Journal of Athletic Training 2006;41(3):251–259

www.journalofathletictraining.org

The Independent and Interactive Effects of Navicular Drop and Quadriceps Angle on Neuromuscular Responses to a Weight-Bearing Perturbation

Sandra J. Shultz*; Christopher R. Carcia†; Bruce M. Gansneder‡; David H. Perrin*

*University of North Carolina at Greensboro, Greensboro, NC; †Duquesne University, Pittsburgh, PA; ‡University of Virginia, Charlottesville, VA

Sandra J. Shultz, PhD, ATC, CSCS, contributed to conception and design; acquisition and analysis and interpretation of the data; and drafting, critical revision, and final approval of the article. Christopher R. Carcia, PhD, PT, SCS, contributed to acquisition and analysis and interpretation of the data and critical revision and final approval of the article. Bruce M. Gansneder, PhD, and David H. Perrin, PhD, ATC, contributed to conception and design, analysis and interpretation of the data, and critical revision and final approval of the article.

Address correspondence to Sandra J. Shultz, PhD, ATC, CSCS, Department of Exercise and Sport Science, University of North Carolina at Greensboro, 237B HHP Building, Greensboro, NC 27402-6170. Address e-mail to sjshultz@uncg.edu.

Context: Little is known about the effects of static alignment on neuromuscular control of the knee during dynamic motion.

Objective: To evaluate the isolated and combined effects of quadriceps angle (QA) and navicular drop (ND) on neuromuscular responses to a weight-bearing perturbation.

Design: Mixed-model, repeated-measures design.

Setting: Sports medicine and athletic training research laboratory.

Patients or Other Participants: Seventy-nine National Collegiate Athletic Association Division I collegiate female athletes, classified with below-average ND and QA (LND-LQA); below-average ND and above-average QA (LND-HQA); above-average ND and below-average QA (HND-LQA); or above-average ND and QA (HND-HQA).

Intervention(s): A lower extremity perturbation device produced a forward and either internal or external rotation of the trunk and femur on the weight-bearing tibia to evoke a reflex response.

Main Outcome Measure(s): Neuromuscular responses were examined in the quadriceps, hamstrings, and gastrocnemius muscles: preperturbation amplitude 50 milliseconds before the perturbation, reflex time, and postperturbation amplitude 150 milliseconds immediately postperturbation.

Results: Navicular drop had the greatest effect on preperturbation amplitude of the lateral hamstrings and postperturbation amplitude of all muscles, with greater activation amplitude noted in subjects in the HND classifications. Quadriceps angle primarily affected reflex time of the quadriceps; in subjects with LQA, reflex time was faster for internal rotation than external rotation perturbations. The interaction between ND and QA had the greatest effect on reflex time of the lateral hamstrings. For internal rotation perturbations, subjects in the LND classifications had faster reflex times in the lateral hamstrings if they had HQA values rather than LQA values. With external rotation perturbations, HND-LQA subjects had slower reflex times than those in all other alignment classifications.

Conclusions: Navicular drop and QA have both independent and interactive effects on neuromuscular responses to a weight-bearing, rotational perturbation. These interactive effects highlight the importance of considering the entire lower extremity posture rather than a single alignment characteristic, given the potential for one alignment factor to compensate for or interact with another.

Key Words: long latency reflex time, lower extremity alignment, anatomical risk factors

Anatomical characteristics represent 1 of 4 risk factor classifications (environmental, anatomic, hormonal, and neuromuscular/biomechanical) that have been proposed to explain the increased risk of anterior cruciate ligament (ACL) injury in women. Although much has been learned about sex differences in neuromuscular and biomechanical function in recent years, the influence of lower extremity malalignments on neuromuscular and biomechanical function and ACL risk remains elusive. Gaining a better understanding of the potential underlying causes for dynamic knee joint dysfunction and injury risk is an important step if we are to accurately identify those at greatest risk for injury and target our intervention strategies accordingly.

Two measures commonly used to describe lower extremity alignment that have received attention as potential ACL injury risk factors in the female population are excessive pronation (often measured as navicular drop [ND]) and quadriceps angle (QA).[1–6] Increased subtalar joint pronation is thought to cause a compensatory increase in internal tibial rotation, which may increase rotational joint laxity and create a preloading, rotary stress to the knee joint during weight-bearing activities when the pelvis is externally rotating.[1,7–9] Similarly, excessive QA, reflecting a composite measure of pelvic angle, hip rotation, tibial rotation, patella position, and foot position,[10,11] may increase rotary stress on the weight-bearing knee when the pelvis is internally rotating and may reduce biomechanical efficiency at the knee. The biomechanical changes brought about by these malalignments also may influence proprioceptive orientation or feedback (or both) from the hip and knee, resulting in altered musculoskeletal reflex behavior and joint stabilization.[5,10] Furthermore, the mechanical efficiency and relative contribution of a muscle to knee joint stabilization may be affected if its orientation and/or length-tension relationship is sufficiently altered as a result of the malalignment. Therefore, neuromuscular function and control of knee stability may be substantially different in athletes who possess lower extremity malalignments.

A few authors[12–15] have found significant changes in lower extremity kinematics and muscular activation patterns with orthotic control of hyperpronation. However, we found no published studies that directly evaluated the influence of lower extremity malalignments on protective neuromuscular response characteristics at the knee specifically. Understanding the influence of anatomic alignment factors on neuromuscular control of knee stability may elucidate further their potential contribution to ACL injury risk. Our purpose was to examine differences in muscle reflex time and preperturbation and postperturbation amplitude after a functional, weight-bearing perturbation in subjects who have above-average or below-average QA and above-average or below-average ND values. Our hypothesis was that ND and QA would have both independent and interactive effects on muscle activation patterns, depending on the direction of the rotational perturbation. In particular, we expected that subjects with above-average ND would exhibit faster and higher-amplitude responses with external rotation (ER) perturbations and that these altered responses would be further accentuated in subjects who also had above-average QA. Further, we expected subjects with above-average QA to exhibit faster and higher-amplitude responses with internal rotation (IR) perturbations.

METHODS

We performed all testing on each subject's dominant limb (ie, the leg used to kick a ball) in a university sports medicine and athletic training research laboratory. Participants consisted of 79 healthy National Collegiate Athletic Association Division I collegiate female athletes (2 basketball, 30 crew, 12 field hockey, 8 soccer, 8 volleyball, 3 track, 7 lacrosse, 6 softball, and 3 swimming athletes) who were prescreened for ND and QA. Because we were examining an intrinsic risk factor, we did not limit our sample to sports that are known to be at high risk for ACL injury (eg, basketball and soccer). Rather, our goal was to actively sample and identify female athletes who fell below (<7 mm) or above (>8 mm) average ND values and below (<16°) or above (>17°) average QA values. Although the division for these alignment classifications is consistent with normative data on female populations previously reported in the literature for ND[1,16,17] and standing QA,[18,19] we purposely sampled people who fell well above and well below these population mean values. This resulted in 20 subjects each being classified with below-average ND and QA (LND-LQA), below-average ND and above-average QA (LND-HQA), and above-average ND and below-average QA (HND-LQA) and 19 subjects being classified with above-average ND and QA (HND-HQA) (see Table 1 for group demographics). A sample size of 20 subjects per group was determined a priori through pilot analyses. We chose to study only women to ensure a sufficient range in the HQA group classifications and to avoid sex-related confounding variables. All subjects were healthy, defined as having no history of knee ligament injury or surgery, no history of connective tissue disorders or diseases, and no lower extremity injury in the past 6 months. Before participating, all subjects read and signed a written informed consent form approved by the university's institutional review board, which also approved the study.

Measurement of Navicular Drop and Quadriceps Angle

We defined ND as the difference in navicular height in millimeters from standing subtalar joint neutral to standing relaxed foot posture. To obtain the measure, we used a modification of the Brody technique.[20] We marked the most prominent aspect of the navicular and positioned subjects in barefoot stance on a hard, elevated surface with feet a comfortable width (shoulder width) apart and toes pointing forward. We identified subtalar joint neutral by asking the subject to pronate and supinate the hindfoot and ankle while the examiner, using the thumb and the forefinger, palpated the anterior medial and anterior lateral head of the talus for congruency. In this position, we read the distance from the mark on the navicular to the floor using a straight ruler (mm) to obtain the navicular height in the subtalar joint neutral foot posture. We then instructed the subject to relax the foot and evenly distribute the weight between the left and right feet. In this position, we again measured the distance between the mark on the navicular and the floor to obtain the navicular height in the standing relaxed foot posture.

We measured QA as the angle (°) formed by the intersection of a line from the anterior superior iliac spine to a mark on the center of the patella and a line from the center of the patella to the center of the tibial tubercle. To obtain the measure, we positioned subjects standing with their feet a comfortable width apart (shoulder width), knees straight, and toes positioned anteriorly.[21] The superior, inferior, medial, and lateral margins of the patella were palpated and a mark was placed on the center of the patella. The measure was recorded to the nearest degree using a standard goniometer with the stationary arm modified with an adjustable extension rod to allow more accurate alignment along the length of the thigh to the anterior superior iliac spine. All measures were performed by a single experienced investigator who established day-to-day intratester reliability on 15 subjects by repeating measures within 1 week while blinded to the previous measure (intraclass correlation coefficient, 2,k [SEM] = 0.89 [1.2 mm] ND, 0.84 [1.4°] QA). To determine whether groups were relatively comparable on other structural factors, the same investigator also measured anterior knee laxity, pelvic angle, hip anteversion, genu recurvatum, and tibial torsion (Table 1).

