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The Effects of Joint Position and Direction of Joint Motion on Proprioceptive Sensibility in Anterior Cruciate Ligament-Deficient Athletes

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ABSTRACT

We studied a group of anterior cruciate ligament-deficient athletes to identify whether joint position and direction of joint motion have a significant effect on proprioception. Twenty-nine anterior cruciate ligament-deficient athletes were tested for their threshold to detect passive motion at both 15° and 45° moving into the directions of both flexion and extension. The single-legged hop test was used to identify function in the deficient limb. Results demonstrated statistically significant deficits in threshold to detect passive motion for the deficient limb at 15° moving into extension. For the deficient limb, threshold to detect passive motion was significantly more sensitive moving into extension than flexion at a starting angle of 15°; at a starting angle of 15° moving into extension threshold was significantly more sensitive than at a starting angle of 45° moving into extension. We conclude that in deficient limbs proprioception is significantly more sensitive in the end ranges of knee extension (15°) and is significantly more sensitive moving into the direction of extension. To effectively restore reflex stabilization of the lower limb we recommend a rehabilitation program emphasizing performance-based, weightbearing, closed kinetic chain exercise for the muscle groups that act on the knee joint.

In addition to its mechanical restraining function, the ACL provides important sensory (afferent) feedback that directly mediates joint position sensibility and muscular reflex stabilization about the knee joint.[12,13] This sensory feedback mechanism is referred to as proprioception. The ACL has an extensive afferent neural network providing the anatomic basis for proprioception.[13,17,18] Proprioception is a specialized variation of the sensory modality of touch and encompasses the neurosensibility of joint motion and position. The proprioceptive mechanism serves to protect against excessive strain on the passive joint restraints during functional activity and provides prophylaxis to recurrent injury.[5,11,16]

Recent investigations involving the knee have drawn attention to the sensory role of the ACL and the proprioceptive deficits after injury.[1,14] Researchers have postulated that proprioception is related to function[2] and proprioceptive feedback depends on joint position and direction of movement.[9,10,14] The purpose of this study was to assess selected proprioceptive characteristics associated with ACL deficiency. We hypothesize that the ACL-deficient limb will possess significant deficits in proprioception when compared with the healthy (control) limb at starting angles of 15° and 45° moving into the directions of flexion and extension. We also hypothesize that proprioception will be significantly more sensitive at the starting angle of 15° moving into the directions of flexion and extension, and will also be significantly more sensitive moving into extension from the starting angles of 15° and 45°. Finally, we hypothesize that proprioception will be significantly correlated to function.

MATERIALS AND METHODS

Subjects

Twenty-nine ACL-deficient athletes (15 men and 14 women) participated in this investigation. The subjects

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ranged in age from 18 to 50 years (mean, 28.7 ± 1.7) and were tested at an average of 41.7 ± 11.7 months (range, 2 to 228) after injury. Subjects spent an average of 2.4 ± 0.33 months in postinjury rehabilitation. Twenty-four subjects (83%) indicated that they had significantly altered (decreased) their levels of sports activity as a result of the injury, although Tegner activity ratings indicated that the sample remained physically active (level 0 to 3, activities of daily living, $N = 12$; level 4 to 6, recreational sports, $N = 13$; level 7 to 10, competitive sports, $N = 4$). Most injuries were sports-related with 12 (41%) occurring as a result of a downhill skiing accident, 5 (17%) from football, and 5 (17%) from basketball. Nine subjects (31%) underwent arthroscopic exploratory surgery; five (17%) had partial medial meniscectomies and two had grade III medial collateral ligament (MCL) tears, with one of these tears being repaired.

The clinical diagnosis of ACL deficiency was made in each subject by an orthopaedic surgeon who used contemporary diagnostic procedures. The subjects were tested in a postacute stage after the initial injury and were then completing or had completed a consistent rehabilitation protocol for ACL deficiency emphasizing hamstring muscle strengthening with functional progression. The postacute stage was characterized as the subject having no acute symptoms of inflammation, pain, and limitations in range of motion. Subjects reviewed and signed consent forms approved by the Human Subjects Committee.

