Effects of Pronated and Supinated Foot Postures on Static and Dynamic Postural Stability

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Abstract:

Context: The foot is the most distal segment in the lower extremity chain and represents a relatively small base of support on which the body maintains balance (particularly in single-leg stance). Although it seems reasonable that even minor biomechanical alterations in the support surface may influence postural-control strategies, the implications of a hypermobile or hypomobile foot on balance have received little attention to date.

Objective: To determine if supinated and pronated foot types influence measures of static and dynamic balance.

Design: Participants were assigned to 1 of 3 groups depending on foot type, as defined by navicular-drop measures: pronated (≥10 mm), neutral (5–9 mm), or supinated (≤4 mm). Measures of static and dynamic balance were obtained for each participant and compared across groups.

Setting: Sports medicine and athletic training research laboratory.

Patients or Other Participants: Sixteen individuals with pronated (navicular drop = 13.0 ± 3.7 mm), neutral (navicular drop = 6.2 ± 1.1 mm), or supinated (navicular drop = 2.2 ± 1.7 mm) foot postures volunteered to participate in the study.

Main Outcome Measure(s): We used the Chattecx Balance System to measure center of balance, stability index, and postural sway during static single-limb stance under eyes-open and eyes-closed conditions. Center of balance was defined as the point on the foot at which the body weight was equally distributed between the medial-lateral and anterior-posterior quadrants and was recorded in centimeters. Stability index was defined as the mean deviation in sway around the center of balance. Postural sway was expressed as the maximum sway distance recorded (cm) in the medial-lateral and anterior-posterior directions. The Star Excursion Balance Test was used to measure dynamic balance, which was reported as the reach distance (cm) in each of the 8 directions tested. The average of 3 trials of each measure was calculated and normalized to the subject's height.

Results: We found no difference in center of balance or postural sway as a function of foot type. The stability index was greater in pronators than in supinators, but neither group was different from those with neutral foot types. Dynamic reach differed among groups but only in some directions. Generally, pronators reached farther in the anterior and anterior medial directions and supinators reached farther in the posterior and posterio-lateral directions. In the lateral direction, supinators reached farther than pronators but not farther than neutrals.

Conclusions: Our results suggest that postural stability is affected by foot type under both static and dynamic conditions. These differences appear to be related to structural differences as opposed to differences in peripheral input. These effects should be considered when clinicians use such balance measures to assess injury deficits and recovery.

Keywords: postural sway | proprioception | foot mechanics | foot injury | limits of stability | arch height

Article:

During stance, the foot must be able to adapt to the ground surface, aid in shock absorption, and transition to a rigid lever to propel the body forward during push off.[1] Proper foot motion, specifically subtalar pronation and supination, is critical to achieving these functions. Upon weight acceptance, the foot moves into pronation and achieves maximum pronation in midstance.[2] With pronation, the midtarsal joint unlocks, and the foot becomes more flexible to adjust to the underlying surface, assisting in maintaining balance.[2]Conversely, the midtarsal joint becomes locked in supination to maximize foot stability and provide a rigid lever for push off.[2] Although the normal foot effectively transitions between pronation and supination to optimize adaptability versus stability as needed, foot malalignments that negatively affect foot mobility may diminish the ability of the lower leg to function optimally during weight-bearing stance.[1]

Balance has often been used as a measure of lower extremity function and is defined as the process of maintaining the center of gravity within the body's base of support.[3] To maintain upright stance, the central and peripheral components of the nervous system are constantly interacting to control body alignment and the center of gravity over the base of support.[4,5] Peripheral components in balance include the somatosensory, visual, and vestibular systems. The central nervous system incorporates the peripheral inputs from these systems and selects the most appropriate muscular responses to control body position and posture over the base of support.[6,7] Because balance is maintained in the closed kinetic chain (the foot being fixed beneath the base of support) and relies on the integrated feedback and movement strategies among the hip, knee, and ankle, balance can be disrupted by diminished afferent feedback or deficiencies in the strength and mechanical stability of any joint or structure along the lower extremity kinetic chain.[3,8] Considering that the foot is the most distal segment in the lower extremity chain and represents a relatively small base of support upon which the body maintains balance (particularly in single-leg stance), it seems reasonable that even minor biomechanical alterations in the support surface may influence postural-control strategies. Specifically, excessively supinated or pronated foot postures may influence peripheral (somatosensory) input via changes in joint mobility or surface contact area[9] or, secondarily, through changes in muscular strategies[10] to maintain a stable base of support.

