravity in female control subjects. However, after an ACL injury, women seem to experience greater deficits in balance than men. In addition, the return of single-leg balance after ACL reconstruction is slower in women than in men.

Hewett et al. pose an important question of whether female subjects with ACL ruptures possess deficits in balance or postural control before injury, which creates a predisposition to injury, or the alternative possibility that ACL injury is more traumatic to the proprioceptive systems of women than men. The findings of the current study of better active proprioception in healthy female athletes compared with healthy male athletes are consistent with previous findings in healthy athletes, where women have a superior ability to control body sway on a single limb compared to men. Furthermore, the prospectively measured proprioceptive deficits exhibited by injured female athletes support the theory that these deficits may predispose the athlete to knee injury. The possibility that female athletes with proprioceptive deficits possess a greater propensity for knee injury suggests the need for prescreening before athletic participation to assess injury risk. There is strong evidence that neuromuscular control of the trunk and lower extremity can be improved with neuromuscular training.

Our study had a relatively low number of injuries, particularly of the ACL. This low subject number may have potentially precluded our ability to detect poor APR as a predictor of ligament and ACL injuries. However, the power analysis was met for total injuries. A prior analysis determined that 21 injuries were required to achieve an adequate power of 0.8, whereas 25 injuries occurred in the study cohort of 277 subjects. Therefore, negative findings relative to ligament and ACL injuries are not reported to avoid potential beta-type error.

The tests of proprioception in the lumbar spine were conducted under relatively artificial conditions and postures. The pelvis was immobilized to isolate trunk movement. Most clinical tests of postural sway and proprioception are performed with the subject balancing on a single leg, which involves all segments of the lower extremity and trunk. All these factors are potential confounding variables relative to isolated core proprioception in these clinical tests. In contrast, the current reported method is a more direct measure of core proprioception.

### CONCLUSION

Decreased active core proprioception predicted knee injury risk in female athletes. Athletes may be evaluated for proprioceptive deficits before competition and targeted for specific active neuromuscular training. Interventions that incorporate core neuromuscular training, including
proprioceptive exercises, may significantly reduce knee injury risk in this high-risk athletic population. Future research should focus on neuromuscular training interventions specifically targeted to improve core proprioception. Well-controlled, prospective longitudinal studies of defined populations of athletes should follow athletes through multiple sports seasons to correlate changing core proprioceptive profiles to injury risk.

ACKNOWLEDGMENT

This work was supported by National Institutes of Health grants R01-AR049735-01A1 (TEH) and NIH grant R01-AR46844 (JC) from the National Institute of Arthritis and Musculoskeletal and Skin Diseases.

REFERENCES