Measurement of Neuromuscular Responses

We used a lower extremity perturbation device to produce a forward and either IR or ER of the trunk and femur on the weight-bearing tibia to evoke the reflex response (Figure 1). The design, reliability, and validity of this device have been previously reported.[22] Kinematic analysis of these perturba-

Table 1. **Subject Demographics and Anatomical Characteristics by Low and High Navicular Drop and Quadriceps Angle Group Classifications***

Quadriceps Angle Groups		Navicular Drop Groups: LND (<7 mm)	Navicular Drop Groups: HND (>8 mm)	Total
LQA (<16°)	Age, y	20.0 ± 1.3	19.2 ± 1.3	19.6 ± 1.4
	Height, cm	171.3 ± 7.5	172.6 ± 7.7	171.9 ± 7.5
	Mass, kg	71.2 ± 7.3	71.7 ± 9.9	71.5 ± 8.6
	Navicular drop, mm	3.7 ± 1.2	9.3 ± 2.1	6.5 ± 3.3
	Quadriceps angle, °	11.6 ± 3.2	12.2 ± 2.9	11.9 ± 3.0†
	Knee laxity, mm	6.1 ± 2.3	7.2 ± 2.1	6.7 ± 2.2
	Anterior pelvic tilt, °	6.3 ± 2.5	5.9 ± 2.8	6.1 ± 2.6
	Anteversion, °	9.1 ± 5.7	7.3 ± 4.2	8.2 ± 5.0†
	Genu recurvatum, °	5.1 ± 2.8	6.8 ± 2.7	6.0 ± 2.9
	Tibial torsion, °	23.0 ± 6.4	22.1 ± 6.6	22.5 ± 6.4
HQA (>17°)	Age, y	20.0 ± 1.3	19.3 ± 1.1	19.7 ± 1.2
	Height, cm	170.6 ± 6.7	169.9 ± 6.0	170.3 ± 6.3
	Mass, kg	69.2 ± 8.7	69.2 ± 7.8	69.2 ± 8.1
	Navicular drop, mm	3.6 ± 2.1	9.3 ± 1.8	6.4 ± 3.4
	Quadriceps angle, °	19.3 ± 2.1	18.8 ± 1.6	19.0 ± 1.9
	Knee laxity, mm	6.1 ± 1.7	6.8 ± 2.5	6.4 ± 2.1
	Anterior pelvic tilt, °	6.8 ± 3.6	7.2 ± 2.5	7.0 ± 3.1
	Anteversion, °	5.3 ± 4.9	7.3 ± 4.4	6.2 ± 4.7
	Genu recurvatum, °	4.1 ± 3.6	5.5 ± 2.2	4.8 ± 3.0
	Tibial torsion, °	23.6 ± 6.8	21.6 ± 5.9	22.6 ± 6.4
Total	Age, y	20.0 ± 1.3	19.2 ± 1.2	
	Height, cm	170.9 ± 7.0	171.4 ± 6.9	
	Mass, kg	70.2 ± 8.0	70.5 ± 8.9	
	Navicular drop, mm	3.6 ± 1.6	9.3 ± 1.9‡	
	Quadriceps angle, °	15.4 ± 4.7	15.4 ± 4.0	
	Knee laxity, mm	6.1 ± 2.0	7.0 ± 2.2	
	Anterior pelvic tilt, °	6.5 ± 3.1	6.5 ± 2.7	
	Anteversion, °	7.2 ± 5.6	7.3 ± 4.2	
	Genu recurvatum, °	4.6 ± 3.2	6.2 ± 2.5‡	
	Tibial torsion, °	23.3 ± 6.5	21.9 ± 6.2	

*LND indicates low navicular drop; HND, high navicular drop; LQA, low quadriceps angle; and HQA, high quadriceps angle.
†HQA ≠ LQA ($P < .05$).
‡HND ≠ LND ($P < .05$).

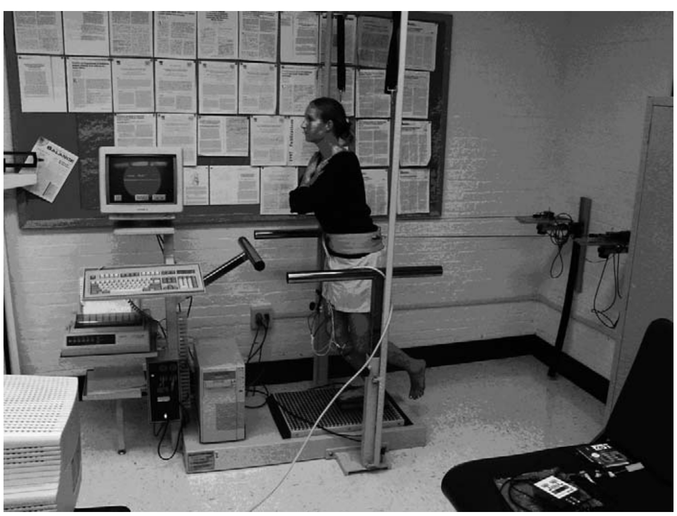

Figure 1. Lower extremity perturbation device.

tions has confirmed that ER perturbations result in IR of the tibia on the femur, IR of the femur on the pelvis, and knee valgus, motions that are consistent with a crossover cut maneuver.[23] Conversely, IR perturbations result in ER of the tibia on the femur, ER of the femur on the pelvis, and knee varus position, motions that resemble a side-cut maneuver.[23] We positioned participants in the lower extremity perturbation device in a single-leg, barefoot stance on the dominant leg, restraining them with 2 Kevlar (DuPont, Richmond, VA) cables attached to each subject's hips via a waist belt and a wall-mounted cable release mechanism that we could adjust in height to maintain the cables in a horizontal line of pull. We standardized the preperturbation body position by instructing participants to look straight ahead, place the arms across the chest, lean into the cables to fully support body weight, maintain the center of pressure over the midfoot, and flex the knee to approximately 30° (see Figure 1). We used a Penny & Giles electrogoniometer (model XM180; Biometrics Ltd, UK) aligned with the femur and tibia on the lateral aspect of the thigh to confirm knee flexion angle and a Chattecx Balance System (Chattanooga Group, Inc, Hixson, TN) visual training target to confirm center-of-pressure position. With participants properly positioned and looking straight ahead, we released either the left or right cable to cause either an IR (right cable) or ER (left cable) perturbation of the trunk and thigh on the weight-bearing tibia (when referenced for the right leg). Although the participants could anticipate that the perturbation was coming, they did not know when the cable would be released or in which direction the perturbation would occur. We instructed participants to try to maintain single-leg balance upon cable release, to ensure they reacted to the perturbation versus just allowing their bodies to fall forward. We completed 10 trials each of IR and ER perturbations, with the direction of rotation randomized to minimize anticipatory responses. We separated trials with 30-second rest periods, during which time participants shifted their weight to the nontest leg to avoid fatigue.

We recorded muscle activity in response to the perturbations using surface electromyography (sEMG) (Myosystem 2000 Surface Electromyogram; Noraxon, Scottsdale, AZ). (Unit specifications: amplification of 1 mV/V, frequency bandwidth of 16 Hz to 500 Hz, common mode rejection ratio of 114 dB, input resistance of 1 GΩ, and sampling rate of 1000 Hz.) To detect the myoelectric signal, we attached 10-mm bipolar Ag-AgCl surface electrodes (Medicotest Blue Sensor model N-00-S; Ambu Products, Bad Nauheim, Germany) over the vastus medialis (MQ) and vastus lateralis (LQ) (midway between the motor point and distal tendon), medial hamstrings (MH) and biceps femoris (LH) (midbelly), and medial (MG) and lateral (LG) gastrocnemius (midbelly of the medial and lateral heads) with a center-to-center distance of 2.5 cm and a ground electrode over the anterior tibia. We confirmed electrode placements and checked for crosstalk with manual muscle testing. To acquire, store, and analyze the data, we interfaced the EMG and lower extremity perturbation device with DATAPAC 2000 Lab Application software (Run Technologies, Laguna Hills, CA). A voltage signal at the time of trigger release was sent from the lower extremity perturbation device to the computer to mark the time of stimulus and to begin data recording of identically timed trials of 100 milliseconds before and 900 milliseconds after cable release.

Before the perturbation trials, we recorded EMG signals during maximal voluntary isometric contractions of each muscle group for later normalization of the EMG data. We positioned participants with 30° of knee flexion in an isokinetic dynamometer (KIN-COM II isokinetic dynamometer; Chattanooga Group, Inc, Chattanooga, TN) and instructed them to complete three 5-second maximal effort knee extension (quadriceps) and knee flexion (hamstrings) contractions with the dynamometer locked at 0°/s. To normalize the gastrocnemius muscle, subjects performed three 5-second maximal-effort, single-leg toe raises.

