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# Foot Characteristics in Association With Inversion Ankle Injury

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**Objective:** To review the literature that provides information to assist in analyzing the role of the foot in acute and chronic lateral ankle injury.

**Data Sources:** We searched MEDLINE, CINAHL, Institute for Scientific Information's Web of Science, and SPORT Discus from 1965–2005 using the terms *lateral, ankle, ligament, injury, risk factors, foot, subtalar joint, talocrural joint, gait analysis, and foot biomechanics*.

**Data Synthesis:** We found substantial information on the incidence and treatment of lateral ankle sprains in sport but very few articles that focused on risk factors associated with these injuries and even less information on the foot as it relates to this condition. Moreover, little information was available regarding the risk factors associated with the development of chronic instability after a lateral ankle sprain. We critically analyzed the

foot articulations and the foot's role in the mechanism of injury to assist our clinical synopsis.

**Conclusions/Recommendations:** An in-depth review of the foot complex in relation to lateral ankle sprains strongly suggested its importance when treating and preventing inversion ankle trauma. Throughout the literature, the only static foot measurements that show a significant correlation to this condition are an identified cavovarus deformity, increased foot width, and increased calcaneal eversion range of motion. Authors also provided dynamic measurements of the foot, which produced several significant findings that we discuss. Although our findings offer some insight into the relationship between foot characteristics and lateral ankle injuries, future research is needed to confirm the results of this review and expand this area of investigation.

**Key Words:** ankle instability, chronic ankle instability, ankle ligaments, ankle sprain, foot classification, risk factors

The ankle joint is one of the most commonly injured joints in the body due to the forces it withstands and the mass it supports. The ankle bears more weight per unit area than any other joint in the body.<sup>1</sup> Seventy-five percent of all ankle injuries are ankle ligament injuries, with 85% of those ankle sprains caused by inversion trauma.<sup>2</sup> For the purposes of this review, a lateral or inversion ankle sprain denotes an acute injury of the lateral ligaments of the ankle complex and is referred to as a lateral ankle sprain (LAS). In a cost analysis study, Soboroff et al<sup>3</sup> found that the cost of treating these injuries ranged from \$318 to \$914 per sprain, with an annual aggregate cost in the United States of \$2 billion. This figure provides a glimpse into the significant problems associated with this condition.

Many LASs resolve with a conservative treatment approach, whereas others have persistent pain, weakness, other symptoms of instability, and recurrent sprains.<sup>1,4,5</sup> Chronic ankle instability (CAI) is a term that is presently used to denote the occurrence of repeated episodes of lateral ankle instability and the presence of residual symptoms such as pain, swelling, "giving way," and loss of motion occurring long after an initial LAS.<sup>1,4</sup>

Potential intrinsic risk factors for the development of an initial LAS that have been examined include patient demographics,<sup>2,4,6,7</sup> ligamentous stability,<sup>2,8,9</sup> muscular strength,<sup>2</sup> anatomic foot and ankle alignment,<sup>2,7,10,11</sup> postural sway,<sup>9,12</sup> gait mechanics,<sup>13</sup> and muscle reaction time.<sup>2,12</sup> No prospective studies currently exist in the literature in which authors have analyzed predictive factors for the development of chronic lateral ankle instability and, therefore, intrinsic risk factors for this condition have yet to be established.

The intrinsic risk factor of interest for this review is that of

anatomic foot and ankle alignment. The ability for the most distal structures of the human body to control and adequately absorb high-impact forces during dynamic, functional activity is essential to injury prevention.<sup>14</sup> The foot is largely responsible for shock absorption during ground contact and lowering the rate of loading to avoid ligamentous sprain.<sup>14</sup> Specifically, the foot is the initial point for ground contact, and its fundamental role in human motion is to provide a base for support and to act as a lever for locomotion. The inability of the foot to do this efficiently can result in insult. Therefore, it is not unreasonable to question the association among the incidence of LASs, the development of CAI, and the alignment and integrity of the foot complex.

Our purpose is to examine the role of static and dynamic foot characteristics on both LAS and CAI. We synthesize the recent literature, discuss clinical implications, and provide suggestions for future research in this area. The relevant joints to be discussed are the talocrural, subtalar, talonavicular, intertarsal, and metatarsophalangeal joints.

