Frontal plane knee angle affects dynamic postural control strategy during unilateral stance

JOHN NYLAND, STEVE SMITH, KURT BEICKMAN, THOMAS ARMSEY, and DAVID N. M. CABORN
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ABSTRACT

NYLAND, J., S. SMITH, K. BEICKMAN, T. ARMSEY, and D. N. M. CABORN. Frontal plane knee angle affects dynamic postural control strategy during unilateral stance. Med. Sci. Sports Exerc., Vol. 34, No. 7, pp. 1150–1157, 2002. Purpose: Center of plantar pressure (COPP) location moves toward the forefoot as ankle plantar flexor muscles attempt to maintain postural control during single leg stance. This study evaluated relationships between frontal plane tibiofemoral joint angulation during relaxed bilateral stance and mean COPP locations during vision-denied single leg stance at 20° knee flexion. Methods: Fifty-six nonimpaired athletes (29 female, 27 male) were evaluated for frontal plane tibiofemoral joint angulation and standing foot angle by using two-dimensional videography (30 Hz). Mean anterior-posterior and mediolateral COPP locations were assessed during single leg stance on a mat (25 Hz, 15 s). One-way ANOVA and Tukey HSD tests evaluated group differences (P ≤ 0.05) based on frontal plane tibiofemoral joint angulation. Results: Group 1 (genu varus or genu valgus < 5°) displayed a mean anterior-posterior COPP location of 54.2 ± 6% from the (0,0) coordinate starting point at the anterolateral foot (10.3 ± 2 cm from the posterior sensor edge). Group 2 (genu varus angulation ≥ 5°) and group 3 subjects (genu valgus angulation ≥ 5°) displayed mean anterior-posterior COPP locations of 60.6 ± 8% and 60.7 ± 7% (8.8 ± 2 cm and 8.7 ± 2 cm from the posterior sensor edges), respectively. Group 2 (12.5 ± 3 N·kg⁻¹) and group 3 (12.4 ± 3.1 N·kg⁻¹) subjects also displayed greater mean plantar force magnitude/body weight than group 1 (10.3 ± 2 N·kg⁻¹) subjects. Mean ankle plantar flexor moment magnitudes did not differ between groups. Conclusions: Rearfoot directed mean anterior-posterior COPP locations and greater plantar force magnitudes/body weight suggests that subjects with genu varus or genu valgus relied more on the subtalar and midtarsal joint control function of the ankle plantar flexor muscle group for lower extremity dynamic postural control. Key Words: PLANTAR PRESSURE, INJURY PREVENTION, REHABILITATION

During adolescence there is a balancing effect between genu varus and genu valgus with few individuals having absolutely straight legs (28). For athletes with genu valgus or genu varus to effectively participate in the repetitive running and jumping demands of many sports, compensatory alignment via the hips, ankle, subtalar, and midtarsal joints is needed (2,26,30). Compensatory lower extremity alignment improves lower extremity muscular efficiency in absorbing impact forces, generating propulsive forces, and modulating muscle activation patterns to maintain postural equilibrium (10,29,30,33) (Fig. 1).

Subtle variations in frontal plane tibiofemoral joint angulation and standing foot angle influence knee and ankle joint forces, moments, and muscle activation characteristics (1,2,7,26). Additionally, frontal plane tibiofemoral joint angulation may influence athletic injury mechanisms by selectively preloading or unloading specific tissues (2,7,15,16,30). The quadriceps femoris is the dominant muscle group at the knee joint (23). Genu valgus or genu varus may predispose the quadriceps femoris muscle group to be less effective as a knee extensor if the quadriceps tendon is directed with more of its resultant force pulling the patella laterally (genu valgus) or medially (genu varus) and with less force pulling the patella proximally (26). Excessive genu valgus is related to the high incidence of patellar pain syndrome among women (7,26,30). Both genu valgus and genu varus deformities markedly alter the foot plant position and increase frontal plane sway during running (30). In particular, athletes with genu varus tend to cross the midline during running stance phase rather than having the foot make contact immediately upon the line of progression under the midline of the head (30). In contrast to this, athletes with genu valgus tend to land on an everted heel resulting in increased soft tissue strain at the medial foot, subtalar, ankle, and knee joints (30,33). Frontal plane tibiofemoral angulation has been associated with both acute athletic knee injuries (3,5,26,30) and progressive tibiofemoral joint degeneration (1,2,7). Arms et al. (4) reported that anterior cruciate ligament (ACL) strain was greatest during simulated eccentric quadriceps femoris muscle group activation when combined with passive varus (between 15° and 45° flexion) or valgus (between 30° and 45° flexion) forces at the knee joint.