Data Reduction and Analysis

We digitally processed the sEMG for the perturbation trials using a centered (symmetric) root mean square algorithm with a 5-millisecond time constant. We visually inspected each trial and selected the first 5 trials each for IR and ER that met the following criteria: a long latency reflex identified within 150 milliseconds after cable release, baseline muscle activity sufficiently quiet and stable (ie, no large spikes in muscle activity during quiet stance) to ensure an acceptable signal-to-noise ratio, and a readable signal obtained from all 6 muscles that was free of movement artifact to allow clear interpretation of the signal. We then signal averaged the 5 trials to obtain a single representative signal from which to determine muscle response times and amplitudes. The reliability of this procedure has been previously established,[22] and the investigator processing the data was blinded to subject and group membership. To normalize the amplitude data from the perturbation trials, we digitally processed the maximal voluntary isometric contractions trials using a centered (symmetric) root mean square algorithm with a 100-millisecond time constant and averaged the peak values obtained from the middle 3 seconds of each maximal effort.

Preperturbation amplitude (AMP_{Pre} = % maximal voluntary isometric contraction) was defined as the mean normalized signal amplitude for 50 milliseconds before the perturbation (ie, while standing in a single-leg stance awaiting the perturbation). Long latency reflex time (RT in milliseconds) was defined as the time delay between the onset of the perturbation and a 1 (quadriceps) or 2 (hamstrings and gastrocnemius) standard deviation increase in muscle activity above baseline activity (100-millisecond pretrigger) for 10 milliseconds or longer.[22] Postperturbation amplitude (AMP_{Post} = % maximal voluntary isometric contraction) represented the mean normalized signal amplitude over 150 milliseconds immediately postperturbation. To examine the effect of ND and QA on AMP_{Pre}, RT, and AMP_{Post}, we used separate, mixed-model repeated-measures analyses of variance with 2 between-subjects factors (ND [LND $<$ 7 mm, HND $>$ 8 mm] and QA [LQA $<$ 16°, HQA $>$ 17°] group classifications) and 2 within-subjects factors (direction of perturbation [IR, ER] and muscle [MG, LG, MH, LH, MQ, LQ]). Post hoc analyses consisted of repeated contrasts for within-subjects effects and simple main effects testing for significant interactions. Bonferroni corrections were used for multiple comparisons. We analyzed all data using the SPSS statistical software package (version 11.5; SPSS Inc, Chicago, IL). Alpha was set a priori at $P \leq .05$.

RESULTS

Table 1 lists group means for all anatomical measures recorded for each subject. With few exceptions, these groups were fairly similar in other alignment characteristics. Table 2 presents the analysis of variance summary results for AMP_{Pre}, RT, and AMP_{Post}.

Preperturbation Amplitude

The analysis for muscle AMP_{Pre} identified significant differences between ND and QA group classifications that depended on the direction of perturbation and the muscle tested (4-way interaction: $F_{5,375} = 2.959$, $P = .008$). In order to interpret the 4-way interaction, post hoc analyses consisted of plotting the 3-way interactions (Figure 2) and running separate analyses of variance (2 between [QA and ND groups] and 1 within [direction of perturbation]) for each muscle, followed by simple main-effects testing to determine the effects of lower extremity alignment on each muscle. Post hoc analyses identified group differences in the MG, LH, and MQ.

For the MG, we identified an interaction between QA group and direction of rotation ($P = .002$). Subjects with HQA had somewhat higher AMP_{Pre} for ER than IR perturbations (15.0% versus 15.8% maximal voluntary isometric contractions, $P = .037$), whereas subjects with LQA had higher perturbation amplitudes for ER than IR perturbations (17.4% versus 16.5% maximal voluntary isometric contractions, $P = .002$) (Figure 2A). This resulted in a modest 2.5% maximal voluntary isometric contraction difference in MG AMP_{Pre} between HQA and LQA for IR that pairwise comparisons did not identify as significant. For the LH, a main effect for ND was found: subjects with HND had significantly higher activation amplitudes than subjects with LND (35.7% versus 25.4%, $P = .030$) (Figure 2D). This effect was not dependent on QA classification or direction of perturbation. For the MQ, groups differed by

Table 2. Analysis of Variance Summary Results for Navicular Drop and Quadriceps Angle Classifications by Muscle and Direction of Perturbation (Internal, External)*

Source	Preactivation Amplitude, % MVIC	Reflex Time, ms	Reflex Amplitude, % MVIC
Within-subjects effects			
Rotation	.157	.054	.011†
× ND group	.633	.921	.121
× QA group	.781	.032†	.269
× ND group × QA group	.150	.139	.026†
Muscle	<.0001†	.0001†	<.0001†
× ND group	.108	.543	.163
× QA group	.722	.070	.395
× ND group × QA group	.645	.768	.948
Rotation × muscle	.137	<.0001†	.011†
× ND group	.082	.553	.672
× QA group	.348	.551	.122
× ND group × QA group	.008†	<.0001†	.849
Between-subjects effects			
ND group	.076	.669	.025†
QA group	.600	.925	.396
ND group × QA group	.896	.561	.825

*MVIC indicates maximal voluntary isometric contraction; ND, navicular drop; and QA, quadriceps angle. Numbers represent *P* values.
†$P \leq .05$.

direction of perturbation ($P = .048$) (Figure 2E); plotting the interaction indicated that subjects classified as HND-HQA had somewhat higher activation levels for IR than for ER (38.0% versus 35.4% maximal voluntary isometric contraction), whereas all other group classifications had higher activation levels for ER than IR (LND-LQA = 37.3% versus 38.6% maximal voluntary isometric contraction, LND-HQA = 35.6% versus 40.8% maximal voluntary isometric contraction, HND-LQA = 36.5% versus 38.7% maximal voluntary isometric contraction). However, simple main-effects testing failed to identify significant pairwise differences among group classifications.

Reflex Time

The analysis for RT identified significant differences between ND and QA group classifications that depended on the direction of perturbation and the muscle tested (4-way interaction: $F_{5,375} = 5.137$, $P < .0001$). To interpret the 4-way interaction, we performed post hoc analysis again, consisting of plotting the 3-way interactions (Figure 3) and running separate analyses of variance for each muscle, followed by simple main effects testing. Group differences were noted in the LH, MQ, and LQ. In the LH, ND and QA had different effects depending on the direction of perturbation (3-way interaction, $P = .002$) (see Figure 3D). With IR perturbations, subjects in the LND group classifications had faster lateral hamstring responses if they had HQA (LND-HQA = 78 milliseconds) rather than LQA (LND-LQA = 95 milliseconds). The QA had no effect on LH RT if subjects were in the HND group classifications. For ER perturbations, subjects classified as HND-LQA had longer reflex delays in the LH (99 milliseconds) than subjects in all other alignment classifications (LND-LQA = 77 milliseconds, LND-HQA = 79 milliseconds, HND-HQA = 76 milliseconds). For the MQ and LQ (see Figure 3E and 3F), RT was 10 to 12 milliseconds faster for IR than ER perturbations for subjects in the LQA classifications (MQ = 86.8 versus 97.5 milliseconds, LQ = 93.2 versus 105.0 milliseconds) but not for participants in the HQA classifications (MQ = 96.8 versus 97.9 milliseconds, $P = .044$, LQ = 104.2 versus 106.3 milliseconds, $P = .040$).

Postperturbation Amplitude

The analysis for AMP_{Post} identified significant differences between ND and QA group classifications by the direction of perturbation (3-way interaction: $F_{1,75} = 5.109$, $P = .026$) (Figure 4). Post hoc analysis revealed that postperturbation amplitude was higher in response to IR than ER perturbations in subjects classified as LND-LQA (34.1% versus 32.8%, $P = .05$) and in subjects classified as HND-HQA (44.7% versus 40.0%, $P = .037$). Direction of perturbation had no effect on AMP_{Post} for subjects classified as LND-HQA or HND-LQA. Postperturbation amplitude was higher for subjects with HND than for subjects with LND (41.7% versus 34.4%, $P = .025$), regardless of the direction of perturbation or their QA classification.

DISCUSSION

Our primary findings were that ND and QA demonstrated independent, as well as interactive, effects on neuromuscular response characteristics at the knee in response to weight-bearing perturbations. In isolation, ND had the greatest effect on AMP_{Pre} and AMP_{Post}. When compared with subjects with LND, subjects with HND had increased LH AMP_{Pre} while in single-leg weight-bearing stance awaiting the perturbation and an increase in AMP_{Post} for all muscles, regardless of the direction of the perturbation. The QA classifications primarily affected quadriceps RT, which was faster for IR than ER perturbations in subjects classified with LQA, whereas no differences were noted between IR and ER in subjects with HQA. The interaction between ND and QA classifications had the greatest effect on RT of the LH, with subjects in the LND-LQA classification having slower responses during IR perturbations compared with subjects in the LND-HQA classification, and subjects in the HND-LQA classification having slower responses to ER perturbations than subjects in all other alignment classifications. Each of these findings yielded a mean difference consistent with moderate to large effect sizes (range, .41–.78).[24] Of interest, subjects classified as HND-HQA demonstrated neuromuscular activation patterns that were most similar to the more neutrally aligned LND-LQA subjects. In the following paragraphs, we will explore the implications of these independent and interactive effects.

