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# Normal Kinematics of the Syndesmosis and Ankle Mortise During Dynamic Movements

**Veronica Hogg-Cornejo, MS[1], Kenneth J. Hunt, MD[2], Jonathan Bartolomei, MS[2], Paul J. Rullkoetter, PhD[1], Casey Myers, PhD[1], and Kevin B. Shelburne, PhD[1]**

## Abstract

**Background:** Documenting the healthy articulation of the syndesmosis and talocrural joints, and measurement of 3D medial and lateral clear spaces may improve diagnostic and treatment guidelines for patients suffering from severe syndesmotic injury or chronic instability. This study aimed to define the range of motion (ROM) and displacement of the fibula and talus during static and dynamic activities, and measure the 3D movement in the tibiofibular (syndesmosis) and medial clear space.

**Methods:** Six healthy volunteers performed dynamic weightbearing motions on a single-leg: heel-rise, squat, torso twist, and box jump. Participants posed in a nonweightbearing neutral stance as well as weightbearing neutral standing, plantarflexion, and dorsiflexion. High-speed stereoradiography measured 3D rotation and translation of the fibula and talus throughout each task. Medial clear space and tibiofibular gap distances were measured under each condition.

**Results:** Total ROM for the fibula was greatest in internal-external rotation (9.3 $\pm$ 3.5 degrees), and anteroposterior (3.3 $\pm$ 2.2 mm) and superior-inferior (2.5 $\pm$ 0.9 mm) translation, rather than lateral widening (1.7 $\pm$ 1.0 mm). The total rotational ROM of the talus was greatest in dorsiflexion-plantarflexion (34.7 $\pm$ 12.9 degrees) and internal-external rotation (15.0 $\pm$ 3.4 degrees). Single-leg squatting increased the lateral clear space ($P = .045$) and widened the medial tibiofibular joint, whereas single-leg heel-rises decreased the lateral clear space ($P = .001$) and widened the tibiotalar space. Gap spaces in the tibiofibular and medial clear spaces did not exceed 2.3 $\pm$ 0.9 mm and 2.7 $\pm$ 1.2 mm, respectively.

**Conclusion:** These data support a potential shift in the clinical understanding of fibula displacements during dynamic activities and how implant device constructs might be developed to restore physiologic mechanics.

**Clinical Relevance:** Syndesmosis stabilization and rehabilitation should consider restoration of normal physiologic rotation and translation of the fibula and ankle mortise rather than focusing solely on the restriction of lateral translation.

**Keywords:** ankle, syndesmosis, fluoroscopy, ligament, radiography, kinematics, repair

## Introduction

In the world of athletics, syndesmotic injuries account for up to 30% of all ankle injuries.[28] In collision sports such as football, soccer, and hockey, the incidence of syndesmotic injury rises drastically, reaching 75% of all ankle injuries reported.[15,23,27,30] Of all ankle injuries reported during a sporting activity, more than half resulted in a severe fracture of the bones or complete rupture of the surrounding ligaments.[18] Hermans et al found that 40% of people with severe high ankle sprains report experiencing subjective instability 6 months after the initial injury,[13] likely resulting in lifelong dysfunction. The high occurrence rate of syndesmotic injury

[1] Center for Orthopaedic Biomechanics, Department of Mechanical and Materials Engineering, The University of Denver, Denver, CO, USA
[2] Department of Orthopedic Surgery, The University of Colorado, Denver, CO, USA

**Corresponding Author:**
Kevin B. Shelburne, PhD, Center for Orthopaedic Biomechanics Department of Mechanical and Materials Engineering, The University of Denver, 2155 East Wesley Ave, Denver, CO, 80208, USA.
Email: kevin.shelburne@du.edu


**Figure 1.** Sample radiographic image illustrating the location of the lateral and medial clear spaces measured in subjects.

among athletes and its inherent risk for chronic disability emphasized the importance of understanding the injury better to improve diagnosis and treatment.