During stance, the quadriceps femoris and ankle plantar flexor muscle groups synergistically act to modulate knee extension and flexion (23). Contraction of the quadriceps...
femoris and hamstrings during stance also act to compress both the lateral and medial compartments of the knee joint, thereby resisting the dominant adduction moment in the frontal plane (16,27). When genu varus or genu varus alignment is present, the ability of the quadriceps femoris muscle group to provide dynamic postural stability in both the sagittal and frontal planes may be compromised (23,26,30). Concurrently, compensatory lower extremity alignment through the ankle, subtalar, and midtarsal joints may change the way that the ankle plantar flexor muscle group assists with providing dynamic postural control of the knee joint (10,29,30,33). Most dynamic control of transverse plane knee motion is dictated by rotational moments occurring at the ankle-foot complex (23).

Previous reports have identified forefoot directed mean anterior-posterior (18,31,32,34) and laterally directed (18) mean mediolateral COPP locations with increased ankle plantar flexor muscle group activation during single leg stance. The slightly oblique ankle joint axis mandates that both transverse plane movement of the foot (toeing out or toeing in) and rotation about the long axis of the foot accompanies sagittal plane motion. The orientation of the subtalar joint axis enables it to function as a directional torque convertor so that torques induced about the long axis of the foot are transmitted to the tibia as either internal rotation or external rotation torques. Secondarily, as with the ankle joint, the oblique orientation of the subtalar joint causes the foot to move relative to the tibia in a complex manner of pronation (external rotation or toeing out of the foot on the tibia, rearfoot eversion, and depression of the medial longitudinal arch) or supination (internal rotation or toeing in of the foot on the tibia, rearfoot inversion, and elevation of the medial longitudinal arch). Associated with these movements, midtarsal joint (talonavicular and calcaneocuboid) movement increases foot mobility with pronation or foot rigidity with supination (10). When both cross-sectional area and perpendicular distance from the subtalar joint axis are considered, the gastrocnemius-soleus, tibialis posterior, tibialis anterior, and long flexors of the toes (in decreasing order of importance) are the major dynamic stabilizers preventing excessive pronation of the foot (10). The majority of ankle plantar flexors (soleus, tibialis posterior, flexor digitorum longus, and flexor hallucis longus) also contribute to subtalar joint inversion (only the peroneus longus and brevis muscles provide combined ankle plantar flexion and eversion), thereby directly influencing transverse plane tibial rotation (30). Tibialis posterior, flexor digitorum longus, and flexor hallucis longus also help control midtarsal joint motion. As subtalar inversion occurs the midtarsal joint also becomes dynamically locked increasing foot rigidity.

Standing foot angle or “Fick’s angle” represents the amount of toeing in (decreased foot angle) or toeing out (increased foot angle) observed during stance (19). Andrews et al. (1) and Andriacchi (2) reported that external rotation or “toeing out” of the leg and foot moves the frontal plane alignment of the ground reaction force vector away from the medial tibiofemoral joint compartment (closer to the knee joint center), thereby reducing the lever arm of the external ground reaction force that contributes to medial tibiofemoral compartment degeneration from compressive forces. Standing foot angle and tibial torsion in the transverse plane are closely associated (19).