Navicular Drop

Navicular drop is a commonly used clinical measure that represents a composite measure of foot pronation.[16] We chose to examine the influence of excessive ND on neuromuscular response characteristics because of the coupling motion that exists between pronation (as measured by rearfoot eversion) and internal tibial rotation.[25,26] This coupling motion at the foot is thought to lead to an obligatory increase in internal

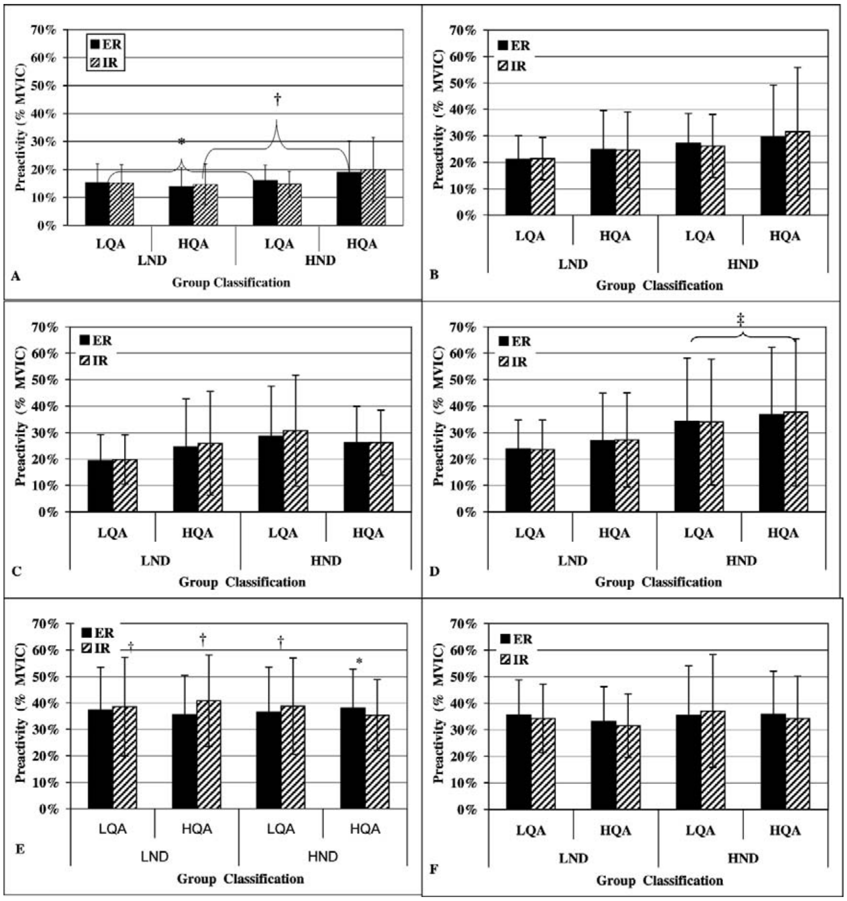

Figure 2. Muscle preperturbation amplitude by navicular drop and quadriceps angle classifications for internal (IR) and external (ER) rotation perturbations for the medial (A) and lateral (B) gastrocnemius, medial (C) and lateral (D) hamstrings, and medial (E) and lateral (F) quadriceps muscles. *ER > IR; †IR > ER; ‡HND > LND. Error bars denote SDs. MVIC indicates maximal voluntary isometric contraction; LQA and HQA, below-average and above-average quadriceps angle, respectively; and LND and HND, below-average and above-average navicular drop, respectively.

tibial rotation at the knee,[1,5,27] which can increase ACL strain in weight bearing.[28] Hence, excessive pronation may result in a preloading stress to the ACL during the stance phase of gait. This idea is supported by authors who demonstrated an increase in rotational[27] and anterior[17] knee laxity in subjects with excessive pronation and by investigators of retrospective epidemiologic studies who reported a relationship between increased pronation (measured by ND) and ACL injury risk.[1,5,6]

Our findings are consistent with these reports, because subjects in the HND classifications had significantly higher AMP_{Pre} in the LH while standing in a single-leg weight-bearing stance, which may represent an attempt to externally rotate the tibia on the femur and reduce ACL loading. Further, these subjects demonstrated higher AMP_{Post} across all muscles in response to the perturbation, which suggests a greater reliance on the dynamic stabilizers to control knee motion. However, although these responses appear to be protective, the 20-millisecond or greater RT delay in the LH in subjects with HND-LQA compared with other alignment classifications in response to the ER perturbation may be problematic. Kinematic analysis of the joint motions produced by the lower extremity perturbation device indicates a significant increase in ER of the femur on the fixed tibia during ER perturbations.[23] Given the role of the LH in stabilizing and externally rotating the tibia on the femur, this delayed response may result in excessive loading of the ACL as the trunk and femur continue to externally rotate on a fixed, internally rotated tibia. Both timing and amplitude of the muscular response are important in generating sufficient muscular forces to successfully counteract external loads to the knee joint, so further studies incorporating both neuromuscular and biomechanical analyses are needed to fully interpret the clinical implications of these combined responses (ie, higher amplitude and slower RT). The extent to which these combined responses collectively affect tibiofemoral joint motion and forces will have a significant influence on our approach to injury prevention.

Quadriceps Angle

Many have proposed that excessive QA may pose a greater risk of ACL injury, but very little research exists regarding this relationship.[3,5] Although not specifically related to ACL injury, evidence suggests that when QA and genu valgus are excessive, increases in chronic injury, medial knee stress, and patellofemoral disorders often are found.[9,29] These studies are not specific to ACL injury; however, they do suggest that increased stress is placed on the knee and lower extremity during dynamic, functional activity as a result of this static biomechanical fault.

The QA is a frontal-plane clinical measure that is intended to approximate the resultant quadriceps muscle force acting on the patella[30] and is defined by intersecting lines from the cen-

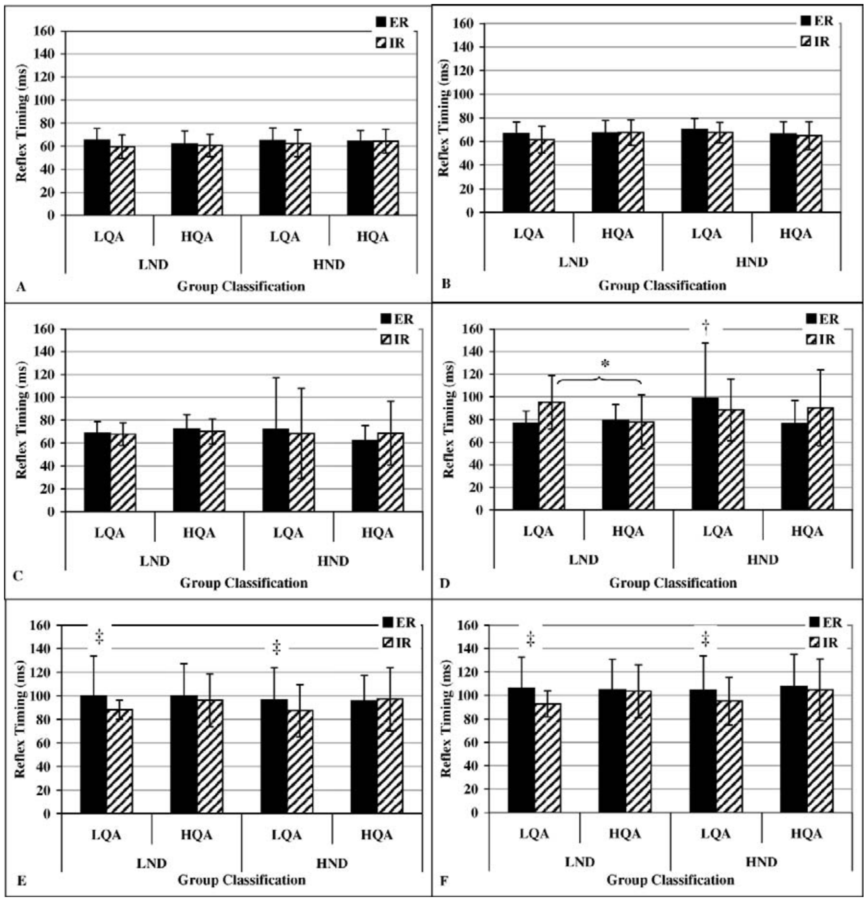

Figure 3. Muscle reflex timing by navicular drop and quadriceps angle classifications for internal (IR) and external (ER) rotation perturbations for the medial (A) and lateral (B) gastrocnemius, medial (C) and lateral (D) hamstrings, and medial (E) and lateral (F) quadriceps. *LND-HQA faster than LND-LQA; †HND-LQA slower than all other classifications; ‡IR faster than ER. Error bars denote SDs. LQA and HQA indicate below-average and above-average quadriceps angle, respectively; LND and HND, below-average and above-average navicular drop, respectively.