## FOOT MOTION AND POSITIONING IN THE MECHANISMS OF INJURY

Common mechanisms for LAS include excessive foot inversion or supination, extreme plantar flexion, and, most often, a combination of both.<sup>15</sup> To properly assess the role the foot plays in LAS and CAI, it is advantageous to begin by briefly addressing the involvement of the foot articulations in each of the actions of the foot-ankle complex.

To analyze the role of the joints distal to the talocrural joint in pronation and supination, Hicks<sup>16</sup> studied the axes of several joints of the foot-ankle complex in cadaveric feet. He

found rotation in the talonavicular joint of the foot occurred around 3 different axes, all with directions allowing for pronation and supination. The first ray articulation comprises the joints between the navicular and the medial cuneiform and between the medial cuneiform and the first metatarsal. The first ray rotates obliquely in the anterolateral to posteromedial direction, also allowing pronation-supination.<sup>16</sup> A final contributor to this motion in the foot is the subtalar joint (STJ). The STJ is the articulation between the talus and the calcaneus, with an oblique axis that allows the foot to pronate and supinate.<sup>17</sup> One can postulate that an increase or decrease in motion of any of the previously mentioned segments may contribute to the stability of an individual subjected to a vulnerable supinated mechanism.

In a later *in vivo* study, Lundberg et al<sup>15</sup> looked specifically at the joint axes of the foot in relation to plantar flexion and dorsiflexion. Even though most of the rotation around the transverse axis caused by plantar flexion and dorsiflexion took place at the talocrural joint, the joints distal to the talus also were involved in this movement. In addition, they noted that all of the joints of the arch, including the talonavicular, were capable of rotating around axes that allow a substantial amount of plantar flexion and dorsiflexion. Hicks<sup>16</sup> had earlier determined that the complex first tarsometatarsal articulation contributed to these motions as well. This evidence suggests that motion in the foot articulations during the various mechanisms involved with an LAS warrant further scrutiny in the prevention and treatment of such injuries.

In addition to illustrating joint motion at the foot during the actions occurring in an LAS mechanism, Wright et al<sup>18</sup> examined the influence of changes in foot positioning at touchdown (initial contact) during a simulated LAS. Analyzed using mathematical modeling and perturbed simulations, the data suggested that an increased foot supination angle caused an apparently small increase in the occurrence of sprains, whereas a decrease in the initial supination angle caused a slight decrease in sprains. They also demonstrated that, for large supination torques, an increase in the initial dorsiflexion angle at the foot caused a decrease in the sprain occurrence, whereas a decrease in the initial dorsiflexion angle caused a slight increase in sprains. The researchers speculated that increased supination and plantar flexion at touchdown may increase the ground reaction force moment arm about the STJ and cause the excessive supination necessary to create lateral ankle injury.<sup>18</sup>

## STATIC FOOT POSTURE AND LATERAL ANKLE INJURY AND INSTABILITY

Although an initial LAS and subsequent LASs occur during dynamic activity, static measurements of foot characteristics have been performed most frequently to examine the relationships between the foot and lateral ankle injury. Static characteristics have been evaluated at the rearfoot, midfoot, and forefoot sections.

### Rearfoot

The rearfoot can be defined as the interaction of the distal one third of the tibia and the calcaneus, or the interaction of the distal one third of the tibia and the STJ in a neutral position. Therefore, both the talocrural and the STJs are considered part of the rearfoot, and these definitions are used inter-

changeably. The STJ is considered part of the rearfoot, but in the first part of this section, we evaluate static measurements of this articulation that indicate its role in LAS and CAI separately due to the specific increase in interest over recent years.

Structural STJ hypermobility has been implicated as a factor associated with LAS and CAI.<sup>19</sup> The static restraints of the STJ collectively combine to resist excessive supination, and, therefore, the integrity of these structures may play a role in the development of an initial LAS and eventually CAI. Evidence supports the association of STJ injury with LAS. Stress radiographs enable views of the foot-ankle complex and the integrity of the STJ after acute and recurrent LAS. Few authors have published the results of this method of analysis, but those who have<sup>20–23</sup> reported an association between talocrural and STJ instability. Kjaersgaard-Anderson et al<sup>24</sup> suggested that when the calcaneofibular ligament was sectioned *in vitro*, adduction in the transverse plane of the talocalcaneal joint increased, and when the interosseus ligament was sectioned, dorsiflexion increased at this same joint. Ishii et al<sup>21</sup> performed a cadaveric study demonstrating that, as the lateral ligamentous structures were injured, movement of the lateral process of the talus articulating with the posterior articular facet of the calcaneus subsequently increased, increasing motion at the STJ.