An excessively supinated foot, characterized by a high arch and hypomobile midfoot, may not adequately adapt to the underlying surface, increasing the demand on the surrounding musculoskeletal structures to maintain postural stability and balance.[10] Further, it has been suggested that the cavus foot has less plantar sensory information to rely on than the normal or pronated foot.[9] Conversely, excessive pronation is characterized by a flattening of the medial arch and a hypermobile midfoot but may also place greater demands on the neuromuscular system to stabilize the foot and maintain upright stance. Researchers examining orthotic intervention in those with excessive pronation support this contention, finding changes in muscle activity at the ankle,[11,12] knee,[13] and hip[11] when the degree of pronation is altered sufficiently.

The implications of a hypomobile or hypermobile foot and associated neuromuscular changes on peripheral input and balance have received little attention to date. In their work comparing single-stance postural control in individuals with different foot types as defined by the degree of forefoot and rearfoot varus and valgus, Hertel et al[9] found individuals with a cavus, or supinated, foot type had significantly larger center-of-pressure excursions than individuals with pronated or normal foot types. They noted no postural deficits in those with a pronated foot posture. However, their findings were limited to testing in a static stance with eyes open. Although the influence of orthotic intervention on dynamic balance in subjects with different foot postures was subsequently examined,[14] analyses and discussion focused primarily on changes in balance resulting from orthotic wear. It is unclear from the results whether significant differences in dynamic balance existed among different foot postures. Further, whether postural deficits secondary to excessive foot pronation or supination would be noted or magnified in static stance with greater challenges to the support surface via loss of visual feedback (ie, eyes closed, relying more on somatosensory input) has not been explored.

Poor foot position sense is thought to hinder accommodation between the plantar surface of the foot and the support surface, thus requiring postural adjustments more proximally to maintain upright posture and balance.[15] Although investigators found static and dynamic balance to be adversely affected by changes in peripheral input secondary to joint injury[16–19] and changes in the stability of the surface on which one is standing,[20,21] far less attention has been focused on whether more subtle alterations in the surface, stability, or peripheral input of the support foot may also affect balance in those with different foot types. Other than the work by Hertel et al,[9,14] we are not aware of any other studies that have examined balance as a function of foot type.

Understanding this relationship is important for 2 reasons. First, this information may aid in our understanding of factors inherent to individual subjects that may influence and confound measures of balance when these measures are used to assess potential deficits related to injury mechanisms (eg, effects of mild head injury or ankle injury). Second, this information may further elucidate the potential influence of anatomical alignment on the neuromuscular and biomechanical function of the lower extremity. Hence, our purpose was to further clarify the effect of foot type on measures of static balance (center of pressure, stability index, and postural sway) and dynamic reach. We hypothesized that those with supinated and pronated foot postures would have greater difficulty with balance than those with a neutral foot type.

METHODS

Sixteen subjects with pronated feet (age = 20.7 ± 2.2 years, height = 169.0 ± 7.3 cm, mass = 68.4 ± 11.0 kg, navicular drop = 13.0 ± 3.7 mm), 16 subjects with neutral feet (age = 20.7 ± 2.2 years, height = 170.4 ± 9.5 cm, mass = 72.6 ± 16.7 kg, navicular drop = 6.2 ± 1.1 mm), and 16 subjects with supinated feet (age = 20.4 ± 1.3 years, height = 174.4 ± 7.9 cm, mass = 74.6 ± 19.1 kg, navicular drop = 2.2 ± 1.7 mm) volunteered for the study. Subjects were selected on 4 conditions: (1) They had no repeated lower extremity injuries and were free of all lower extremity injury on the affected side in the past 6 months. (2) They had no history of surgery to the lower extremity. (3) They had no history of cerebral concussions or visual or vestibular disorders. (4) They had no inner ear infection, upper respiratory infection, or head cold at the time of the study. Each subject signed an informed consent before participating in the study, which was approved by the university's institutional review board.