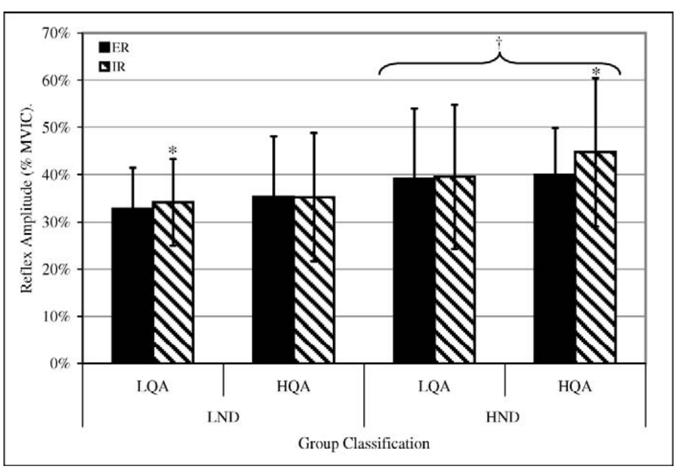

Figure 4. Comparison of muscle postperturbation amplitude (% MVIC) between navicular drop and quadriceps angle classifications for internal (IR) and external (ER) rotational perturbations. *Greater reflex amplitude IR versus ER within group (*P* < .05); †greater reflex amplitude in HND versus LND groups (*P* < .05). Error bars denote SDs. MVIC indicates maximal voluntary isometric contraction; LQA and HQA, below-average and above-average quadriceps angle, respectively; and LND and HND, below-average and above-average navicular drop, respectively.

ter of the patella to the anterior superior iliac spine and the center of the patella to the tibial tubercle. Yet given the anatomical landmarks from which this measure is derived, QA also can be influenced by abnormal tibia and femur positions in the transverse and frontal planes. Specifically, when measured in a weight-bearing posture, excessive QA may reflect one or more of a combination of anterior pelvic tilt (changing the orientation of the acetabulum and internally rotating the femur),[10] hip anteversion and knee valgus (moving the patella medially relative to the anterior superior iliac spine and tibial tubercle), and external tibial rotation (moving the tibial tubercle laterally).[31] These structural and functional malalignments may lead to a dynamic valgus collapse of the knee, thereby increasing rotary stress on the weight-bearing knee when the pelvis and femur are internally rotating on a fixed tibia. Kinematic studies of the influence of QA on tibiofemoral motion during running[32] and in vitro simulation of squatting[30] lend some support to this biomechanical theory. Although one group[32] found that subjects with a high QA (>15°) had similar maximal internal tibial rotation angles during running compared with those with low QA, those with high QA had greater maximal tibial ER and achieved maximal tibial IR later in the stance phase.

Because of these potential biomechanical relationships, we expected that increased femoral rotation on the tibia created by the IR perturbation would increase the rotary stress on the knee in subjects with HQA, as evidenced by altered neuromuscular response characteristics. Our findings support our hypothesis, because differences in muscle activation between QA group classifications were noted primarily with IR perturbations. Although HQA had no effect on RT with ER perturbations, subjects in both HQA group classifications had quadriceps RTs that were 10 to 12 milliseconds slower with IR perturbations, and subjects classified as LND-HQA had faster LH RTs than LND-LQA subjects had. However, the effect of QA on LH RT was not apparent in subjects in the above-average ND group classifications.

The biomechanical consequences of these neuromuscular alterations on tibiofemoral joint loading in LND-HQA subjects (ie, faster LH response, slower quadriceps response) are somewhat unclear. It is well recognized that isolated quadriceps contractions increase anterior and internal tibial rotation on the thigh,[33,34] whereas the LH acts independently to stabilize the tibia and reduce anterior-medial tibial translation.[33,35] Under normal circumstances, earlier firing of the LH relative to the quadriceps would seem to protect the knee joint. However, because the IR perturbation creates IR of the femur on the fixed tibia upon cable release,[23] the activation pattern demonstrated by subjects with HQA seems somewhat counterintuitive when they attempted to control transverse tibiofemoral motion in response to the IR perturbation. Earlier activation of the LH during an event causing internal femur-on-tibia rotation would appear to accentuate excessive transverse-plane knee motion, thus placing rotary stress on the knee.

It may be that the neuromuscular patterns observed in the HQA group are more related to patellofemoral joint function. Given the increased lateral quadriceps force vector created with HQA in combination with increasing femoral rotation on the tibia,[31] the delayed quadriceps firing may be an effort to avoid excessive lateral forces on the patella that could lead to subluxation. However, this may not explain the earlier firing of the LH. Moreover, should this neuromuscular activation pattern reflect a protective response to control excessive patellofemoral joint motion and forces, such a response may come with the consequence of increased tibiofemoral joint stress and risk of injury. Further work is needed to determine the biomechanical consequences of these altered neuromuscular patterns in response to an ER perturbation in subjects with HQA. In order to fully interpret the effects of HQA on neuromuscular and biomechanical function of the tibiofemoral joint during dynamic motion, it may be necessary to classify and to further differentiate HQA based on the relative contributions of soft tissue, structural, or functional faults that define the measure.[31]

Interactive Effects of Navicular Drop and Quadriceps Angle

We were somewhat surprised by the finding that subjects classified as HND-HQA responded to the ER and IR perturbations in a similar manner (in both timing and activation amplitude) to those with a more neutral alignment (LND-LQA). This was contrary to our hypothesis, because our expectation was that the combination of HND and HQA would accentuate a valgus knee posture, thereby increasing tibiofemoral joint loading and stress, particularly with an ER perturbation. However, our findings suggest that when both HND and HQA are present, these malalignments may have somewhat opposing biomechanical effects on tibiofemoral motion and essentially may cancel each other out to some extent. This result was particularly apparent in the LH. The HND influenced LH activation with an ER perturbation but only in subjects with LQA. Similarly, HQA influenced only LH activation with IR perturbations in subjects with LND.

These findings are clinically important, because they suggest that examining a single anatomical factor while not accounting for the presence of other alignment factors may make it difficult to identify the relationships among anatomic alignment, dynamic knee function, and the potential for ACL injury risk. This may in part explain why a recent (2005) consensus conference sponsored by the American Orthopaedic Society of Sports Medicine on ACL injury concluded that no anatomic factors had been reliably associated with an increased risk of noncontact ACL injury.[36] The few groups that have examined this relationship[1,3,5,6] differed considerably in the variables examined, with most focusing on an isolated or select group of alignment factors. The alignment of the entire lower extremity, from the pelvis to the foot, must be considered, because malalignment at one segment or joint may profoundly influence the alignment of other segments or joints[5,10,37] and, in turn, may differentially affect neuromuscular and biomechanical function. This idea is supported by authors of retrospective injury risk studies, who have found that a combination of anatomic variables is more predictive of ACL injury than a single variable is[3,5,6] and that the predictive ability of a particular anatomical risk factor may depend on its relationship with other anatomical variables examined.[5] In order to clarify the relationship between anatomical alignment and injury risk, prospective epidemiologic studies that account for all relevant variables are needed. In order to accomplish this, much larger sample sizes will be needed.

The interactive effects of these anatomical alignment factors also may have implications for clinicians when correcting for alignment faults. Clinicians commonly correct for excessive pronation through orthotic intervention. Our results emphasize the need to perform a complete postural assessment and consider other alignment faults (eg, excessive QA) before making these alterations, because correcting one malalignment without addressing other malalignments actually may increase neuromuscular and biomechanical stresses more than if they were left uncorrected. Additional work is needed to fully understand and define the lower extremity postural characteristics that combine to pose the greatest risk for abnormal joint stresses and injury.

The influence of lower extremity malalignments on neuromuscular function and ACL injury risk remains relatively unknown. In the majority of studies to date, only select static alignment variables have been examined relative to ACL injury risk, based solely on the average values compared in injured and uninjured subjects.[1,3,5,6,29] No mechanism for the potential relationship among static posture, neuromuscular responses, and possible ACL injury risk has been determined or adequately explained. In an effort to better understand the potential influence of static posture faults on dynamic knee function, we examined how subjects who were high or low on ND and QA may differ in their neuromuscular control strategies under functional, weight-bearing conditions. Although our findings suggest that these static postures influence neuromuscular response characteristics in response to a weight-bearing, rotational perturbation, the biomechanical consequences of these alterations require additional study. Moreover, our findings are limited to only 2 postural factors. Future authors should expand on these findings by examining both neuromuscular and biomechanical variables and taking a more comprehensive approach to describing lower extremity posture if we are to fully understand the effect of static posture on dynamic knee motion. Completing these studies may help to clarify the postural characteristics that combine to alter biomechanical stresses at the knee, so that we can better focus our prescreening and prevention strategies accordingly.

In summary, our goals of this study were to classify subjects based on common clinical measures of anatomical alignment and to examine how subjects who are high and low on these values may differ in their neuromuscular responses to a weight-bearing, rotational perturbation. Subjects classified as having above-average ND and QA exhibited different neuromuscular responses, depending on whether one or both of these alignment characteristics are present. The interactive effects of ND and QA classifications on neuromuscular timing and amplitude highlight the importance of taking a more comprehensive approach to lower extremity postural assessment, given the potential for one alignment factor to compensate for or interact with another. We believe these findings are relevant to both clinicians and researchers when developing preseason assessments, epidemiologic and biomechanical studies aimed at analyzing factors contributing to lower extremity dysfunction and injury risk, and rehabilitation and prevention strategies.

ACKNOWLEDGMENTS

This research was supported by grant 999A003 from the National Athletic Trainers' Association Research & Education Foundation, Dallas, TX. This grant was awarded originally to the University of Virginia and later was transferred to the University of North Carolina at Greensboro.