Diagnosis of injury includes screening for frank diastasis by assessing for a widened clear space between the tibia and fibula at the syndesmosis (tibiofibular-lateral clear space) and between the tibia and talus at the medial gutter (tibiotalar-medial clear space) (Figure 1). These spaces can be measured via 2-dimensional (2D) radiography, magnetic resonance imaging, or computed tomography (CT).[29] The medial clear space is defined as the distance between the medial talar dome and the lateral face of the tibial malleolus. The syndesmosis width is measured by the gap between the lateral posterior incisura of the tibia and the medial border of the fibula taken 1 cm proximal to the joint line (Figure 1). Radiographic measurements of a tibiofibular (lateral) clear space >6 mm, loss of tibiofibular overlap, or a tibiotalar (medial) clear space >4 mm is potentially indicative of higher-grade injury requiring surgical fixation.[16] These normative values of clear space were based on measurements made from intraoperative fluoroscopy, which requires careful subject positioning and measurement and does not describe the natural deformation of the joints during weightbearing and activity.[24]

Three-dimensional (3D) measurements of medial and lateral clear space during dynamic activity currently do not exist. Understanding the kinematics of the distal tibiofibular joint and ankle mortise may provide a more accurate assessment of syndesmotic injury. Misdiagnosis of high ankle sprains because of inaccurate 2D clear space measurements could result in potential unnecessary surgery for moderate sprains, increased risk of malreduction after severe sprains, and lifelong complications or discomfort.

**Table 1.** Participant Anthropometric Data.

| | Anthropometric Summary | | | |
|---|---|---|---|---|
| | Female (n = 3) | | Male (n = 3) | |
| | Mean | SD | Mean | SD |
| Age, y | 30.7 | 3.1 | 28.0 | 1.0 |
| Height, cm | 168.8 | 4.0 | 179.8 | 3.3 |
| Weight, lb | 129.8 | 2.4 | 186.3 | 23.7 |
| Dominant leg, R/L | 3/0 | – | 2/1 | – |

The scope of this work focused on documenting healthy articulation of the syndesmosis and talocrural joints, and the measurement of 3D medial and lateral clear spaces to improve diagnostic and treatment guidelines for patients with severe syndesmotic injury or chronic instability. Measurements of the 6 degrees of freedom kinematics of the syndesmosis and talocrural joints were used to define the healthy range of motion (ROM) and normal limits of bone displacement in the syndesmotic and medial clear space. Defining these healthy ranges for normal clear space changes in the ankle joint could ultimately improve diagnostic measures for syndesmotic injuries and identify optimal treatment strategies. We hypothesized that normal healthy, uninjured athletes would experience increasing gap distances in the syndesmosis and medial clear space as a result of weightbearing and dynamic activity when compared to a static nonweightbearing neutral pose.

## Materials and Methods

### *Participants and Experimental Protocol*

Six active healthy athletic volunteers (29.3 $\pm$ 2.5 years, 174.3 $\pm$ 6.9 cm height, 71.7 $\pm$ 11.1 kg body weight, 23.3 $\pm$ 3.8 body mass index; Table 1) with no prior history of lower limb injury were recruited locally and provided consent, in accordance with the Institutional Review Board to participate in the study. Kinematics for the syndesmosis and talocrural joints were measured in vivo via high-speed stereoradiography (HSSR) and used to define normal ROM of the fibula and talus relative to the tibia during static and dynamic activities. These measurements were used for 3D assessment of the medial and lateral clear space widening that occurs during weightbearing and high-stress maneuvers. HSSR is an in vivo imaging technique that allows precise measurement of joint motions in 6 degrees of freedom.[9,25] Prior work has shown that the use of HSSR enables 3D measurement of bone motion during dynamic activities to submillimeter and subdegree accuracy.[17,20] Four floor-embedded force plates captured ground reaction force data in synchrony with the optical motion capture system (Bertec, Columbus, OH).

Measurements were made while each participant held 4 static poses and performed 4 dynamic movements. Static