Single leg stance at 20° knee flexion is a commonly assumed athletic posture that places the ACL under stress (4), the quadriceps femoris muscle group under increased dynamic postural control demands (17,24), and the hamstrings in an alignment where they provide minimal ACL protection (17,24). Additionally, this posture places the ankle plantar flexor muscles in an alignment from which they can contribute more to dynamic postural control of the knee joint (8,34). Single leg standing balance is commonly assessed clinically; however, reports on nonimpaired subjects are limited (9,18,31,32). Kinzey et al. (18) in evaluating the effect of ankle brace use on the mean COPP locations of nonimpaired subjects during single leg stance suggested that increased ankle plantar flexor muscle function resulted in more anterior and lateral mean COPP locations. Tanaka et al. (31,32) have also reported a direct relationship between foot directed mean COPP locations of nonimpaired subjects and increased ankle plantar flexor muscle activation for dynamic postural control during single leg stance.

During unilateral flexed knee support, the line of gravity acting upon the body center of gravity moves posterior to the knee joint axis and anterior to the ankle joint axis (Fig. 2), creating external knee flexion and ankle dorsiflexion moments. For postural equilibrium to be maintained, these moments must be balanced by internal knee extension and ankle plantar flexion moments. Several reports have identified the importance of the ankle plantar flexor muscles for providing dynamic postural control at the knee joint during stance (8,17,24,29,34). Using an instrumented cadaveric specimen, White et al. (34) reported that the mean anterior-posterior COPP location moved toward the forefoot as the ankle plantar flexors...
plane tibiofemoral joint angulation of anterior and more lateral compared to subjects with frontal plane tibiofemoral joint angulation (7,21) would be more than the mean COPP location of subjects with neutral frontal joint angulation and mean COPP location changes during single leg stance. Likewise, no previous studies have tested these relationships at functionally relevant knee flexion angle range than the gastrocnemius muscle (34). If the contribution of the quadriceps femoris muscle group to dynamic postural control is affected by frontal plane tibiofemoral joint angulation (26), changes may also exist in its functional synergist during stance, the ankle plantar flexor muscle group (34).

Our literature review failed to identify any studies that focused on the relationship between frontal plane tibiofemoral joint angulation and mean COPP location changes during single leg stance. Likewise, no previous studies have tested these relationships at functionally relevant knee flexion angles. The purpose of this study was to test the hypothesis that the mean COPP location of subjects with neutral frontal plane tibiofemoral joint angulation (7,21) would be more anterior and more lateral compared to subjects with frontal plane tibiofemoral joint angulation of $\geq 5^\circ$ genu varus or genu valgus. A forehead directed shift in mean anterior-posterior COPP and a lateral shift in mean mediolateral COPP were considered suggestive of increase ankle plantar flexor muscle group function acting as plantar flexors through the ankle joint and invertors through the subtalar and midtarsal joints (17,18,31,32,34).

**METHODS**

**Subjects.** During preparticipation physical examinations, 56 nonimpaired athletes (29 female, 27 male) volunteered to serve as test subjects (age = 15.4 ± 2 yr). All subjects and their parent or guardian signed a University of Kentucky Institutional Review Board approved consent form before study participation. The lower extremity that subjects preferred to use for single leg stance when kicking a soccer ball was tested. All subjects preferred to use the left lower extremity for single leg stance, and all subjects were right-hand dominant.

**Plantar pressure monitoring instrumentation.** Appropriately sized 0.01778 cm thick F-Scan (Tekscan, Boston, MA) insole sensors positioned over appropriately sized 0.32 cm thick athletic shoe sock liners (to improve foot-sensor congruity) were used during data collection. At the 25 Hz sampling rate that was used during this study, a 70 mA current was cycled through the system every 0.04 s. The sensor was connected via a cuff transducer unit to a 9.1 m shielded cable, terminating at an F-Scan system interface board (Tekscan) within a desktop computer (Toshiba Corp., Irvine, CA).

**System calibration.** Before practice sessions and data collection, sensors were calibrated to subject body weight during single leg stance according to the manufacturer’s protocol (13). During this procedure, the subject initially stood on the side contralateral to the test side. Subject body weight was then input into the F-Scan version 3.621-calibration file software program (Tekscan). Two seconds after a verbal cue to switch their single leg stance to the test limb, a body-weight calibration file was recorded and saved to a laptop computer (Toshiba Corp.). Calibration file records were reviewed before data collection and were accepted if their peak value was within ± 5% of actual subject body weight measured with a physician’s scale at a previous physical examination station. All initial calibration file recordings were deemed acceptable.