Stress fluoroscopy has provided a more contemporary approach in evaluating STJ motion. A group<sup>20</sup> using this method found that 75% of subjects suffering from talocrural instability also presented with signs of STJ injury. This result is consistent with that of previous researchers using stress radiography, showing significant differences in both the subtalar and talar tilt angles between the acutely injured subjects and their uninjured controls and between subjects with CAI and their control counterparts.<sup>20,25</sup>

Static clinical and radiographic measurements such as calcaneal position relative to the tibia and calcaneal range of motion have also been recorded to evaluate the relationship between static rearfoot function and LAS.<sup>2,12,20–22,24–27</sup> Beynnon et al<sup>12</sup> prospectively evaluated calcaneal range of motion and found that women with increased calcaneal eversion range of motion in the open chain were significantly more likely to suffer an LAS. No support for this correlation currently exists in the literature and, therefore, further research is needed to examine this possible relationship.

The static alignment of the calcaneus depicts rearfoot positioning and has also been evaluated as a potential risk factor for LAS. The normal valgus alignment of the calcaneus relative to the tibia theoretically protects the ankle and STJ from excessive inversion stress.<sup>12</sup> Beynnon et al<sup>12</sup> evaluated rearfoot (calcaneus) varus and valgus static alignment goniometrically to examine a possible correlation with LAS. This assessment was performed on the subject's non-weight-bearing limb and in an STJ neutral position. The investigators then measured the resulting angle between lines drawn to bisect the calcaneus and calf in the midsagittal plane. The results from these measurements were inconclusive and provided no significant correlation with LAS.<sup>12</sup> Another group<sup>2</sup> prospectively studying LAS risk factors examined degrees of rearfoot (calcaneal) valgus and varus positioning using weight-bearing goniometric assessment and also found no significant correlation with injury.

Goniometric and visual clinical assessment of the rearfoot are considered by some to be unreliable<sup>26</sup> and, subsequently, radiographic analysis of rearfoot alignment as it relates to CAI has been suggested.<sup>20–22,24,25,27</sup> Van Bergeyk et al<sup>27</sup> retro-

spectively used computerized tomography to evaluate rearfoot alignment as a means of accurately examining the structures in the coronal plane. They concluded that those suffering from CAI showed a trend toward increased varus alignment of the calcaneus, with a significant difference in the measured central calcaneal varus angle.<sup>27</sup> The central calcaneal varus angle was one of several measurements taken to identify static rearfoot alignment and was obtained from coronal images at the posterior aspect of the STJ and the calcaneal tuberosity while the subject was supine with both feet resting on a footplate to simulate a weight-bearing condition. To specifically assess varus alignment of the calcaneus, they determined the long axis of the calcaneus against the horizontal, measuring along the central axis of the calcaneus. Increased values were thought to increase calcaneal varus, and subjects with this increase were referred to as having a calcaneal varus malalignment. These results support the notion that an increased calcaneal varus malalignment is more prevalent in patients with CAI than in controls and suggests a theoretic advantage to correcting the malalignment in a CAI treatment protocol.<sup>27</sup>

### Midfoot and Forefoot

Static measurement of midfoot and forefoot posture has also been evaluated in conjunction with lateral ankle injury. The midfoot comprises the navicular, cuboid, and corresponding cuneiforms, whereas the forefoot is composed of the metatarsals and phalanges. The involvement of the forefoot and the midfoot in LAS has not been clarified in the literature. Most investigators<sup>2,10,12,28,29</sup> have focused on the static anatomical position classifications of the midfoot and rearfoot known to clinicians as pes cavus (excessively supinated) and pes planus (excessively pronated). Thus far, most findings suggest that neither foot abnormality appears to be a risk factor associated with LAS.<sup>12,28-30</sup> It should be noted, however, that the static methods used to classify these foot types are very subjective<sup>11</sup> and may be an inadequate method of describing and classifying dynamic foot mechanics.