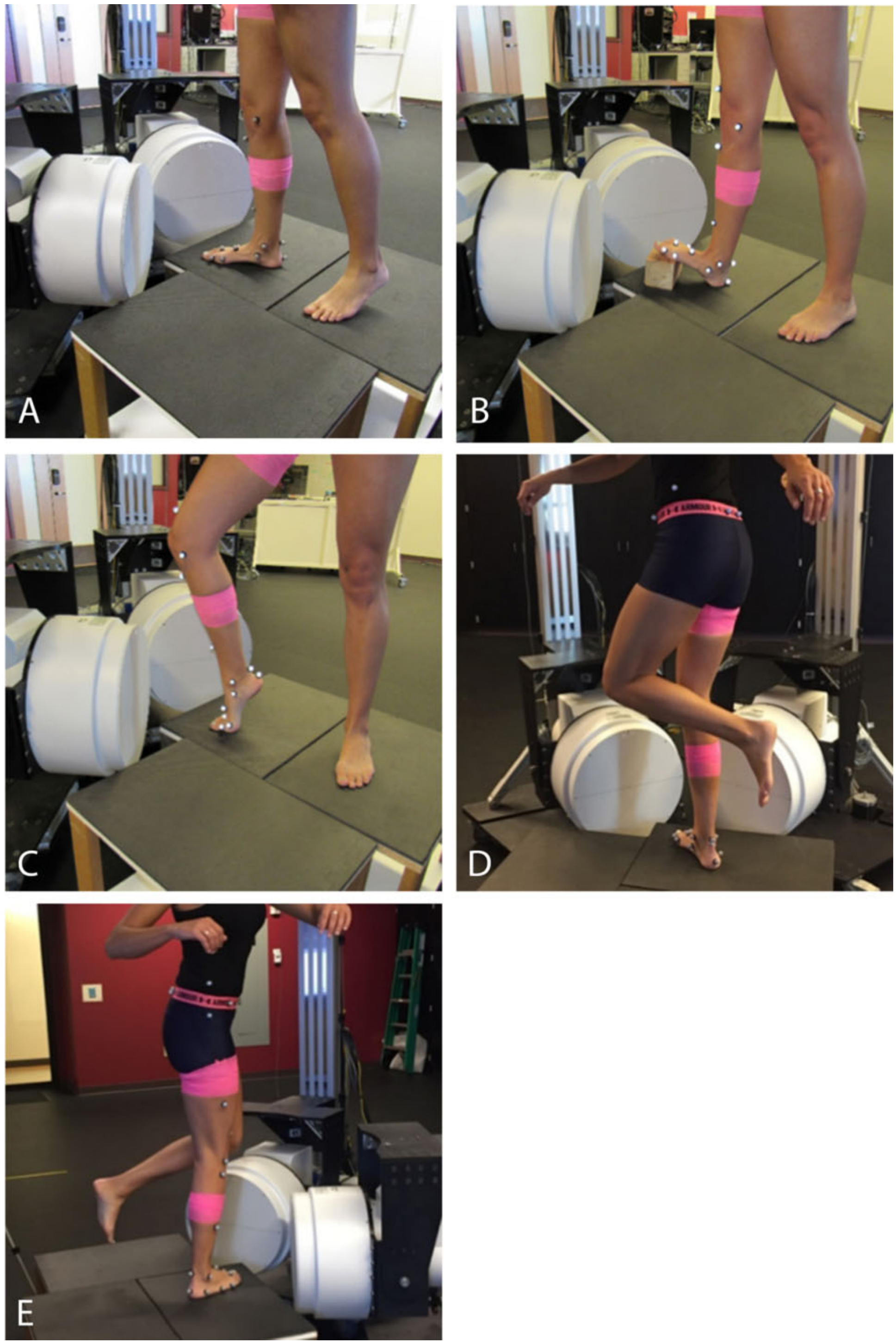


**Figure 2.** Series of static weightbearing poses captured within the HSSR volume: (A) neutral standing, (B) maximum dorsiflexion, (C) maximum plantarflexion, (D) single-leg squat, (E) maximum internal-external rotation. HSSR, high-speed stereoradiography.

poses of the ankle included a nonweightbearing neutral position, weightbearing neutral stance, as well as weightbearing plantarflexed and dorsiflexed positions (Figure 2). We defined neutral nonweightbearing as the participant standing with a shifted weight onto the contralateral foot, and neutral weightbearing as a normal stance. The 4 dynamic movements used to illustrate the maximum ROM of the ankle included a heel rise (calf raise), squat, torso twist (Figure 2), and box jump (Figure 3). These activities were chosen to stress the syndesmosis similarly to high ankle sprain injuries