REFERENCES

1. Beckett ME, Massie DL, Bowers KD, Stoll DA. Incidence of hyperpronation in the ACL injured knee: a clinical perspective. *J Athl Train.* 1992; 27:58–61.
2. Griffin LY, Agel J, Albohm MJ, et al. Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies. *J Am Acad Orthop Surg.* 2000;8:141–150.
3. Hertel JN, Dorfman JH, Braham RA. Lower extremity malalignments and anterior cruciate ligament injury history. *J Sports Sci Med.* 2004;3:220–225.
4. Ireland ML, Gaudette M, Crook S. ACL injuries in the female athlete. *J Sport Rehabil.* 1997;6:97–110.
5. Loudon JK, Jenkins W, Loudon KL. The relationship between static posture and ACL injury in female athletes. *J Orthop Sports Phys Ther.* 1996; 24:91–97.
6. Woodford-Rogers B, Cyphert L, Denegar CR. Risk factors for anterior cruciate ligament injury in high school and college athletes. *J Athl Train.* 1994;29:343–346.
7. Bates BT, Osternig LR, Mason B, James LS. Foot orthotic devices to modify selected aspects of lower extremity mechanics. *Am J Sports Med.* 1979;7:338–342.
8. Cornwall MW, McPoil TG. Footwear and foot orthotic effectiveness research: a new approach. *J Orthop Sports Phys Ther.* 1995;21:337–344.
9. Cowan DN, Jones BH, Frykman PN, et al. Lower limb morphology and risk of overuse injury among male infantry trainees. *Med Sci Sports Exerc.* 1996;28:945–952.
10. Hruska R. Pelvic stability influences lower extremity kinematics. *Biomechanics.* 1998;6:23–29.
11. Ilahi OA, Kohl HW III. Lower extremity morphology and alignment and risk of overuse injury. *Clin J Sport Med.* 1998;8:38–42.
12. McCullouch MU, Brent D, Vander Linden D. The effect of foot orthotics and gait velocity on lower limb kinematics and temporal events of stance. *J Orthop Sports Phys Ther.* 1993;17:2–10.
13. Nawoczenski DA, Ludewig PM. Electromyographic effects of foot orthotics on selected lower extremity muscles during running. *Arch Phys Med Rehabil.* 1999;80:540–544.
14. Rose HM, Shultz SJ, Arnold BL, Gansneder BM, Perrin DH. Acute orthotic intervention does not affect muscular response times and activation patterns at the knee. *J Athl Train.* 2002;37:133–140.
15. Tomaro J, Burdett RG. The effects of foot orthotics on the EMG activity of selected leg muscles during gait. *J Orthop Sports Phys Ther.* 1993;18: 532–536.
16. Mueller MJ, Host JV, Norton BJ. Navicular drop test as a composite measure of excessive pronation. *J Am Podiatr Med Assoc.* 1993;8:198–202.
17. Trimble MH, Bishop MD, Buckley BD, Fields LC, Rozea GD. The relationship between clinical measurements of lower extremity posture and tibial translation. *Clin Biomech (Bristol, Avon).* 2002;17:286–290.
18. Woodland LH, Francis RS. Parameters and comparisons of the quadriceps angle of college-aged men and women in the supine and standing positions. *Am J Sports Med.* 1992;20:208–211.
19. Horton MG, Hall TL. Quadriceps femoris angle: normal values and relationship with gender and selected skeletal measures. *Phys Ther.* 1989; 69:897–901.
20. Brody DM. Techniques in the evaluation and treatment of the injured runner. *Orthop Clin North Am.* 1982;13:541–558.
21. Livingston LA, Mandigo JL. Bilateral within-subject Q angle asymmetry in young adult females and males. *Biomed Sci Instrum.* 1997;33:112–117.
22. Shultz SJ, Perrin DH, Adams JM, Arnold BL, Gansneder BM, Granata KP. Assessment of neuromuscular response characteristics at the knee following a functional perturbation. *J Electromyogr Kinesiol.* 2000;10: 159–170.
23. Schmitz RJ, Shultz SJ, Kulas AS, Windley TC, Perrin DH. Kinematic analysis of functional lower body perturbations. *Clin Biomech (Bristol, Avon).* 2004;19:1032–1039.
24. Cohen J. *Statistical Power Analysis for the Behavioral Sciences.* 2nd ed. Hillsdale, NJ: Laurence Erlbaum Assoc; 1988.
25. Hintermann B, Nigg BM, Sommer C, Cole GK. Transfer of movement between calcaneus and tibia in vitro. *Clin Biomech.* 1994;9:349–355.
26. Nigg BM, Cole GK, Nachbauer W. Effect of arch height of the foot on angular motion of the lower extremities in running. *J Biomech.* 1993;26: 909–916.
27. Coplan JA. Rotational motion of the knee: a comparison of normal and pronating subjects. *J Orthop Sports Phys Ther.* 1989;10:366–369.
28. Fleming BC, Renstrom PA, Beynnon BD, et al. The effect of weightbearing and external loading on anterior cruciate ligament strain. *J Biomech.* 2001;34:163–170.
29. Shambaugh JP, Klein A, Herbert JH. Structural measures as predictors of injury in basketball players. *Med Sci Sports Exerc.* 1991;23:522–527.
30. Mizuno Y, Kumagai M, Mattessich SM, et al. Q-angle influences tibiofemoral and patellofemoral kinematics. *J Orthop Res.* 2001;19:834–840.
31. Powers CM. The influence of altered lower-extremity kinematics on patellofemoral joint dysfunction: a theoretical perspective. *J Orthop Sports Phys Ther.* 2003;33:639–646.
32. Heiderscheit BC, Hamill J, Caldwell GE. Influence of Q-angle on lower-extremity running kinematics. *J Orthop Sports Phys Ther.* 2000;30:271–278.
33. Hirokawa S, Solomonow M, Lu Y, Lou ZP, D'Ambrosia R. Anterior-posterior and rotational displacement of the tibia elicited by quadriceps contraction. *Am J Sports Med.* 1992;20:299–306.
34. DeMorat G, Weinhold P, Blackburn T, Chudik S, Garrett W. Aggressive quadriceps loading can induce noncontact anterior cruciate ligament injury. *Am J Sports Med.* 2004;32:477–483.
35. Renstrom P, Arms SW, Stanwyck TS, Johnson RJ, Pope MH. Strain within the anterior cruciate ligament during hamstring and quadriceps activity. *Am J Sports Med.* 1986;14:83–87.
36. Griffin LY, Albohm MJ, Arendt EA, et al. Update on ACL prevention: theoretical and practical guidelines. *Am J Sports Med.* In press.
37. Kendall FP, McCreary EK. *Muscles: Testing and Function.* 3rd ed. Baltimore, MD: Williams & Wilkins; 1983.

COMMENTARY

Glenn N. Williams

Editor's Note: Glenn N. Williams, PhD, ATC, PT, is an Assistant Professor for the Graduate Program in Physical Therapy and Rehabilitation Science and the Department of Orthopaedics and Rehabilitation at the University of Iowa in Iowa City, IA. He is also the Director of Research for the University of Iowa Sports Medicine Center and the Director of the Musculoskeletal Biomechanics and Sports Medicine Research Laboratory.

The aim of this study was "to evaluate the isolated and combined effects of quadriceps angle (QA) and navicular drop (ND) on neuromuscular responses to a weight-bearing perturbation." The weight-bearing perturbation method is an innovative approach that the authors have pioneered and used in several meaningful studies cited in the article. The "Introduction" and "Discussion" sections of the article establish that the underlying premise is that pronation and QA are potential risk factors for noncontact anterior cruciate ligament injuries in female athletes. The authors use ND as an indicator of pronation. This measure is well established in the literature, and the authors' measurement technique is consistent with that described in the literature; however, it should be acknowledged that the validity of this measure has been questioned because it does not adjust for foot size.[1] The authors establish a gap in the literature by stating that "we found no published studies that directly evaluated the influence of lower extremity malalignments on protective neuromuscular response characteristics at the knee." Their end goal is to further elucidate the potential contributions of ND and QA as risk factors for noncontact anterior cruciate ligament injury in females by examining the influence of anatomic alignment on neuromuscular function about the knee. To do this, they divided a sample of 79 "healthy" National Collegiate Athletic Association (NCAA) Division I collegiate female athletes into 4 groups and contrasted the groups' muscle activation patterns when subjected to a weight-bearing perturbation (forward and rotatory). The authors hypothesized that ND and QA would have both independent and interactive effects on muscle activation patterns that would depend on the direction of perturbation.

This article has several strengths. The perturbation method is novel and innovative and is being used in a line of research related to a "hot" topic in sports medicine: neuromuscular risk factors for noncontact anterior cruciate ligament injury and the female predisposition to these injuries. The authors are established leaders in athletic training and sports medicine research. The manuscript is clearly written and focused on clinical relevance.

As is the case with nearly all research, the study also makes assumptions and has limitations. I will discuss a few issues that I believe are important for readers to consider when evaluating this article, as I believe these issues have important implications for the interpretation of the results. I do not consider any of these to be major issues; however, failure to recognize these issues and their potential implications when reading the article may lead to errors in the interpretation and application of the results. The issues I would like to discuss include (1) the heterogeneity of the sample with respect to the conceptual framework of noncontact anterior cruciate ligament injury, (2) the grouping of subjects, (3) the methods of categorization and analysis, and (4) issues related to electromyographic studies and the use of data recorded when subjects are barefoot.

The sample size and enrollment of NCAA Division I female athletes are appropriate, although extrapolating the results outside of this population is questionable. Also, by including only "healthy" athletes (those with no history of knee ligament injury or surgery), the authors may have introduced a selection bias in that those female athletes who are most likely to have abnormal anatomical alignment and associated alterations in neuromuscular function may have already sustained injuries and been excluded from the sample. I am not challenging this method, as the alternative of including people who have sustained ligament injuries brings with it the likelihood of confounding factors that would be even more problematic. Rather, I am simply identifying that the potential selection bias needs to be recognized when interpreting the results.