**Data collection procedures.** Foot length was assessed with a metric ruler while subjects assumed a position of relaxed bilateral stance. Frontal plane knee angulation and standing foot angle were determined using the following two-dimensional video graphic techniques and a 30 Hz sampling rate (8 mm video camera, CCD-TR87, Sony Electronics Inc., Tokyo, Japan):

$$\text{COPP}(x, y) = \frac{\sum \text{pressure} \times x\text{-coordinate}}{\sum \text{pressure}} - \frac{\sum \text{pressure} \times y\text{-coordinate}}{\sum \text{pressure}}$$

Marker placements were selected to approximate the radiographic landmarks employed by Chao et al. (7) and Moreland et al. (21) during radiographic investigations of frontal plane tibiofemoral joint angulation. Three 1 cm diameter reflective markers with adhesive backing were placed upon the left lower extremity by the same investigator. One marker was placed on the anterior thigh at a point approximating the intersection of a medially directed horizontal line from the greater femoral trochanter and a distally directed lateral line from the greater trochanter to the greater trochanter.

*FIGURE 2—Sagittal plane view of the line of gravity acting upon the body center of gravity during single leg stance with the knee extended (A) and flexed $20^\circ$ (B).*
directed vertical line from the anterior superior iliac spine (midpoint of femoral neck base). A second marker was placed over the midpoint of the patellar tendon (knee joint). This landmark was selected to effectively approximate the knee joint center while decreasing the influence of patellar movement on frontal plane tibiofemoral joint angulation measurement. A third marker was placed on the anterior ankle midway between the medial and lateral malleoli to approximate the ankle joint center. This technique was used to provide a two-dimensional measurement of frontal plane tibiofemoral joint angulation.

After marker placement, subjects assumed a relaxed bilateral standing posture with comparable anterior toe placement on a 0.71 m × 0.51 m mat with a 1.27 cm × 1.27 cm grid pattern, while facing a video camera positioned on a tripod perpendicular to their midline. The video camera was positioned at 2.75 m from each subject, and tripod height was positioned to approximate the tibiofemoral joint line of each subject. Subjects were videotaped for approximately 5 s while maintaining a relaxed bilateral standing posture. After this, with the video camera tilted approximately 10° horizontally and focused to provide close-up viewing of the bilateral feet for standing foot angle calculation, subjects were videotaped for 2 s while facing the video camera, and for 2 s after having turned to face away from the video camera. The latter view was used when subjects displayed an internally rotated or “toed in” standing foot angle.

After kinematic data collection, frontal plane tibiofemoral joint angulation was determined by analyzing the videotape record. A protractor with one degree intervals was used to manually measure the difference between the angle formed by the intersection of lines formed between the anterior thigh-knee markers, and the anterior ankle-knee markers and 180° (Fig. 3) off of a flat surface monitor. Standing foot angle (\( \Theta \)) was also estimated by analyzing the videotape record. The distance between the alignment of the great toe marker and the medial aspect of the rear foot was visually recorded in 1.27 cm grid mat intervals to the nearest 0.6 cm. By using a trigonomic function, this value divided by foot length was equal to the sine of \( \Theta \) (Fig. 4).

After kinematic data collection, subjects were instructed in single leg stance on a 3.8 cm thick, 45.7 × 45.7 cm high-density foam rubber mat while attempting to maintain 20° knee flexion. Subjects were instructed to maintain 20° knee flexion at the stance lower extremity, erect trunk position, and a steady posture during testing. The nonweight-bearing lower extremity was maintained in approximately neutral hip joint alignment with the knee flexed approximately 45°. A blindfold was used to deny vision and increase the sway response during single leg stance. An investigator used a handheld goniometer to verify stance lower-extremity knee-joint flexion angle at the onset of data collection. Subjects were allowed one or two practice repetitions before data collection. Co-investigators were positioned to effectively observe subject sagittal and frontal plane movements to confirm safe and acceptable technique. Subjects were not allowed to let their lower extremities come in contact, or to contact the floor, with their upper extremities during testing. During all trials, subjects positioned the test lower extremity foot on a plantar pressure sensor that was positioned directly over an appropriately sized athletic shoe sock liner. The sensor-sock liner unit was then placed perpendicular to the frontal plane of the mat. Pilot testing revealed that sensor-sock liner slippage did not occur during single leg stance activities using this method.
A 25 Hz sampling rate over a 15-s test duration was used for COPP data collection.