A recent group<sup>10</sup> prospectively examined the structure of the medial longitudinal arch and its relationship with LAS incidence. The Tx-Smirak index was used to categorize medial arch heights in 65 military recruits as low, normal, or high.<sup>10</sup> At the end of training, those who were classified as having a low medial longitudinal arch suffered a significantly higher number of acute and recurrent LASs as compared with those with a high or normal arch height. It is well known that a pes planus foot type allows overpronation, and this entity accompanies a low arch.<sup>10</sup> It has been previously suggested that a low arch is accompanied by permanent eversion, leading to shorter, looser, and weakened peroneus longus and brevis muscles, which may delay reaction time and lead to subsequent sprain.<sup>2,10</sup> However, the cause of the low arch and overpronation was not discussed or examined by these authors.

In a retrospective radiographic study, researchers analyzed differences in the arch height of subjects (using a series of 3 defined angles on a lateral non-weight-bearing radiograph) with and without CAI and found contrasting results.<sup>31</sup> Higher arches were seen in the subjects with CAI than in the matched controls. Consistent methods<sup>11</sup> and further biomechanical analysis of these individuals may allow for a more thorough examination of the problem and perhaps well-defined trends will emerge as a result.

Flexion and extension range-of-motion measurements at the

first metatarsophalangeal joint in the forefoot region were not as frequently evaluated in lateral ankle injury as arch height, but one group<sup>32</sup> did look at this association in a prospective study of LAS incidence. Metatarsophalangeal joint range of motion was obtained from static goniometric measurements. Of the 223 subjects, 21 sustained an LAS. Those with an LAS had significantly more metatarsophalangeal joint extension than the controls.<sup>32</sup>

A last approach in the literature for static assessment of the midfoot and forefoot in correlation with LAS involves examining foot size rather than the position or range of motion of the foot segments. In a prospective study of military recruits, foot width and length measurements revealed that those who sustained an LAS had a significantly greater foot width and length.<sup>7</sup> This may suggest that during inversion injury, increased foot width and length is associated with an increased moment arm and corresponding inversion moment compared with a foot that is significantly shorter and more narrow.<sup>7</sup> However, it is important to note that these authors also showed that those individuals with greater height and weight were significantly more at risk for suffering an LAS, and it would seem that larger individuals would have a larger foot. An increase in body mass index has also been reported<sup>8,33</sup> to correlate significantly with an initial LAS and the development of CAI and may logically explain the results examining foot size.

### Complex Foot Postures

Studies of static foot postures have also been conducted to examine complex foot deformities involving malalignments at the rearfoot, midfoot, and forefoot. Regarding LAS, specific attention has been focused on cavovarus foot deformity, a combination of rearfoot varus, pes cavus, and excessive plantar flexion of the first ray. Researchers have not identified a cavovarus foot as a predictive factor for an LAS, but this deformity has been correlated with CAI.<sup>31</sup>

In 1990, an author<sup>31</sup> examining standard radiographs noted a higher frequency of cavovarus foot deformity in patients with CAI. Later, this relationship was evaluated again by a group<sup>34</sup> that obtained clinical and radiographic measurements from 10 subjects with CAI and severe degenerative changes. Interestingly, these measurements identified all 10 subjects with CAI as having a cavovarus deformity. After surgical correction of the deformity, all subjects had resolution of pain and instability.<sup>34</sup> Fortin et al<sup>34</sup> suggested that correction of the cavovarus foot deformity in patients with CAI may help to normalize forces across the ankle, aiding in the effectiveness of lateral soft tissue reconstruction.

Detailed statistical information for the results presented throughout this section is found in Tables 1 and 2.

### GAIT CHARACTERISTICS AND LATERAL ANKLE INJURY AND INSTABILITY

The investigation of static foot type in association with LASs and instability is helpful to establish structural risk factors for these conditions, but it is important to determine how these static alignments of the foot affect the dynamic activity in which these injuries occur. Although various ranges of dynamic actions incorporate foot motion and can create an LAS mechanism, currently only foot characteristics in gait have been assessed. Evaluation of gait can be performed using 3-