Group Classification

We screened subjects for foot type by measuring the degree of subtalar pronation using the navicular-drop test. Navicular drop was measured using a modification of the Brody method,[22] with the subject in a weight-bearing position. We asked the subject to stand barefoot on a 4-in (10.16-cm) box, placing all weight on the foot being measured, while the other foot rested lightly on the box. The clinician palpated the medial and lateral aspects of the talar dome with the thumb and index finger placed just in front of the anterior aspect of the fibula and just anterior and inferior to the medial malleolus. The subject slowly inverted and everted the hindfoot and ankle until the depressions felt by the thumb and index finger of the clinician were equal. With the foot in this subtalar neutral position, the clinician measured the distance between the navicular tubercle and the floor in millimeters with a ruler. We then asked the subject to completely relax the foot into full weight bearing, and the resulting position of the navicular was measured with the ruler. The clinician recorded the distance between the original height of the navicular and its final weight-bearing position as the subject's navicular-drop score.

We measured navicular drop 3 times, using the average measurement to classify the subject into 1 of 3 groups: a normal foot (between 5 and 9 mm of navicular drop), an excessively pronated foot (more than 10 mm of navicular drop), and an excessively supinated foot (less than 4 mm of navicular drop). The subject's dominant foot (determined by which leg the subject used to kick a ball) was used for group assignment. All measurements were taken by the primary investigator (K.P.C.), with intratester reliability determined to be .96 during pilot testing.

Testing Procedures

Subjects reported to the sports medicine and athletic training research laboratory for 1 session. At the start of the session, we recorded the subject's height, weight, age, and a confirmatory measurement of navicular drop. The subject then performed 2 balance tests: a single-leg static balance test (eyes-open and eyes-closed conditions) on the Chattecx Balance System (Chattanooga Corp, Chattanooga, TN) to assess location of center of balance, sway deviation about the center of balance (COB), and maximal sway distance during quiet stance and the Star Excursion Balance Test (SEBT) to measure dynamic reach in 8 directions. The subject performed each balance test and condition 3 times, and we used the average of the 3 trials for data analysis.

Single-Leg Balance Test

The Chattecx Balance System uses 4 strain gauges placed under the foot to measure COB and postural sway. We asked each subject to stand in a unilateral stance on the dominant leg on the system so we could collect COB and postural-sway data. Each subject was barefoot and dressed in shorts. Subjects were instructed to stand with the opposite knee flexed at 90°, arms crossed at the chest, and to look at the X marked on the wall. Two test conditions were evaluated, eyes open and eyes closed. The non–weight-bearing extremity was not allowed to touch the stance leg during testing. The subject was given a practice trial in each testing condition. We performed three 15-second trials in each testing condition with data sampled at 15 Hz/s. A trial was repeated if the subject touched part of the apparatus or touched down with the other foot.

Star Excursion Balance Test

The SEBT is a functional, unilateral balance test that integrates a single-leg stance of 1 leg with maximum reach of the opposite leg. The reliability of the SEBT has previously been established for our specific measurement methods.[23] The SEBT was performed with the subject standing in the middle of a grid placed on the floor with 8 lines extending at 45° increments from the center of the grid. The 8 lines on the grid were named in relation to the direction of reach with regard to the stance leg: anterolateral (AL), anterior (A), anteromedial (AM), medial (M), posteromedial (PM), posterior (P), posterolateral (PL), and lateral (L). The grid was constructed in the laboratory using a protractor, tape, and tape measure and was enclosed in a 6-foot by 6-foot (1.83-m × 1.83-m) square on the hard tile floor.

We provided verbal and visual demonstrations of the test to each subject before data collection. Each subject was allowed 1 practice trial. We asked the subject to look straight ahead and maintain a single-leg stance on the stance leg while reaching with the opposite, or reach, leg. We asked the subject to reach to the furthest point possible on the line, touching the line as lightly as possible to make certain that steadiness was achieved through adequate neuromuscular control of the stance leg. The examiner marked the touch point and measured the distance from the center of the grid with a tape measure in centimeters. The subject then returned to the starting stance at the center of the grid while maintaining balance. Measurements were taken after each reach.

We recorded 3 reaches in each direction separated by 10 seconds of rest. We then calculated the average of the 3 reaches for each of the 8 directions. Order of reaches performed (clockwise, counterclockwise) and direction of the first reach (A, M, L, P) were counterbalanced to control for any order effect. Trials were repeated if the subject touched the line at any point other than the endpoint with the reach foot while retaining weight bearing on the stance leg, lifted the stance foot from the center grid, lost balance at any point during the trial, or did not maintain start and return positions for 1 full second.