After plantar pressure data collection, trial records were converted to ASCII format. Each transducer was assigned a coordinate as follows: the starting point (0,0) was located at the anterolateral part of the left foot. An increasing x-coordinate indicated movement toward the medial side of the foot, and an increasing y-coordinate indicated movement toward the rear foot. Mean COPP coordinates represented the summed products of the plantar pressures recorded by individual transducers divided by the total pressure recorded by all transducers.

Mean anterior-posterior and mediolateral COPP coordinate locations were determined using a spreadsheet program (MS Excel for Windows 97, version 7.0). Percentage values for mean anterior-posterior and mediolateral COPP coordinate locations within the 60 column by 21 row sensor matrix are reported as percentage values relative to the (0,0) starting point at the anterolateral foot. From these data and subject foot length measurements, the distance from the posterior edge of the plantar sensor to the anterior-posterior COPP location was calculated (1 −% value) × foot length.

Subject data were divided into three groups based on frontal plane tibiofemoral joint angulation. Chao et al. (7) and Moreland et al. (21), using anatomical markers similar to those employed in this study, reported tibiofemoral joint angulation of 1.2 ± 2.2° genu varus and 1.3 ± 2° genu varus, respectively, among adult subjects. With consideration for taking two times the standard deviations reported by those employed in this study, reported tibiofemoral joint angulation of 5° were placed in group 1 (N = 29, 12 female, 17 male, mean ± SD = 0.1 ± 2°, range −4° to 4°). Subjects with genu varus angulation ± 5° were placed in group 2 (N = 11, 5 female, 6 male, mean ± SD = 6.2 ± 2°, range 5–12°). Subjects with genu valgus angulation ± 5° were placed in group 3 (N = 16, 10 female, 6 male, mean ± SD = −5.8 ± 2°, range −5° to −10°).

**Measurements of reliability.** Five adolescent subjects (three male, two female) participated in a test-retest assessment of measurement reliability before study initiation. The reliability of the mean standing foot angle estimation was ICC (1,1) = 0.89, SEM = 1.2°. The reliability of the anterior-posterior and mediolateral COPP location measurements were ICC (1,1) = 0.85, SEM = 1.6%, and ICC (1,1) = 0.81 SEM = 6%, respectively. The reliability of the frontal plane tibiofemoral joint angulation measurement from the videotape record was ICC (1,1) = 0.94, SEM = 0.65°. All measurements displayed good reliability (25).

**RESULTS**

Subject height, body weight, foot length, and standing foot angle data are reported in Table 1. All subjects successfully completed the blindfolded, single leg stance test. Mean mediolateral COPP location did not differ between groups (Table 2). Group 1 (genu varus or genu valgus < 5°) displayed a mean mediolateral COPP location of 43.5 ± 6% from the (0,0) coordinate starting point at the anterolateral left foot. Group 2 (genu varus angulation ≥ 5°) and group 3 subjects (genu valgus angulation ≥ 5°) displayed mean mediolateral COPP locations of 41.8 ± 9% and 43.8 ± 6%, respectively, from the (0,0) coordinate starting point at the anterolateral left foot.

Mean anterior-posterior COPP location displayed significant differences between groups (Table 3). Group 1 (genu varus or genu valgus < 5°) displayed a mean anterior-posterior COPP location of 54.2 ± 6% from the (0,0) coordinate starting point at the anterolateral left foot (10.3 ± 2 cm from the posterior sensor edge). Group 2 (genu varus angulation ≥ 5°) and group 3 subjects (genu valgus angulation ≥ 5°) displayed mean anterior-posterior COPP locations of 60.6 ± 8% and 60.7 ± 7% from the (0,0) coordinate starting point at the anterolateral left foot (8.8 ± 2 cm and 8.7 ± 2 cm from the posterior sensor edge, respectively).