**Table 1. Prospective Studies of Foot Measures in Subjects With Lateral Ankle Sprains**

Authors	Subjects: No. Males/No. Females	No. Lateral Ankle Sprain/No. Sprain	Measurement	No Lateral Ankle Sprain*	Lateral Ankle Sprain*	P Value	Findings
Milgrom et al	390/0	69/321	Foot width (static measurement)	101.4 ± 4.7 mm	99.2 ± 5.8 mm	.003	Foot width was greater in subjects who sustained lateral ankle sprains
Milgrom et al	390/0	69/321	Foot length (static measurement)	268.7 ± 11.5 mm	264.9 ± 20.9 mm	.037	Foot longitudinal length was greater in subjects who sustained lateral ankle sprains
Mei-Dan et al (2005) <sup>10</sup>	0/65	27/38	Medial longitudinal arch height (ankle sprain incidence) (static measurement)	42.0% (SD unknown)	50.0% (SD unknown)	<.05	Through use of the Chippaux-Smirak index, those subjects in the low medial longitudinal arch group (index > 0.4) sustained a higher percentage of lateral ankle sprains
Beynon et al (2001) <sup>12</sup>	50/68	20/98	Calcaneal eversion range of motion (static measurement)	Females: 5.2 ± 1.8°; males: 4.3 ± 2.4°	Females: 6.1 ± 2.6°; males: 5.4 ± 2.3°	Females: .038; males: .56	Lateral ankle sprains were more common among females with an increased calcaneal eversion range of motion determined via weight-bearing goniometric assessment
Willems et al (2005) <sup>32</sup>	36/21	21/36	Maximal calcaneal inversion/resupination velocity (dynamic measurement)	81.9 ± 18.7%	91.9 ± 6.1%	.05	Through gait analysis, this variable was found to occur later in the gait cycle of subjects who suffered a lateral ankle sprain
Willems et al (2005) <sup>32</sup>	36/21	21/36	Metatarsophalangeal joint range of motion (static measurement)	67.3 ± 16.5°	78.3 ± 13.7°	.021	Through goniometric assessment, metatarsophalangeal joint extension was found to be greater in subjects who sustained a lateral ankle sprain <sup>13</sup>
Willems et al (2005) <sup>32</sup>	36/21	21/36	Total foot contact time (dynamic measurement)	0.22 ± 0.02 s	0.23 ± 0.02 s	.02	Those who sustained a lateral ankle sprain had a longer total foot contact time in gait
Willems et al (2005) <sup>32</sup>	36/21	21/36	Percentage of pressure displacement of the forefoot (medial/lateral) (dynamic measurement)	18.6 ± 8.9%	11.3 ± 11.0%	.004	Those who sustained a lateral ankle sprain had a more laterally directed pressure displacement of the forefoot push-off phase in gait
Willems et al (2005) <sup>32</sup>	36/21	21/36	Percentage of center of pressure (medial/lateral) (dynamic measurement)	8.4 ± 7.6%	3.0 ± 9.0%	.012	Those who sustained a lateral ankle sprain had a more laterally situated center of pressure at last foot contact in the gait cycle

\*Values are mean ± SD.

**Table 2. Retrospective Studies of Foot Measures in Subjects With Chronic Ankle Instability**

Authors	Subjects: No. Males/No. Females	Chronic Ankle Instability/No Instability	Measurement	No Chronic Ankle Instability*	Chronic Ankle Instability*	P Value	Findings
Yamamoto et al (1998) <sup>25</sup>	55/48	23/80	Subtalar joint motion (radiographic subtalar tilt angle)	5.2 ± 2.6°	10.3 ± 3.9°	<.0001	Radiographic subtalar tilt angles are greater in the chronic ankle instability group, suggesting a link with increased subtalar joint motion
Van Bergeyck et al (2002) <sup>27</sup>	20/4	12/12	Varus alignment of the calcaneus (computed tomography image of central calcaneal varus angle)	92.7 ± 5.3°	96.7 ± 4.0°	<.01	Computed tomography images showed increased varus alignment of the calcaneus in subjects with chronic ankle instability
Larsen and Angermann (1990) <sup>31</sup>	62/67	95/34	Medial longitudinal arch height (indicated by lower TMT angles)	Right: 161 ± 4.8° 161 ± 4.8°	Right: 164.2° ± 9.1°; left: 166.4 ± 9.0°	Right: .004; left: <.001	Lateral non-weight-bearing radiographs demonstrated higher arches in subjects with chronic ankle instability
Larsen and Angermann (1990) <sup>31</sup>	62/67	95/34	Cavovarus deformity (Indicated by higher TC‡ by radiographic angles, lower TMT and C‡ radiographic angles)	TC: 35 ± 4.3° (right), 35 ± 4.2° (left); C: 113 ± 5.1° (right), 114 ± 5.1° (left)	TC: 33.4 ± 8° (right), 33 ± 8.1° (left); C: 114.5 ± 11.4° (right), 115.7 ± 9.8° (left)	Right: .03; left: .005; nonsignificant .04	More cavovarus deformity in subjects with chronic ankle instability
Nyska et al (2003) <sup>35</sup>	24/0	12/12	Duration of contact time from heel to forefoot (percentage of total stance time)	17.9 ± 1.7%	18.8 ± 1.2%	<.01	Longer duration of contact from the heel to central forefoot in gait in subjects with chronic ankle instability
Nyska et al (2003) <sup>35</sup>	24/0	12/12	Center of pressure (ratio of force under forefoot in stance [medial/lateral])	0.2 ± 0.07 N	0.03 ± 0.07 N	<.05	More lateral shift of the center of pressure in subjects with chronic ankle instability
Nawata et al (2005) <sup>36</sup>	13/5	8/10	Mean foot angle (between foot bisecton line and forward line of progression)	11.8 ± 2.9°	7.9 ± 4.9°	<.05	Mean foot angle is lower among subjects with chronic ankle instability, indicating a more toe-in gait
Nawata et al (2005) <sup>36</sup>	13/5	8/10	Pronation-supination index (indicates location of center of pressure; higher = more lateral)	49.2 ± 3.3°	55.2 ± 3.5°	<.05	Index at the mid-support phase of gait was higher in subjects with chronic ankle instability, indicating a more lateral center of pressure during stance