It is well established that people who play sports involving jumping, cutting, pivoting, and quick changes of direction are at risk for noncontact anterior cruciate ligament injuries, because these activities increase the likelihood that large loads will be experienced at the knee. Conversely, those who participate in other sports generally have relatively little risk for this type of injury. With the focus on noncontact anterior cruciate ligament injuries in mind, it seems logical that the study's subjects would primarily be athletes at risk for this injury. Yet more than half of the 79 subjects in this sample participated in sports with little risk for noncontact anterior cruciate ligament injury (30 in crew, 3 in track, 6 in softball, and 3 in swimming). This heterogeneity is potentially problematic and should be recognized. Although the authors' primary objective is to evaluate the effects of static foot and knee alignment (intrinsic factors) on neuromuscular responses, it is plausible that the sensorimotor function and performance of people who play high-risk sports (eg, basketball and soccer) is inherently different than that of those who play low-risk sports (eg, crew and track). People choose to participate in specific sports for a number of reasons: natural ability, early success, peer involvement, because they enjoy the aggressiveness and challenge required for successful performance, and a variety of other reasons. At least some of these reasons may be related to a person's sensorimotor function (eg, excellent sensorimotor control may facilitate a high level of performance and "success"). The heterogeneity that I identify here is only an issue because the authors suggest that their goal is to further elucidate the potential contributions of ND and QA as risk factors for noncontact anterior cruciate ligament injury in females by examining the influence of these factors on neuromuscular function in the current sample. It could be argued that the subjects who were regular participants in low-risk sports could indeed be at high risk for noncontact anterior cruciate ligament injuries if they participated in other sports, but enrolling only subjects known to be at risk because they regularly participate in sports that require cutting, pivoting, and jumping would have provided a stronger design for this study. With that said, the breadth of the sample actually broadens the applicability of the results to a larger population of athletes, which is meaningful because excessive pronation is thought to contribute to other lower extremity injuries (eg, medial tibial stress syndrome, patellofemoral pain syndrome). Nevertheless, because the current manuscript focuses so closely on anterior cruciate ligament injury, it is important for readers to recognize the potential limitations of this heterogeneity.

The subjects in this sample were categorized into 4 groups based on their ND and QA. Data were analyzed based on these categorizations, which makes the groupings a critical component of the study. The thresholds established for the groupings are odd in that the thresholds for being considered in the low versus high ND and QA groups are only 1 mm and 1° apart, respectively. Measurements were taken with a standard rule and a standard goniometer, which have maximal precision that is no greater than the thresholds for group separation. An experienced investigator took the measurements, which is critical for reliability. High measurement reproducibility was established by the authors, but even with the high degree of reproducibility, the standard error of the means exceeds the 1 mm and 1° used for group thresholds. Although the thresholds for grouping are questionable for the above reasons, it is clear that the high and low groups were truly different based on the means and standard deviations for the groups. Consequently, it does not appear that this issue has affected the study's validity at all. Conversely, the fact that the ''high'' group means for both ND and QA fall within what is considered to be ''normal'' in the literature has potential implications for the interpretation of the data. Authors of 2 of the most frequently cited papers related to ND report that values above 10 or 15 mm should be considered abnormal[2,3]; the mean of the high ND in the current sample was 9.3 mm. Similarly, the threshold value for abnormal QA in females from the literature is $>20°$ and the mean in the current sample was 19°.[4–6] The position of the subject during testing should also be considered when looking at the QA norms in the literature. The authors measured the QA with subjects standing, which is the most appropriate method for this study. Quadriceps angles in standing are generally slightly greater than those measured in the supine position, which provide the basis for most of the normative values in the literature. Although variation exists in the norms presented in the literature, those I have presented are common. The fact that most of the subjects in this study must be considered to have normal NDs and QAs is problematic, as this apparent selection bias decreases the likelihood that the subjects would have significant alterations in their neuromuscular control or knee mechanics. Hence, although the findings do provide some insight related to the effect of ND and QA on muscle activity patterns, it is unclear if the findings are relevant to the manuscript's underlying framework of noncontact anterior cruciate ligament injury risk.

Another issue related to grouping the subjects into 4 categories is the question of whether or not grouping the subjects is the best approach to answer the research question. The abstract states that the objective of this study was ''to evaluate the isolated and combined effects of QA and ND on neuromuscular responses to a weight-bearing perturbation.'' Hence, the research question appears to be ''Does the amount of ND or QA (or both) affect the neuromuscular responses observed when a weight-bearing perturbation is induced?'' The authors divided the subjects into 4 groups based on their ND and QA measurements and then used a repeated-measures analysis of variance to evaluate the differences among groups and the interactions among variables. Post hoc analyses were used to further explain the main effects and interactions. This approach is appropriate and certainly defendable. Yet when data are grouped and means are analyzed, we often mask some of the meaningful information in the data. The mean is used as a representation of the sample. The same mean can be reached with grossly different distributions of scores. Although the statistical methods take variability into account to some degree, some scores in the sample certainly have more of an effect on the mean than others. It is hard to know if a subset of the group (low or high) has very different neuromuscular responses from the average subject in the other group, with the rest having similar responses, or if the entire group has different responses from the other group. Looking at the authors' Figures 2 through 4, it is clear that there is a fair degree of variability in the data. This is expected with neuromuscular responses. A close look reveals that the mean differences between groups with significant differences usually fall within the standard deviations. This lessens confidence in the meaningfulness of the data. Using the reported method of analysis, we can simply conclude that the means for certain contrasts were statistically significant and that some variables had significant interactions.

Another approach to analyzing these data is correlation/regression analysis, which allows us to evaluate the relationship between 2 or more factors. For example, we can assess whether long latency reflex time increases as ND increases or evaluate the degree to which the combination of ND and QA explains variability in long latency reflex times. In analysis of variance, differences observed in a factor (eg, reflex latency) between 2 groups (eg, those with low or high ND) are assumed to be related to the grouping item, whereas in correlation/regression analysis, we assess whether the factors are related. In my opinion, assessing the relationships between ND and QA and the neuromuscular responses of interest without grouping the subjects would have provided more meaningful information related to the research question than was obtained using the analysis of variance method. The fact that most of the subjects in the current sample fall within normal limits on the factors of interest increases my preference for correlation/regression analysis in the current study. Obviously, there is more than one ''correct'' way to analyze a data set. Readers should, however, recognize that it is unclear if the reported differences observed between groups are truly related to the grouping factors and should also appreciate the level of variability in the data.

Electromyographic (EMG) studies can provide meaningful information regarding neuromuscular function. The authors evaluated 3 variables in this study: preperturbation amplitude, reflex latency (long), and postperturbation amplitude. The amplitude of EMG activity is a measure of muscle activation. It is difficult to know what meaning should be given to EMG amplitude measurements in the absence of other supporting measurements (eg, force, moments). In the present study, inverse dynamics measurement and force measurements at the knee or ankle are not discussed; thus, it is impossible to determine if the stiffness or mechanics of the knee were different among subjects who had different EMG amplitudes. I specifically mention these variables as they are commonly discussed in the context of noncontact anterior cruciate ligament injuries, and it is assumed that the neuromuscular variables measured are thought to be related to these factors. A variety of factors can affect muscle activation level. For example, if 2 subjects have the same mass and one has significantly weaker quadriceps or hamstrings strength, the weaker subject would be expected to need to activate her muscles at a higher level to support her mass during a 30° squat (assuming the muscle composition and other morphologic factors were similar). This increased activity would be measured as higher preactivity in the current study, when the conditions at the knee may indeed be similar. As a clinical scientist who studies neuromuscular function, I am fully aware of the difficulties with EMG studies, and I am not challenging the authors' methods. The variables chosen and EMG methods are consistent with the literature and quality. Nevertheless, the reader should be aware that it is difficult to ascertain how clinically meaningful the differences in preactivity or postperturbation activity are because of the inherent limitations of isolated EMG amplitude measurements alluded to above and the assumptions of EMG studies (eg, that what we measure from the muscle is truly representative of the whole muscle and that all subjects maximally activate their muscles during the maximum trials used for normalization). It is also unclear if statistically significant but relatively small values (10 milliseconds in reflex response time) are clinically significant. The results do provide insight that should be considered with respect to the confluence of evidence related to the focus areas of the study. However, care should be taken that undue weight is not assigned to the data when considering injury epidemiology.

Finally, the authors performed their experiments with the subjects barefoot. This is appropriate, as a focus of the study is subtalar joint position and motion. Nevertheless, this factor may limit the applicability of the study's findings, as most athletes wear athletic shoes during sport participation. Athletic shoes are often built to minimize pronation and can affect neuromuscular patterns.[7,8] An ideal but less convenient study design would include testing the same subjects using a with-shoes and without-shoes design in which the order of testing is randomized. The authors should consider a study with this or a similar design as a follow-up to the present study.

In closing, I would like to commend the authors on an interesting and nicely written manuscript that is timely, clinically focused, and based on a study that has an innovative and fairly sound design. As stated previously, I think most of the issues I have discussed are relatively minor, and some are debatable. I encourage the authors to continue study on this topic and the female predisposition to noncontact anterior cruciate ligament injuries. I look forward to their future work.