The independent variable in this study was the ACL-deficient limb; the contralateral healthy limb served as the control. The dependent measures for proprioception included threshold to detect passive motion at reference angles of 15° and 45° of flexion moving into both flexion and extension. The functional performance measure was the one-legged hop test (Table 1).

Proprioception Measures

Proprioception was measured using a proprioception testing device (Fig. 1) that measured the subject's threshold to detect passive motion. The proprioception testing device moved the knee at a slow, constant angular velocity (0.5 deg/sec). A rotational transducer interfaced with a digital microprocessor counter provided angular displacement values to the nearest tenth of a degree. Test-retest reliability on the proprioception testing device has been established at intraclass correlation coefficients (ICC) of 0.92.[14]

Testing order was randomized and counterbalanced relative to the ACL-deficient and control limbs, starting position, and direction of movement. The subjects were seated in a neutral angle of lumbar flexion (approximately 75°) with the popliteal fossa situated 4 to 6 cm from the edge of the seat to prevent any cutaneous stimulation of the joint. Both feet were placed in pneumatic compression sleeves inflated to 30 mm Hg. The limb being tested was attached to a movable shaft and the contralateral limb was fastened to a stationary shaft. The movable shaft was connected to a motor-driven rotational transducer interfaced with the digital microprocessor counter that measured angular displacement of the movable shaft. Subjects manipulated an on-off switch to start and stop angular rotation. Also, each subject was blindfolded and wore headphones with "white noise" to eliminate any audiovisual cues.

Threshold to detect passive motion for flexion and extension was randomly tested from starting positions of 15° (near the end range of extension) and 45° of flexion (midrange of motion) on both the ACL-deficient and control limbs. At the beginning of the test, subjects were alerted with a tap on the thigh. The subjects responded with a "thumbs-up" sign to signal their readiness before engaging the motor. At some random time after the thumbs-up signal (between 1 and 10 seconds) the motor was engaged and moved slowly into flexion or extension. The subject pressed the on-off switch as soon as motion was perceived. Angular displacement values were re-

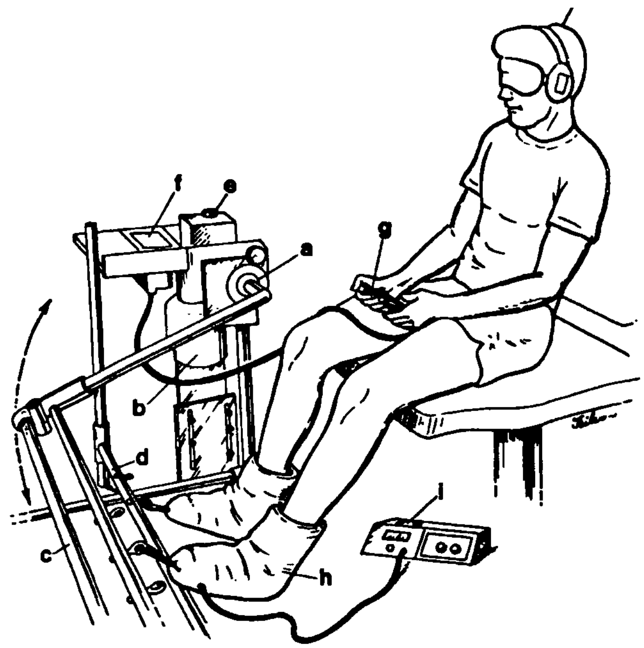

Figure 1. The proprioceptive testing device: a, rotational transducer; b, motor; c, moving arm; d, stationary arm; e, control panel; f, digital microprocessor; g, hand-held disengage switch; h, pneumatic compression sleeve; i, pneumatic compression device. The threshold to detection of passive motion is assessed by measuring the angular displacement (in degrees) until the subject senses knee joint motion.

TABLE 1
Dependent Measures for Proprioception

Measurement	TTDPM[a]
Limb	ACL-deficient limb vs control limb
Position of joint	15° vs 45° of flexion
Direction of motion	15° moving into flexion
	15° moving into extension
	45° moving into flexion
	45° moving into extension

[a] Threshold to detect passive motion.

corded from the digital microprocessor counter to the nearest tenth of a degree.