\*Values are mean ± SD.

†Indicates angle between a line through the posterior articular talar trochlea and midpoint of the caput tali and line through the midpoint of base of first metatarsal.

‡Indicates angle between a line through the posterior articular talar trochlea and midpoint of caput tali and longitudinal line through the calcaneus corpus.

§Indicates angle between lines through the posterior calcaneal joint surface and the posterosuperior part of the calcaneal body.

dimensional motion analysis systems, forceplates, and plantar pressure measurement systems.

A uniquely designed prospective study by Willems et al<sup>32</sup> used dynamic 3-dimensional kinematic data of 223 subjects to determine gait-related risk factors for inversion sprains. The results were based on those subjects who sustained an LAS during the investigation. Video data showed the subjects walking barefoot at a speed of 3.3 m/s. After a thorough kinematic gait analysis, they reported 2 findings. First, the instant of maximal calcaneal inversion or resupination velocity occurred significantly later in the LAS group than in those who did not suffer a sprain. They stated this most likely occurred because of the prolonged pronation phase in the LAS group, which means that resupination has to occur in a shorter time. Second, metatarsophalangeal joint extension range of motion was greater during the gait cycle in subjects who sustained an LAS. These results support the previous findings of increased metatarsophalangeal joint range of motion with static goniometric assessment.

Willems et al<sup>32</sup> also measured plantar pressure to analyze gait patterns in association with an initial LAS. They used a Footscan pressure plate (RSscan INTERNATIONAL, Olen, Belgium) mounted on a force platform to obtain plantar pressure data during gait in the 223 subjects. Those who sustained an LAS had a longer total foot contact time, more laterally directed pressure displacement of the forefoot push-off phase, and more laterally situated center of pressure at last foot contact. Although most LASs occur at initial contact in the stance phase of gait, the authors suggested that a more laterally situated center of pressure at last foot contact during the push-off phase could place the athlete in a more vulnerable position when in plantar flexion at push-off, producing an LAS.<sup>32</sup> However, this mechanism is more likely to occur in high-level activities at greater speeds. Conversely, it is important to note that at the first metatarsal contact of gait, the pressure distribution was directed more medially, and, overall, levels of loading beneath the medial border of the foot were higher than beneath the lateral border.<sup>32</sup>

Two other groups<sup>35,36</sup> have retrospectively evaluated plantar pressure and force distribution during gait specifically in subjects with CAI. Nyska et al<sup>35</sup> evaluated the changes in force transfer and peak forces under the feet using the mini-EMED plantar foot pressure system (Novel GmbH, Munich, Germany) during level walking in 12 subjects with CAI (more than 3 LASs in 6 months) and in 12 healthy controls. The CAI subjects had a different pattern of walking, with a longer duration of contact from the heel to the central forefoot, which indicated a slowing down of weight transfer from heel strike to toe off. The CAI subjects also showed greater forces under the midfoot and lateral forefoot, causing a lateral shift of the center of pressure.<sup>35</sup>