Statistical Analysis

The average of 3 trials for each dependent measure (postural sway, COB, stability index, and reach distance) was used for data analysis. We defined postural sway as the maximum distance the subject traveled away from his or her COB in the medial-lateral and anterior-posterior planes, recorded in centimeters. The COB represented the intersecting point on the x- and y-axes of the foot where the body weight was equally distributed between the medial-lateral (x-axis) and anterior-posterior (y-axis) quadrants. The COB measures were based on the average position of the COB across the length of the entire trial and were recorded in centimeters for both the x and y coordinates. Stability index defined the mean deviations in sway about the COB over the test period. Reach distance was defined in 8 directions as the maximum distance the subject reached with the big toe along the line of direction away from the center of the grid and recorded in centimeters. Because we found height to be significantly correlated to all balance measures, all scores were normalized to the subject's height (variable [cm]/height [cm]) before analyses for both the SEBT and Chattecx measures.

We used a mixed-design, repeated-measures analysis of variance with 1 between (foot type at 3 levels [neutral, supinated, pronated]) and 1 within (eye condition at 2 levels [open, closed]) factor to determine group differences in stability index. We used separate repeated-measures analyses of variance with 1 between (foot type) and 2 within (postural sway [medial-lateral, anterior-posterior] factors or location of COB [x, y] and eye condition [open, closed]) to assess group differences in postural sway and COB during static stance. Finally, we used a repeated-measures analysis of variance with 1 between (foot type at 3 levels) and 1 within (reach direction at 8 levels [AL, A, AM, M, PM, P, PL, L]) factor to determine if dynamic reach differed among groups. The alpha level was set at $P = .05$ for all analyses.

RESULTS

Means and standard deviations for static and dynamic balance measures are listed in Tables 1 and 2, respectively. For the stability index, we found a main effect for foot type ($P = .05$), with supinators (.0071) showing significantly less sway deviation per centimeter height about the COB (ie, less variability) than pronators (.0082), but neither group was different from neutrals (.0073). Although stability index was greater in the eyes-closed than the eyes-open condition ($P < .001$), this effect did not differ across foot types ($P = .377$, $\beta = .213$). For postural sway, all groups swayed more with eyes closed than eyes open ($P \leq .001$), but this effect was consistent across foot types ($P = .764$, $\beta = .090$). Sway was greater in the anterior-posterior versus medial-lateral directions ($P \leq .001$), with no significant difference in sway distance by foot type ($P = .537$, $\beta = .149$). Finally, a significant difference was noted in the eyes-by-sway interaction ($P \leq .001$); this was also not affected by foot type ($P = .661$, $\beta = .114$). Our results were similar for COB, with a significant difference between eye conditions ($P = .001$) and location ($P \leq .001$) but no difference resulting from foot type-by-eye ($P = .541$, $\beta = .148$) or foot type-by-location ($P = .252$, $\beta = .289$) conditions. A significant COB location-by-eye condition interaction ($P \leq .001$)

was also not influenced by foot type (*P* = .708, β = .102). Neither postural sway (*P* = .481, β = .169) nor COB (*P* = .979, β = .053) showed a main effect for foot type across conditions.

Table 1. Static Balance Measures of Center of Balance, Postural Sway, and Stability Index (Mean ± SD)*

	Neutral	Pronated	Supinated
Center of Balance			
Eyes open			
Medial-lateral	−0.02 ± 0.27	−0.04 ± 0.36	−0.11 ± 0.23
Anterior-posterior	0.34 ± 0.70	0.18 ± 0.81	0.37 ± 0.52
Eyes closed			
Medial-lateral	−0.12 ± 0.27	0.05 ± 0.34	−0.19 ± 0.29
Anterior-posterior	0.65 ± 0.55	0.57 ± 0.74	0.76 ± 0.38
Postural Sway			
Eyes open			
Medial-lateral	1.29 ± 0.23	1.34 ± 0.22	1.28 ± 0.23
Anterior-posterior	1.81 ± 0.38	2.00 ± 0.43	1.64 ± 0.39
Eyes closed			
Medial-lateral	2.50 ± 0.32	2.56 ± 0.40	2.50 ± 0.33
Anterior-posterior	4.25 ± 1.36	4.68 ± 1.00	4.48 ± 1.82
Stability Index			
Eyes open	0.45 ± 0.09	0.49 ± 0.10	0.43 ± 0.09
Eyes closed	1.01 ± 0.25	1.14 ± 0.21	0.98 ± 0.18