Functional Performance Measure

The single-legged hop test is a standardized functional performance test and was used as an objective measure of function. Function of the knee was emulated in this test by the ability of the subject to propel the body forward and land on the same limb. The test protocol was consistent with the protocol by Noyes et al.[15] With hands placed behind the back, each subject jumped for distance, taking off and landing on the same limb. This method measured the horizontal distance in centimeters; three trials were performed for each limb, and the best score for each limb was recorded as the criterion measure. The quotient of the ACL-deficient/control limb was recorded as the hop index.

Data Analysis

Proprioception values were analyzed using paired t-tests to identify significant ($P < 0.05$) mean differences. The dependent measures subjected to statistical analysis included 1) threshold to detect passive motion for the ACL-deficient versus the control limb moving into flexion and extension from starting positions of 15° and 45°, 2) threshold to detect passive motion for the ACL-deficient limb moving into extension versus flexion from a starting position of 15°, and 3) threshold to detect passive motion for the ACL-deficient limb moving into extension at 15° versus 45° (Table 1). Pearson Product Moment Correlations were used to identify statistically significant ($P < 0.05$) correlations between proprioception and function. No statistical adjustments were made to correct for multiple t-tests in this study.

RESULTS

Statistically significant deficits in threshold to detect passive motion were demonstrated for the ACL-deficient limb compared with the control limb at 15° moving into extension ($t[28] = 2.76, P < 0.01$) (Fig. 2). For the ACL-deficient limb, threshold to detect passive motion was significantly more sensitive moving into extension than flexion at a starting angle of 15° ($t[28] = 1.85, P < 0.05$) (Fig. 3), and threshold to detect passive motion at a starting angle of 15° moving into extension was significantly more sensitive than threshold to detect passive motion at a starting angle of 45° moving into extension ($t[28] = 2.80, P < 0.01$) (Fig. 4). The correlation matrix revealed significant intercorrelations between the measures of proprioception ($P < 0.05$) (Table 2). The correlation matrix demonstrated significant relationships between the hop index and threshold to detect passive motion at 15° moving into extension ($r = -0.46, P < 0.05$), and at 45° moving into extension ($r = -0.56, P < 0.01$) (Table 2).

DISCUSSION

Histologic studies have identified the presence of mechanoreceptors in the human ACL.[17,18] The ACL mechanoreceptors are sensitive to mechanical deformation of the tissue and, when activated, send a frequency-modulated neural signal to the central nervous system indicating direction and speed of joint motion. Damage to this ligamentous structure has been shown to cause a partial deafferentation of the joint.[1,14] The results of this study demonstrate a sensory deficit in the ACL-deficient limb when compared with the healthy limb. This is consistent with the findings of Barrack et al.[1] and Corrigan et al.[6]

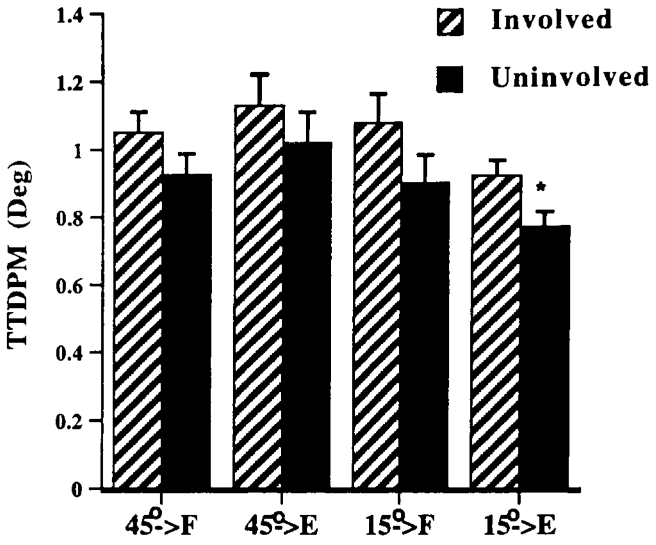

Figure 2. Mean (±SD) threshold to detect passive motion (TTDPM) for the ACL-deficient and the control limbs moving into flexion and extension from starting positions of 15° and 45°. *$P < 0.01$.