Nawata et al<sup>36</sup> evaluated plantar pressure distribution in 8 CAI subjects (2 or more episodes of “giving way” in the past 6 months) and in 10 healthy control subjects using the MP-4800 pressure measuring system (Anima, Tokyo, Japan). They evaluated the pressure distribution of a final footprint from combined frames using 2 factors identified as the mean foot angle and pronation-supination index. The mean foot angle was defined as the angle between a line that bisected the heel and the forward line of progression (Y-axis) and was lower in the CAI group, suggesting that these subjects had greater “intoeing” during gait.<sup>36</sup> The pronation-supination index measured the relative amount of pronation or supination at the

stance phase of gait and was defined as the distance between the medial footprint border and the center of pressure divided by the distance from the medial to the lateral borderline.<sup>36</sup> The pronation-supination index at the midsupport phase was higher among the CAI subjects. The authors stated that this increase in adduction-supination at the midsupport phase seen in the CAI subjects could suggest an impaired ability of the pronators to counteract inversion. Both groups concurred that further examination of the foot using these plantar pressure measurement techniques is needed, especially during dynamic conditions.<sup>35,36</sup>

Further detailed statistical information for the results presented throughout this section can be found in Tables 1 and 2 of this review.

## LIMITATIONS IN LITERATURE

After one reviews the literature, it is evident that some inconsistency in the reported findings has occurred. This variability may be due, in part, to the inability to obtain accurate and reproducible measurements of foot alignment and motion. Discrepancies may also result from the clinical tools used and the variation among examiners.<sup>37</sup> Some authors reviewed goniometric data that calculated STJ or rearfoot measurements and included calcaneal range of motion and static positioning of the calcaneus and tibia in STJ neutral. Rearfoot and forefoot relationships were also measured in STJ neutral. Assessments of the reliability of goniometric measurements at the STJ have been sparse but have provided us with some insight into the validity of this measurement tool.<sup>19,38</sup>

Calcaneal inversion and eversion range-of-motion measurements on normal subjects in a non-weight-bearing position displayed a moderate correlation coefficient of 0.83.<sup>39</sup> However, one criticism is that the authors did not state if they measured intratester or intertester reliability, nor did they report measurement precision data. Elveru et al<sup>38</sup> explored the goniometric reliability of subtalar and ankle measurements and provided intratester intraclass correlation coefficient values of 0.74 and 0.75, respectively, for calculating calcaneal inversion and eversion range of motion. Intertester reliability provided low intraclass correlation coefficient values of 0.32 and 0.17, respectively. Once more, SEM values were not reported, nor could they be calculated from the data provided. Two years later, a second set of researchers<sup>26</sup> evaluated this measurement, and they, too, reported consistently low intertester measurement reliability for calcaneal inversion and eversion range of motion in the non-weight-bearing position. Calculated SEM values for inversion and eversion were 4.82° and 3.5°, respectively, indicating low measurement precision.<sup>26</sup>

Smith-Oricchio and Harris<sup>26</sup> also investigated the reliability of palpated STJ neutral, a position commonly used in research and clinical evaluation. They reported less than moderate intraclass correlation coefficient values of 0.60 for intertester reliability, with an SEM of 2.95°. Subtalar joint neutral reliability is crucial because the position provides the clinician with a relative zero point of reference from which to measure range of motion and a starting point for other lower extremity measurements.<sup>19</sup> Further emphasis needs to be placed on improving measurement and palpation techniques and developing more reliable tools to obtain these measurements.

Due to the perceived inaccuracy of clinical measurements, some researchers<sup>21-25</sup> have chosen to measure foot alignment with radiographs. We recognize that the angles measured from

these radiographs to classify foot type also have the potential to contain intertester and intratester error. In addition, the radiographs we discuss in this review were taken with subjects in an open chain position and do not provide the functional view of the foot that a closed chain position would offer.

An additional methodologic limitation affecting this area of research is the need for more advanced strategies for motion analysis of the foot. Three-dimensional kinematic and kinetic analysis of gait is an effective way to functionally examine these orthopaedic structures and provides valuable information in the area of foot research, but to this point, the foot has been evaluated as a rigid structure. Although current motion analysis systems have greater resolution than previous models, some foot marker placements for popular marker sets prohibit accurate measurement of foot frontal-plane motion, a very important element in foot mechanics.<sup>40</sup> Other marker set placements, such as that of Willems et al<sup>32</sup> using motion analysis, have given more information regarding rearfoot frontal motion; however, the midfoot has not been assessed.