**TABLE 1. Subject characteristics.**

<table>
<thead>
<tr>
<th></th>
<th>Group 1 (Neutral) (N = 29; 17 Women, 12 Men)</th>
<th>Group 2 (Varus) (N = 11; 6 Women, 5 Men)</th>
<th>Group 3 (Valgus) (N = 16; 6 Women, 10 Men)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height (cm)</td>
<td>Mean 171.6 SD 8</td>
<td>Mean 170.8 SD 6</td>
<td>Mean 174.9 SD 8</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>64.1 SD 15</td>
<td>70.3 SD 20</td>
<td>69.7 SD 13</td>
</tr>
<tr>
<td>Foot length (cm)</td>
<td>22.3 SD 3</td>
<td>23 SD 3</td>
<td>23.1 SD 2</td>
</tr>
<tr>
<td>Standing foot angle (°)</td>
<td>10.3 SD 7</td>
<td>10 SD 10</td>
<td>9.7 SD 6</td>
</tr>
</tbody>
</table>

**TABLE 2. One-way ANOVA for mean mediolateral center of plantar pressure location.**

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between groups</td>
<td>31.3</td>
<td>2</td>
<td>15.7</td>
<td>0.35</td>
<td>0.71</td>
</tr>
<tr>
<td>Within groups</td>
<td>2364.2</td>
<td>53</td>
<td>44.6</td>
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<td></td>
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</tbody>
</table>


Post hoc assessment revealed that group 2 and group 3 subjects displayed more posterior or rearfoot directed mean anterior-posterior COPP locations than group 1 subjects (Table 4).

Mean plantar force magnitudes/body weight displayed significant differences between groups (Table 5). Mean plantar force magnitude/body weight for group 1 was 10.3 \( \pm \) 2 N·kg\(^{-1}\). Group 2 and group 3 subjects displayed mean plantar force magnitude/body weight of 12.5 \( \pm \) 3 N·kg\(^{-1}\) and 12.4 \( \pm \) 3.1 N·kg\(^{-1}\), respectively. Post hoc assessment revealed that group 2 and group 3 subjects displayed greater mean plantar force magnitude/body weight than group 1 subjects (Table 6).

Mean ankle plantar flexor moment estimates (mean plantar force magnitude \( \times \) mean anterior-posterior COPP location from the posterior sensor edge/body weight) did not reveal significant differences between groups (Table 7). Group 1 subjects displayed mean ankle plantar flexor moments/body weight of 1.19 \( \pm \) 0.4 Nm·kg\(^{-1}\), whereas group 2 and group 3 subjects displayed mean ankle plantar flexor moments/body weight of 1.01 \( \pm \) 0.2 Nm·kg\(^{-1}\) and 1.2 \( \pm \) 0.6 Nm·kg\(^{-1}\), respectively.

**DISCUSSION**

Studies of balance and posture during single leg stance have identified a major role of the ankle plantar flexor muscles in maintaining the body’s center of gravity over the foot (12,14,18,22,29,31,32). Our findings suggest that subjects with genu varus or genu valgus frontal plane tibiofemoral joint angulation rely on a different postural control strategy during vision denied single leg stance at 20° knee flexion than subjects with neutral frontal plane tibiofemoral joint angulation. Although group differences in ankle plantar flexor moment estimates were not evident, differences did exist in the mechanism by which this moment was produced. Subjects with neutral frontal plane tibiofemoral joint angulation used a more forefoot directed mean anterior-posterior COPP location and lesser mean plantar force magnitudes to generate the ankle plantar flexor moment needed to maintain postural equilibrium during single leg stance. Subjects with genu varus or genu valgus displayed more rearfoot directed mean anterior-posterior COPP locations and greater mean plantar force magnitudes to generate the ankle plantar flexor moment to maintain postural equilibrium during single leg stance. The more rearfoot directed mean anterior-posterior COPP location displayed by subjects with neutral frontal plane tibiofemoral joint angulation suggests a greater use of ankle plantar flexor muscle group function through the ankle joint and a more rigid foot lever to maintain postural equilibrium during single leg stance. The more rearfoot directed mean anterior-posterior COPP locations displayed by subjects with genu varus or genu valgus suggest greater reliance on the ankle plantar flexor muscle group function as a subtalar and midtarsal joint inversion-eversion modulator on a more mobile foot lever to maintain postural equilibrium during single leg stance. Because subtalar joint motion occurs primarily in the frontal and transverse planes, it can effectively compensate for structural deformities in the frontal plane (10,33).