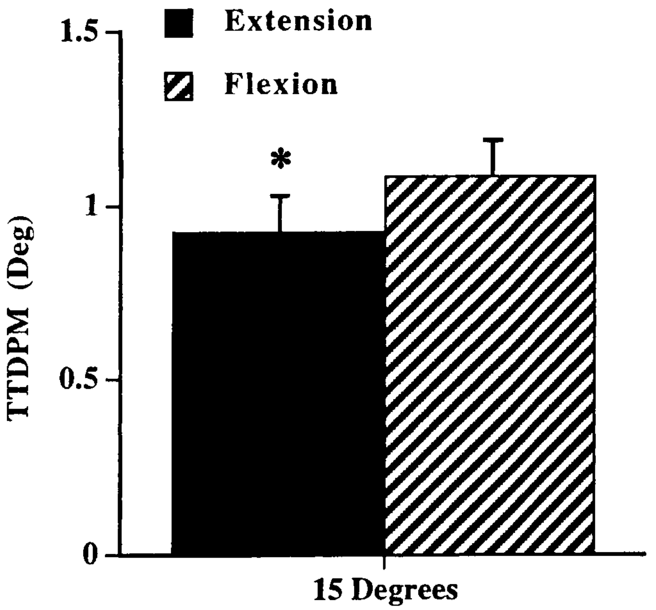

Figure 3. Mean (±SD) threshold to detect passive motion (TTDPM) for the ACL-deficient limb moving into extension versus flexion from a starting position of 15°. *$P < 0.05$.

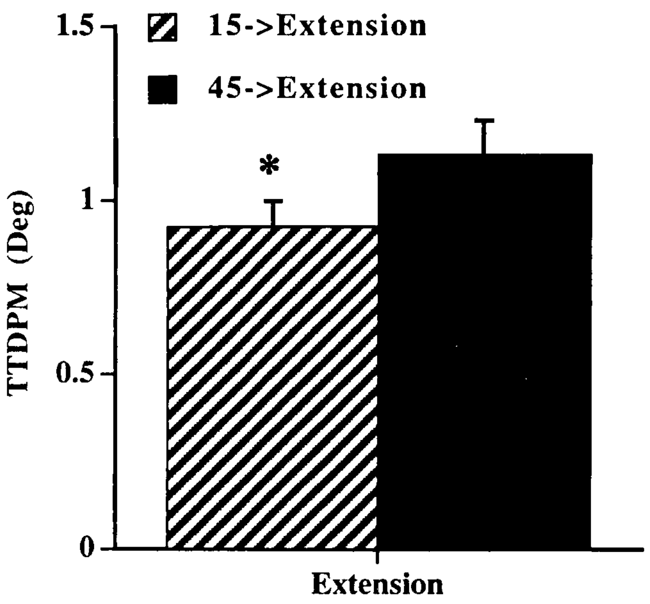

Figure 4. Mean (±SD) threshold to detect passive motion (TTDPM) for the ACL-deficient limb moving into extension at 15° versus 45°. $*P < 0.01$.

demonstrating that ACL-deficient limbs have a significantly higher threshold to detect passive motion than healthy limbs. However, these investigations[1,2,6] demonstrated threshold to detect passive motion deficits at the midranges of knee flexion (30° to 40°), and this study demonstrated threshold to detect passive motion deficits at the end ranges of knee extension (15°). This is consistent with the finding of Lephart et al.,[14] demonstrating that threshold to detect passive motion at a starting angle of 15° is diminished after ACL reconstruction. The threshold to detect passive motion at 15° moving into flexion was also higher in the ACL-deficient limb but not statistically significant ($P = 0.051$). The threshold to detect passive motion values at 45° moving into both flexion and extension for this study also indicated a trend toward ACL-deficient limb deficits.