Although authors of prospective studies in the literature identify links between foot characteristics and the development of an initial LAS, at this time, no prospective studies have been conducted to associate any static or dynamic foot traits and CAI. All research to this point has been retrospective and, therefore, cannot show causality but only identify relationships. In order for foot characteristics to be recognized as risk factors for CAI, prospective studies must be conducted. In addition, more studies of that design must be performed when evaluating the foot and LASs to provide stronger support for the risk factors already identified.

Lastly, odds ratios for LAS and CAI risk in subjects who have and do not have given foot characteristics were not presented in any of the articles we reviewed. Odds ratios can give us an idea of how strongly a given variable may be associated with the outcome of interest compared with other variables. The absence of these ratios in the literature can be regarded as a major limitation in understanding relationships between foot structure and lateral ankle injury risk. If odds ratios were given in the literature, they would refer to the ratio of the odds of an event (LAS or CAI) occurring in a group with a certain foot characteristic versus the control group. This method is an effective way of expressing the relative risk of sustaining an acute or chronic lateral ankle injury when a subject possesses certain foot characteristics.

## CLINICAL IMPLICATIONS

Structural variations of the foot have been implicated as potential risk factors for lower extremity injury.<sup>41</sup> Although these links do exist, little emphasis is placed on the foot and its structures regarding the treatment and prevention of LAS and CAI.

We suggest that in addition to the assessment of talocrural joint laxity, the STJ also be evaluated. Hertel et al<sup>20</sup> described the medial subtalar glide as an effective assessment tool in examining STJ laxity; however, its use has not been widespread. Clinicians should also be encouraged to evaluate first ray mobility, static calcaneal positioning both in weight bearing and in STJ neutral position, the midtarsal joints, and the longitudinal arches to assess the midfoot. Additionally, an evaluation of the joints and articulations distal to the talocrural joint is needed to help identify and correct damage and abnormalities in these areas during the treatment of LASs.

No information in the literature targets the foot region specifically for prevention strategies in those with either LAS or CAI. Orthotic devices successfully modified selected aspects of lower extremity mechanics and enhanced foot stability during the support phase of running.<sup>42</sup> Also, the effect of orthotic intervention on conditions such as peroneal tendinitis, anterior compartment syndrome, tibialis anterior tendinitis, and stress fractures has been examined.<sup>42</sup> Recent studies<sup>20,25</sup> on STJ motion and the effect of this motion on the position of the talus at the talocrural joint may provide the basis for extending this line of research to the conditions of interest in this review.

## CONCLUSIONS

The recent literature has provided important advances with regard to identifying lateral ankle injury risk factors for both acute and chronic ankle injury. Although progress has been made, more work still needs to be done to properly identify the role of the foot in acute and chronic ankle sprain conditions. Based on this review of the related literature, the factors that most strongly identify at-risk individuals include a high longitudinal arch, greater foot width, cavovarus foot deformity, women with increased calcaneal eversion range of motion (open chain), greater metatarsophalangeal joint extension, STJ instability, and a more laterally situated gait. However, very few studies have been devoted to evaluating these factors, and more evidence is needed to confirm these findings. Also, the inability to develop consensus among the results illustrates the need for advanced and more consistent methods of understanding the connection between the foot and ankle segments.

Accurately capturing foot motion is pivotal to understanding lower extremity mechanics and injury mechanisms. Variations in both foot structure and foot mechanics greatly influence motion of the more proximal segments of the lower extremity.<sup>40</sup> However, to assess the role of the foot in inversion ankle trauma, more reliable measurement techniques need to be developed. The foot is an incredibly complex structure, comprising 26 or more bones and more than 30 articulations, most with 6 degrees of freedom of movement. This anatomy suggests that analysis of motion at the foot is a difficult task and new techniques are needed to gain insight into this phenomenon. Specifically, new techniques for marker placement in motion analysis should be developed to produce kinematic and kinetic variables from the midfoot and forefoot to enhance our knowledge of these segments in foot function among the subjects of interest.

More concise and reliable results on this topic will help to define those foot-related risk factors for LAS. Intervention studies can then be performed to reduce the incidence and severity of acute and chronic lateral ankle injury.

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