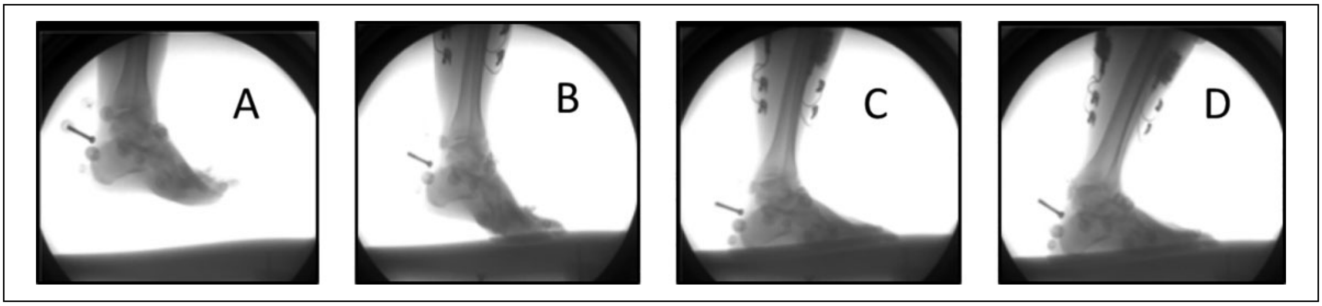


**Figure 3.** Dual-plane high-speed stereoradiography images of a foot in the various phases of dynamic box jump: (A) flight, (B) toe-strike, (C) heel strike, (D) stabilization.

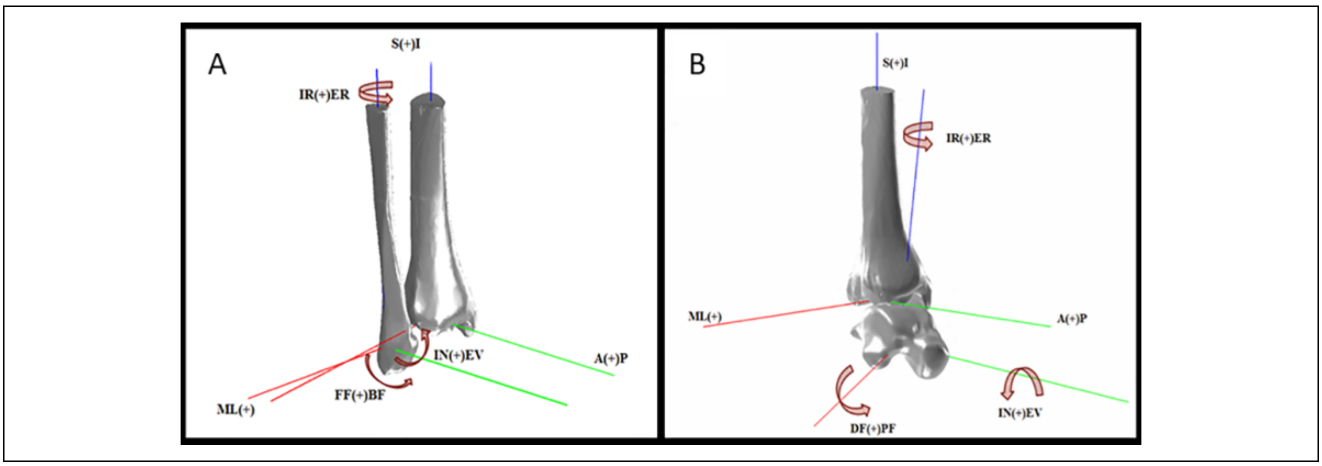


**Figure 4.** Local coordinate system assignments for the tibia and fibula of the syndesmosis (left) and talus and tibia of the talocrural joint (right). A-P, anterior-posterior; DF-PF, dorsiflexion-plantarflexion; FF-BF, forward-backward flexion; IN-EV, inversion-eversion; IR-ER, internal-external rotation; M-L, medial-lateral; S-I, superior-inferior.

and closely correlate to clinical tests used to diagnose syndesmotic instability. All dynamic movements were weightbearing and performed on a single leg.