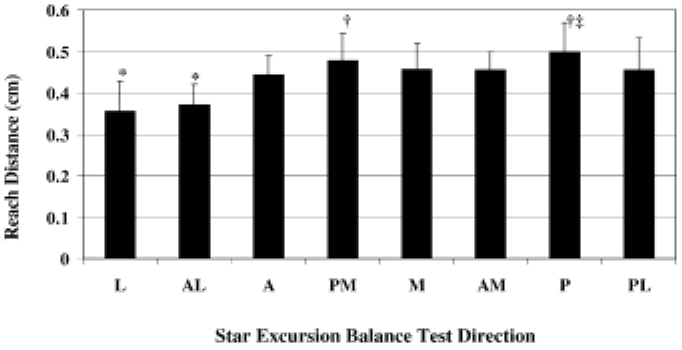
*All values represent normalized data (cm/cm) based on subject height and expressed as 10^{-2}.

Table 2. Dynamic Reach Distance on the Star Excursion Balance Test (Mean ± SD)*

	Reach Direction							
Group	Lateral	Anterolateral	Anterior	Posteromedial	Medial	Anteromedial	Posterior	Posterolateral
Neutral	0.36 ± 0.09	0.36 ± 0.07	0.43 ± 0.06	0.47 ± 0.09	0.45 ± 0.08	0.44 ± 0.07	0.49 ± 0.10	0.45 ± 0.10
Pronated	0.33 ± 0.05	0.39 ± 0.04	0.47 ± 0.04†	0.47 ± 0.05	0.46 ± 0.07	0.47 ± 0.04†	0.49 ± 0.06	0.44 ± 0.06
Supinated	0.38 ± 0.07‡	0.37 ± 0.03	0.44 ± 0.02‡	0.49 ± 0.05	0.46 ± 0.04	0.46 ± 0.02	0.52 ± 0.05†	0.48 ± 0.06†

*All values are normalized to subject height (cm/cm).
†Indicates significantly different from neutral group.
‡Indicates significantly different from pronated group.

For dynamic reach, we found a significant difference in reach by direction and foot type ($F_{14,315}$ = 3.176, *P*< .001). Using the Tukey Honestly Significant Difference test and graphing the interaction of foot type by direction, we determined that pronators reached farther than both neutrals and supinators in A and farther than neutrals but not supinators in AM. Conversely, supinators reached farther than neutrals but not pronators in P, farther than both neutrals and pronators in PL, and farther than pronators but not neutrals in L. The AL, M, and PM directions showed no difference among foot types (see Table 2). Multiple pairwise comparisons with Bonferroni corrections of the main effect for direction ($F_{7,315}$ = 94.012, *P* < .001) indicated that reach was least in the L and AL directions than in all other directions and greatest in the PM and P directions (with P > PM) than in all other directions (Figure). Reach in the A, AM, M, and PL directions was not statistically different.



Dynamic reach distance for each direction of the Star Excursion Balance Test. *Indicates decreased reach compared with A, AM, M, and PL; †, increased reach compared with A, AM, M, and PL; ‡, increased reach compared with PM. L indicates lateral; AL, anterolateral; A, anterior; PM, posteromedial; M, medial; AM, anteromedial; P, posterior; PL, posterolateral.

DISCUSSION

Our primary findings revealed that structural foot type affected sway index in static postural stance and dynamic reach measures but had no effect on postural sway and COB measures. The ability to sense motion in the foot and make postural alterations in response is essential in preventing injury.[24] Although joint abnormalities, such as functional ankle instability, have often been assessed relative to static and dynamic balance, our purpose was to determine whether structural foot alignment alone may represent a foot abnormality that could alter proprioception and postural control. Our findings suggest that some aspects of postural stability are affected by foot type, but we believe structural stability, rather than altered proprioception, is likely the basis for our results.

Static Balance and Foot Type

Proprioceptive feedback during joint motion depends not only on sensory information from joint receptors (ie, ligament and capsule) but also includes divergent information from skin, articular, and muscle mechanoreceptors.[25] In our study, postural sway and COB in static stance were unaffected by foot type. Hence, any changes in surface contact pressures that may exist among the 3 foot types were not sufficient to alter weight distribution or sway distance over the base of support in quiet stance. The fact that no differences were detected once the visual system was eliminated (eyes-closed condition) further suggests that somatosensory feedback from skin and joint mechanoreceptors was not sufficiently altered in static stance.