Differences in the neuromuscular control strategies used by subjects with genu varus or genu valgus suggest that conditioning programs for knee injury prevention and postinjury rehabilitation programs may be more effective if the potential influence of frontal plane tibiofemoral joint angulation on ankle plantar flexor muscle function is considered. Based on our findings, subjects with genu varus or genu valgus may benefit from greater emphasis on frontal plane movement challenges that facilitate ankle plantar flexor muscle group function as controllers of subtalar and midtarsal joint position. Related to this, subjects with genu varus or genu valgus may have a greater disability level associated with single leg stance tasks after injury to subtalar or midtarsal joint capsuloligamentous structures. Because standing foot angle measurements were similar between groups, its influence on mean COPP location was deemed minimal during single leg stance among this subject group. Although multiple combinations of trunk, hip, and

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**TABLE 3. One-way ANOVA for mean anterior-posterior center of plantar pressure location.**

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
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<td>Between groups</td>
<td>589.8</td>
<td>2</td>
<td>294.9</td>
<td>6.4</td>
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<td>Within groups</td>
<td>2460.2</td>
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<td>46.4</td>
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* \( P \leq 0.05. \)

**TABLE 4. Tukey HSD multiple comparisons, matrix of pairwise differences (probabilities) for mean anterior-posterior center of plantar pressure location.**

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<tr>
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<tbody>
<tr>
<td>1</td>
<td>0.000</td>
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<td></td>
</tr>
<tr>
<td>2</td>
<td>0.64%</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.65%</td>
<td>0.042%</td>
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* \( P \leq 0.05. \)

Group 1, neutral; group 2, genu varus; group 3, genu valgus.

**TABLE 5. One-way ANOVA for mean plantar force magnitude/body weight.**

<table>
<thead>
<tr>
<th>Source</th>
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<th>df</th>
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<tbody>
<tr>
<td>Between groups</td>
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<td>31.26</td>
<td>5.30</td>
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<td>Within groups</td>
<td>312.47</td>
<td>53</td>
<td>5.9</td>
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* \( P \leq 0.05. \)

**TABLE 6. Tukey HSD multiple comparisons, matrix of pairwise differences (probabilities) for mean center of plantar force magnitude/body weight.**

<table>
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<tr>
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<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2.15 N·kg(^{-1})</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>2.09 N·kg(^{-1})</td>
<td>0.058</td>
<td>0.000</td>
</tr>
</tbody>
</table>

* \( P \leq 0.05. \)

Group 1, neutral; group 2, genu varus; group 3, genu valgus.
knee flexion-extension angle variations may have contributed to our results, all subjects were positioned in 20° knee flexion during single leg stance and instructed in appropriate technique by the same investigator. Additionally, two investigators visually monitored subjects for maintenance of this position over the entire 15-s test duration of each test trial. Based on this, any postural variance would have been quite subtle and similar between subject groups.

We did not observe differences between groups for mean mediolateral COPP location. Multiple combinations of forefoot, midfoot, and rearfoot compensatory joint alignment may have contributed to the lack of significance of this variable. The comparatively shorter lever arms associated with subtalar and midtarsal joint movements and the considerable variability in the magnitude of their interactions warrant more detailed investigation. Clinical measurements of navicular drop from a subtalar neutral position, standing rearfoot angle, and compensatory forefoot alignment are recommended to better delineate the contributions of these joints to plantar pressure measurements during single leg stance.