For the ACL-deficient limb, threshold to detect passive motion at 15° moving into extension was significantly lower than moving into flexion (0.77° versus 0.92°). Similarly, in the ACL-deficient limb, threshold to detect passive motion at 15° moving into extension was significantly lower than at 45° (0.92° versus 1.1°). These findings are consistent with those of Grigg[9,10] and Lephart et al.[14] that suggest that joint position and direction of joint motion have a significant effect on the magnitude and frequency of mechanoreceptor recruitment. Because greater tensile stress is placed on the static restraints, especially the intact ACL, at the end range of motion for knee extension than at the midranges of motion, rupture of the ACL will significantly diminish the proprioceptive sensibility of the joint. In the ACL-deficient limb, it appears that proprioceptive sensibility is greater at the end ranges of motion while moving into the direction of extension.

Diminished proprioceptive sensibility has been shown to cause giving way or episodes of instability of the ACL-deficient knee, particularly in the end ranges of knee extension. This is demonstrated clinically as the pivot-shift mechanism.[8] Instability occurs because of the combined effects of excessive tibial translation and lack of reflex stabilization when the knee is approaching the end range of extension. The lack of reflex stabilization of the knee is associated with a diminished sensory feedback mechanism, which causes a latent motor response of the hamstring muscles. Researchers have established a latency in the muscle firing patterns in ACL-deficient subjects.[3,11,20] According to Beard et al.,[3] this latency is related to the degree of instability of the limb, and the greater the latency, the more severe is the instability. Our findings of diminished sensory feedback corroborate with these previous findings of increased motor latency. The degree to which the two are related is still unclear.

Proprioceptive deficits after ACL deficiency have been related to a decrease in knee function. The relationship between proprioception and function has been demonstrated by Barrett,[2] who suggests that limb function relies more on proprioceptive input than on strength during activity. The results from this study are consistent with Barrett's findings in that proprioception values for threshold to detect passive motion at 15° and 45° demonstrate moderately high correlations with the single-legged hop test, which is a performance-based test of knee function. The single-legged hop test is an integrated measure of neuromuscular control and dynamic stabilization of the lower extremity. A high degree of proprioceptive sensibility and functional ability is required to successfully propel the body forward and land safely on that limb. Therefore,

TABLE 2
Correlation Matrix for Proprioception and Function[a]

	Hop test	TTD-15-F	TTD-15-E	TTD-45-F	TTD-45-E
Hop test	1.000	−0.365	−0.462*	−0.365	−0.558**
TTD-15-F	−0.365	1.000	0.591	0.791	0.593
TTD-15-E	−0.462	0.591	1.000	0.348	0.685
TTD-45-F	−0.365	0.791	0.348	1.000	0.478
TTD-45-E	−0.558	0.593	0.685	0.478	1.000

[a] TTD, threshold to detect passive motion; F, flexion; E, extension.
$* P < 0.05$.
$** P < 0.01$.

subjects with ACL deficiency would be less likely to hop successfully because of the cumulative effects of proprioceptive and functional deficits.

The findings of this study have clinical significance with reference to physical rehabilitation. The sports medicine practitioner should direct efforts at restoring those sensorimotor mechanisms that enhance reflex stabilization of the knee in the end range of motion for extension. These sensorimotor mechanisms include increased mechanoreceptor recruitment and muscular reflex stabilization. Ihara and Nakayama[11] demonstrated a decrease in reaction time for the hamstring muscles after a dynamic joint control rehabilitation training program in a group of ACL-deficient subjects. More recent studies recommend weightbearing, closed kinetic chain exercise for enhancing neuromuscular coordination of the muscles that act on the knee joint.[4,7,19] We believe that this type of resistance exercise is able to condition the dynamic restraints to consciously or unconsciously stabilize the knee joint during performance-based physical activity.

CONCLUSIONS

From our investigation we conclude that proprioception deficits occur in the ACL-deficient limb compared with the control limb. For the ACL-deficient limb, proprioception is significantly more sensitive in the end ranges of extension (15°) than the midranges of motion (45°). For the ACL-deficient limb, proprioception is significantly more sensitive when the knee is moving into the direction of extension rather than flexion. The measures of proprioception are significantly correlated with function. To effectively restore reflex stabilization of the lower limb, we recommend a rehabilitation program emphasizing performance-based, weightbearing, closed kinetic chain exercise for the muscle groups that act on the knee joint.

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