Radiographic images of the static poses and movements were captured in 2 planes using HSSR at a frame rate of 50 fps, excluding the box jump, which was captured at 100 fps (Figure 3). CT scans of the lower limb were also taken for each volunteer. One-millimeter-thick CT slices of the bone were used to reconstruct 3D subject-specific geometries of the tibia, fibula, and talus (ScanIP, Simpleware, Inc). Local coordinate systems were established from identifying prominent landmarks on the bones using modified methods outlined by Grood and Suntay (1983) and the International Society of Biomechanics (2002) recommendations (Figure 4).[12] Positive translations for the fibula coincide with lateral (L), anterior (A), and superior (S) directions. Positive rotations according to the right-hand rule coincided with forward flexion, inversion, and internal rotation of the distal fibula (Figure 4). Forward and backward flexion was used to describe the sagittal plane rotation of the distal fibula and differentiate from the common nomenclature of dorsiflexion-plantarflexion used to describe whole foot and talocrural joint motions. The same positive coordinate system was assigned to the talus, although dorsiflexion and plantarflexion were used to describe sagittal plane motion. All other annotations for rotation and translation correspond to common terminology in the literature (Figure 4). Open-source software was used to match the relative positioning and orientation of the subject's 3D talus, fibula, and tibia reconstructed from CT to the 2D radiography images to quantify translations and rotations at each pose (XROMM and Autoscoper, Brown University, RI).

## *Data Analysis*

Three-dimensional translational and rotational motions were expressed relative to the positioning of the bones during the nonweightbearing neutral pose of the foot. Kinematics and ROM (how much relative motion occurs during an activity) were expressed as mean $\pm$ SD (Table 2). Small values for kinematics and ROM were indicative of minimal movement between the bones from their initial nonweightbearing neutral position. The limits of the activity for calf raise and squat were defined as a percentage completion from the initial weightbearing neutral stance (0% task completion) to the point of maximum plantarflexion or dorsiflexion (100% task completion). The torso twist was examined at the initial neutral

**Table 2.** Mean ROM for All Dynamic Activities for Syndesmosis (Tibiofibular) and Tibiotalar Joints.

| | FF-BF, degrees | | IN-EV, degrees | | IR-ER, degrees | | M-L, mm | | A-P, mm | | S-I, mm | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | SD | Mean | SD | Mean | SD | Mean | SD | Mean | SD | Mean | SD |
| Dynamic tibiofibular (syndesmosis) ROM | | | | | | | | | | | | |
| Calf raise | 1.3 | 0.3 | 1.7 | 1.0 | 8.1 | 3.3 | 1.7 | 0.9 | 2.8 | 1.4 | 1.9 | 0.8 |
| Squat | 0.8 | 0.2 | 1.0 | 0.2 | 4.7 | 2.8 | 1.2 | 0.6 | 2.2 | 1.2 | 2.1 | 0.8 |
| Torso twist | 1.4 | 0.9 | 1.7 | 1.0 | 8.8 | 2.5 | 1.5 | 0.5 | 3.3 | 2.2 | 2.1 | 0.7 |
| Box jump | 1.7 | 0.7 | 1.4 | 0.5 | 9.4 | 3.5 | 1.7 | 1.0 | 3.2 | 1.0 | 2.5 | 0.9 |
| Dynamic tibiotalar ROM | | | | | | | | | | | | |
| Calf raise | 34.7 | 12.9 | 8.2 | 3.8 | 14.5 | 3.4 | 3.8 | 2.3 | 16.3 | 7.1 | 2.7 | 1.8 |
| Squat | 23.3 | 6.6 | 6.2 | 2.9 | 6.5 | 3.8 | 2.3 | 1.4 | 8.7 | 3.3 | 4.3 | 1.3 |
| Torso twist | 6.6 | 3.9 | 4.3 | 1.7 | 15.0 | 3.4 | 3.0 | 1.6 | 3.5 | 1.5 | 1.2 | 0.8 |
| Box jump | 17.8 | 9.8 | 7.1 | 3.6 | 13.4 | 4.9 | 3.3 | 1.9 | 8.0 | 5.7 | 2.9 | 1.3 |

Abbreviations: A-P, anterior-posterior; FF-BF, forward-backward flexion; IN-EV, inversion-eversion; IR-ER, internal-external rotation; M-L, medial-lateral; ROM, range of motion; S-I, superior-inferior.