Although one might then conclude that an excessively supinated or pronated foot does not adversely affect postural control, it is also possible that quiet stance may simply not place adequate demands on the postural-control system to detect deficits stemming from altered feedback or structural malalignments. Postural sway was not different among groups, but pronators had greater mean deviations in sway around the base of support (ie, increased stability index) than supinators. Whether the increased stability index in pronators was due to differences in the mechanical stability of the foot versus proprioceptive and neuromuscular alterations is difficult to confirm from our study. However, given that we found no differences in COB and postural sway, it would appear that differences in mechanical stability of the foot are likely the cause. This contention is further supported by our direction-specific findings relative to dynamic reach.

Further, it is not yet clear whether more or less variability in sway is beneficial or harmful. Although increased variability has traditionally been associated with reduced performance, it has been argued that increased variability may actually be beneficial, suggesting greater flexibility and adaptability within the system to respond to sudden perturbations or changing constraints.[26] Hence, the increased variability found in pronators may simply represent greater foot flexibility and an improved ability to use more available area for COB excursion over supinators. Conversely, increased variability in COB excursion might suggest that a hypermobile, pronated foot may be less stable than the more rigid, supinated foot structure.

Dynamic Balance and Foot Type

Most activities an individual participates in are functional, or dynamic, as opposed to static.[24] Thus, in addition to well-accepted standard static-balance tests, we chose to also measure an index of dynamic balance. The SEBT is a relatively new assessment tool, described as a functional test that emphasizes dynamic postural control,[16] which has been defined as the extent to which a person can reach or lean without moving the foot and still maintain upright posture.[27] Hence, this test requires a combination of foot, ankle, knee, and hip motion and imposes greater demands on strength and joint range of motion, in addition to proprioception and neuromuscular control within the stance leg to maintain balance while reaching with the opposite leg.[16] Our results relative to this test revealed that only certain reach directions were affected by foot type. We believe this direction-dependent effect further supports our contention that structural stability-mobility of the foot, not proprioceptive changes, is the likely explanation for our findings.

A review of previous literature using the SEBT revealed little information on direction-specific effects in injured versus uninjured groups. Although a recent study by Olmsted et al[16] revealed that reach distance on the SEBT was significantly less in individuals with chronic ankle instability than in uninjured individuals and in their own uninjured limbs, these results were found across all reach directions and were not direction dependent. In contrast, we found differences in only certain directions and, in some of these directions, pronators and/or supinators reached farther than subjects with a neutral foot. This would suggest that different foot structures may affect range of joint motion when reaching in certain directions and represent specific mechanical and neuromuscular advantages or disadvantages affecting the ultimate reach limits in those directions. This concept is supported by recent work by Olmsted and Hertel,[14] who found direction-specific improvements in dynamic reach with orthotic intervention in subjects with pes cavus. They attributed these improvements in dynamic balance to increased mechanical support of the medial aspect of the foot, potentially lending to enhanced sensory receptor activity and neuromuscular function.

All groups reached similar distances in the AL, M, and PM directions, but supinators were able to reach farther than pronators in the L and PL directions. Considering that an individual with a supinated foot places more pressure on the lateral aspect of the foot, it seems reasonable that the limits of stability may be greater in the lateral direction. Conversely, excessive pronators tend to collapse toward the medial aspect of the foot and have a reduced ability to maintain a rigid support in full weight bearing. This medial deviation plus greater foot mobility may account for pronators' reduced dynamic reach in the lateral direction. Increased foot mobility may also explain why pronators reached farther in the anterior direction than both neutrals and supinators and farther than neutrals in the AM direction.

CLINICAL RELEVANCE

Postural control and dynamic balance are essential in activities of daily living and for optimal performance in sport activity. Given the strength, range of motion, and neuromuscular demands on the lower extremity when performing sport-specific functional tasks, factors that alter the limits of stability in which these tasks can be performed may influence performance or alter the demands placed on the joints during these movements. Our findings indicate that, although static balance was minimally affected by foot type, the direction-specific differences in dynamic reach by foot type suggest structural abnormalities of the midfoot may influence joint mechanics sufficiently to alter stability limits during dynamic activities. The implications of these differences on functional performance and injury risk during sport are not yet clear and require further study. However, the fact that dynamic reach in pronators and supinators often exceeded that of neutrals would suggest these concerns may be minimal. Further, researchers should investigate the effect of foot type on muscle activity patterns and joint forces during these balance tasks to better understand potential neuromuscular and biomechanical compensations for altered structural stability. Future investigators may also wish to control for or document foot type when measuring balance because the observed differences may confound the influence of other factors being examined.

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