Hewett et al. (16) in evaluating the effect of a jump-training program on athletic female subjects reported that the knee abduction and adduction moments were the sole significant predictors of peak landing forces. In a prospective study to assess the effectiveness of the jump-training program on reducing knee injury incidence among female athletes, Hewett et al. (15) reported that untrained female athletes had a 3.6 times greater incidence of knee injury than female athletes who participated in the training program. Program effectiveness was considered to be primarily a function of improved neuromuscular control of frontal plane knee joint movement by muscles that assist with controlling knee joint adduction and abduction (presumably the quadriceps femoris and the hamstrings).

Physiological joint movements such as knee abduction-adduction, although vital to maintaining vertical balance over the lower extremity during single-limb support, occur in association with other knee joint movements such as flexion-extension and internal-external rotation (19,23). Although Hewett et al. (16) did not report differences for the external ankle dorsiflexion (internal ankle plantar flexion moment) after jump program participation, neither sagittal or frontal plane preparticipation ankle muscle strength testing was performed. A 10% improvement in vertical jump height suggests that the jump-training program increased the performance characteristics of three-dimensional hip and knee extensor and ankle plantar flexor muscle function (15).

Based on the known associations between ankle plantar flexor muscle group function and knee flexion-extension (gastrocnemius-soleus) (23,29) and knee internal-external rotation (soleus, tibialis posterior, flexor hallucis longus, flexor digitorum) (10,23,30,33) control a strong argument can be made for its assisting with three-dimensional dynamic knee joint control. The differing strategies we observed based on differences in frontal plane tibiofemoral joint angulation provides further support to this concept. Dynamic frontal plane postural control of the knee joint during a single leg standing task requires contributions from hip and ankle joint musculature in addition to muscles that cross the knee joint. Markolf et al. (20) in assessing genu varus-valgus laxity with an instrumented clinical testing apparatus reported an inability to isolate frontal plane movement from transverse plane femoral rotation at any sagittal plane knee angle other than complete extension. When considering potential exercise program interventions to improve lower extremity dynamic postural control in the frontal plane, it is vital to consider the direct association between hip joint adduction-abduction, subtalar-midtarsal joint inversion-eversion, and long-axis transverse plane rotation of the femur and tibia, respectively. Caraffa et al. (6) reported an approximately sevenfold decrease in ACL injury incidence among soccer athletes who participated in a 3-yr within-season knee-injury–prevention program that focused primarily on improving lower-extremity dynamic postural control through multi-plane single leg landing tasks using four different types of wobble-boards (6).

By identifying the possible influences of frontal plane tibiofemoral angulation on ankle plantar flexor muscle function, our findings add to the results reported by Hewett et al. (15,16) for jump landings and Caraffa et al. (6) for single leg stance activities. Our results suggest that athletically active adolescents with frontal plane tibiofemoral knee angulation of 5° or more genu valgus or genu varus may benefit from knee injury prevention programs or postinjury rehabilitation programs which focus on training ankle plantar flexor function as modulators of subtalar and midtarsal joint inversion-eversion for dynamic postural control within the frontal plane. Future study is warranted adding detailed clinical foot assessment, three-dimensional ankle-subtalar joint moment evaluation, and ankle plantar flexor muscle electromyography during dynamic postural control challenges in single leg stance and during single leg jump-landing tasks to further delineate these relationships.

**CONCLUSIONS**

Athletically active adolescent subjects with 5° or more genu valgus or genu varus frontal tibiofemoral joint angulation displayed more posterior (rearfoot directed) mean anterior-posterior COPP locations and greater plantar force magnitudes/body weight than subjects with frontal plane tibiofemoral joint angulation of less than 5° genu varus or genu valgus. These results suggest that subjects with genu valgus or genu varus use a different dynamic postural control strategy during single leg stance at 20° knee flexion. These athletes appear to make greater use of subtalar and midtarsal joint control function of the ankle plantar flexor muscles for lower extremity dynamic
postural control during single leg stance. These results are preliminary, and further testing is warranted before specific exercise regimens are developed.

REFERENCES