REFERENCES

1. Menz HB. Alternative techniques for the clinical assessment of foot pronation. *J Am Podiatr Med Assoc.* 1998;88:119–129.
2. Brody DM. Techniques in the evaluation and treatment of the injured runner. *Orthop Clin N Am.* 1982;13:541–558.
3. Mueller MJ, Host JV, Norton BJ. Navicular drop as a composite measure of excessive pronation. *J Am Podiatr Med Assoc.* 1993;83:198–202.
4. Horton MG, Hall TL. Quadriceps femoris muscle angle: normal values and relationships with gender and selected skeletal measures. *Phys Ther.* 1989;69:897–901.
5. Shelbourne K, Rask B, Hunt S. Knee injuries. In: Schenck R Jr, ed. *Athletic Training and Sports Medicine.* 3rd ed. Rosemont, IL: American Academy of Orthopaedic Surgeons; 1999:441.
6. Theut P, Fulkerson J. Anterior knee pain and patellar subluxation in the adult. In: DeLee J, Drez D, Miller M, eds. *Orthopaedic Sports Medicine: Principles and Practice.* Vol 2. Philadelphia, PA: WB Saunders; 2003: 1779.
7. von Tscharner V, Goepfert B, Nigg BM. Changes in EMG signals for the muscle tibialis anterior while running barefoot or with shoes resolved by non-linearly scaled wavelets. *J Biomech.* 2003;36:1169–1176.
8. Wakeling JM, Pascual SA, Nigg BM. Altering muscle activity in the lower extremities by running with different shoes. *Med Sci Sports Exerc.* 2002;34:1529–1532.

AUTHORS' RESPONSE

We thank Dr Williams for his thorough review and critique of our work. He has raised some good discussion points that we agree are important for readers to understand and consider. In particular, we would like to address the comments regarding the heterogeneity of the sample and the treatment of the data (ie, group classification and choice of statistical approach).

Heterogeneity of the Sample

Studying healthy individuals who may or may not be at risk for injury is an important issue that is a common limitation of early-stage risk factor research. We agree that limiting the population to those who are most at risk for anterior cruciate ligament (ACL) injury would have yielded a stronger study design, (eg, ACL-injured basketball and soccer athletes). However, studying those who are already injured introduces other limitations: most relevant to this study is the potential for the injury to modify neuromuscular response characteristics. Because we felt this would cloud the relationship among navicular drop (ND), quadriceps angle (QA), and neuromuscular timing and activation, we chose to initially study healthy subjects. Ultimately, investigators will need prospective, case-control study designs to examine whether these characteristics truly identify those who will go on to suffer ACL injury.

Our goal for this particular study was to actively sample and identify female athletes with high and low ND and QA values and determine how these variables affected neuromuscular activation patterns during a weight-bearing activity. As such, we did not restrict our sample to sports known to be at greater risk for ACL injury for a couple of reasons. In the collegiate environment (in which our study was conducted), we were not able to achieve sufficient statistical power by restricting our sample to females engaged in lacrosse, basketball, and soccer (ie, those sports in which females were most at risk for suffering an ACL injury [our initial goal]). Not surprisingly, many of these athletes had to be excluded from the study due to previous injury. This required us to broaden the scope of our population to other Division I sports in order to achieve the desired statistical power. Given that our focus was on an intrinsic risk factor, we felt this was an appropriate approach that allowed greater generalization of our findings. Further, because the perturbation in our study is somewhat novel (versus an activity such as landing), we were less concerned about limiting our study to specific sports in which participants are more or less trained on a particular functional task. However, it is well known that training influences neuromuscular timing and activation, and we cannot exclude the possibility that different training practices among sports may have confounded our findings to some extent (the same could be said for teams from the same sport that use very different training practices). Less understood are any inherent sensorimotor differences in females who chose to participate in various sports, and we make no assumptions in this regard. The ultimate effect of this heterogeneity on our findings is that it may have introduced additional variability in the data, which, if anything, would have made it more difficult to identify the unique relationships among ND, QA, and muscle activation. Therefore, it would seem that the greatest concern heterogeneity raises is that it may have suppressed our findings relative to the stated outcomes, rather than introducing spurious findings. Future researchers should consider stratifying subjects by sport to examine any potential interactive effects among sport, static lower extremity alignment, and neuromuscular response characteristics.

Group Classifications and Statistical Approach

Three main concerns were raised regarding our group classification scheme. The first concern focuses on the thresholds established for grouping, in that they only differed by 1 mm or 1°. In reality, these groups are quite different, as we actively sampled females who fell well above and below the population norms. As such, our sampling distribution was not normally distributed (but rather more bimodal), and the above and below average groups were clearly separated. This is evident in the means and standard deviations reported in Table 1. In fact, very few subjects fell at the high end of the below average groups or at the low end of the above average groups. We would have liked for the mean of the high ND group to be somewhat higher, but the reality is that it is very difficult to find females who are well above the population mean. Still, we are confident that our sampling procedures produced distinct groups that allowed us to look at differences in neuromuscular timing and amplitude when selecting people who were high and low in these values.

The concern that the ''high ND and QA groups'' include ''normal values'' within the range was also raised. It is important to note that we did not attempt to identify an ''abnormal'' ND or QA as a cut off for group classification. Although Dr Williams cited authors who presented values that ''should be considered abnormal,'' we do not believe empirical studies are sufficient to support a clear pathologic cut-off or ''abnormal'' value that separates individuals who are at risk versus not at risk. For example, when ND was found to be predictive of ACL injury risk in retrospective studies, mean ND values in the ACL-injured subjects were 5.0 ± 2.5 mm (females),[1] 8.4 ± 2.5 mm,[2] and approximately 13.0 ± 4.0 mm.[3] Although not specific to ACL injury, the patellofemoral literature also highlights the controversy in identifying a clear pathologic cut-off, as authors have noted that fewer than half of subjects symptomatic for patellofemoral pain had QAs greater than 20°.[4,5] Hence, we felt that using a particular pathologic cut-off point would be somewhat arbitrary and difficult to justify. Further, it is possible that when present in combination, individual alignment variables that are not considered alone to be abnormally high may interact with other alignment variables to compound or compensate for one another. Because of these unknowns, we chose to take a more conservative approach and simply examine individuals who fell above and below the population mean.

A final point raised relative to subject grouping was the choice of our statistical analyses. We agree that using a regression analysis is a relevant and equally defensible statistical approach to answer the research question. We chose an analysis of variance (ANOVA) model for 2 major reasons. It fit our sampling design specifics, as discussed above. It also allowed us to present results in a clinically relevant manner. Given that the muscles around the knee work collectively to provide stability to the knee, one of our goals was to examine the potential interactions among ND, QA, and muscle. We believe the ANOVA model allowed us to more easily present and compare the clinical values of muscle activation for the quadriceps, hamstrings, and gastrocnemius resulting from the interactions among ND, QA, and muscle.

We understand the concern about the potential for an ANOVA model to mask individual differences. Upon close inspection of our data, we do not feel this was problematic in our study. Table 1 demonstrates that the distribution of ND and QA values was fairly uniform across the 4 groups. In addition, we retrospectively compared our results with those obtained using regression analyses for the dependent variables that were found to differ by ND and QA. The R^2 values from the ANOVA versus the regression analyses were, respectively, 0.08 versus 0.07 for lateral hamstring preactivation, 0.10 versus 0.06 for lateral hamstring reflex time, 0.06 versus 0.06 for quadriceps reflex time, 0.09 versus 0.08 for combined muscle reflex amplitude for internal rotation, and 0.07 versus 0.07 for combined muscle reflex amplitude for external rotation. For these comparisons, our findings would have been essentially the same if we had used a regression model.

Findings Based on Surface Electromyography and a Barefoot Protocol

We completely agree with the limitations of examining surface electromyography variables without accompanying kinematic and kinetic data. As we readily acknowledged in our discussion, further study is needed before we can fully understand the biomechanical implications of these altered responses or the magnitude of neuromuscular changes that are necessary to alter joint biomechanics. Since the inception of this study, we have modified our perturbation protocol to simultaneously examine neuromuscular and biomechanical variables,[6] and our work is ongoing in this regard. The point about testing subjects barefoot versus in athletic shoes is well taken and is an excellent suggestion for future research.

Again, we appreciate the issues that Dr Williams has raised. This discussion further highlights the complexity of this work and the multitude of issues involved in designing a quality study. Although anatomical factors continue to be considered a potential risk factor for ACL injury, research in this area remains relatively limited. Our work represents just one small step in our long-term goal of understanding the effect of static lower extremity alignment on dynamic knee joint function and, ultimately, the effects of these (mal)alignments on ACL injury risk. Clearly, many questions remain unanswered, and we hope that this discussion will help stimulate further research in this area.

REFERENCES

1. Woodford-Rogers B, Cyphert L, Denegar CR. Risk factors for anterior cruciate ligament injury in high school and college athletes. *J Athl Train.* 1994;29:343–346.
2. Hertel JN, Dorfman JH, Braham RA. Lower extremity malalignments and anterior cruciate ligament injury history. *J Sport Sci Med.* 2004;3:220–225.
3. Beckett ME, Massie DL, Bowers KD, Stoll DA. Incidence of hyperpronation in the ACL injured knee: a clinical perspective. *J Athl Train.* 1992;27:58–62.
4. Aglietti P, Insall JN, Cerulli G. Patellar pain and incongruence I: measurements of incongruence. *Clin Orthop Rel Res.* 1983;176:217–224.
5. Insall J, Falio KA, Wise DW. Chondromalacia patella: a prospective study. *J Bone Joint Surg.* 1976;58:1–8.
6. Schmitz RJ, Shultz SJ, Kulas AS, Windley TC, Perrin DH. Kinematic analysis of functional lower extremity perturbations. *Clin Biomech (Bristol, Avon).* 2004;19:1032–1039.