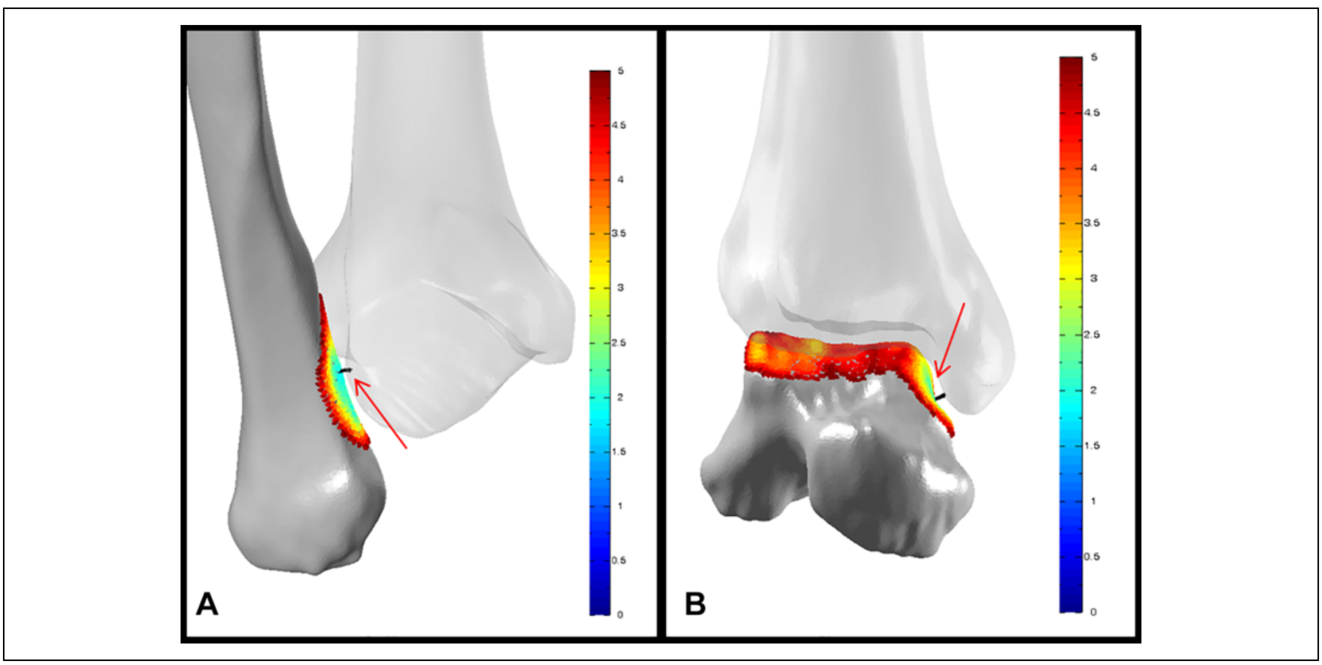


**Figure 5.** Anatomical contour plot of bone spacing and identification of minimum (A) lateral and (B) medial clear spaces, as indicated by the black line connecting the bones. Scaling for the contour plots ranges from 0 to 5 mm, where dark blue represents the absolute minimum separation (0 mm) between the bones and dark red is the upper limit of bone separation (5 mm).

stance, maximum external rotation, second neutral position, and then maximum internal rotation. The box jump was analyzed at five instants (Figure 3): flight (Pre), initial contact typically seen as a toe strike, heel strike (HS), maximum ground reaction force, and immediately after the maximum ground reaction force occurs (Post).

Medial and lateral clear space distances were calculated via a *custom* MATLAB code.[12] First, subject-specific bone geometries were converted into point clouds, which then had their respective kinematic data applied to drive the spatial change of the bone throughout the activity. Minimum point-to-point distances were calculated from one object (fibula or talus) cloud to the nearest cloud defining the second object (tibia). A contour plot displaying all clear space distances <5 mm were mapped along the fibula and talus geometries to visually illustrate changes in anatomical spacing between the bones (Figure 5). All clear space measurements were the maximum values measured—a mean of those maximum measurements for the 6 subjects was then calculated. Changes in clear space were measured throughout an activity and compared across activities. Differences in mean clear space throughout the dynamic activities were examined using 1-way analysis of variance and Tukey honestly significant difference post hoc. The level of significance was set to $\alpha = 0.05$. No significant differences were found between genders.

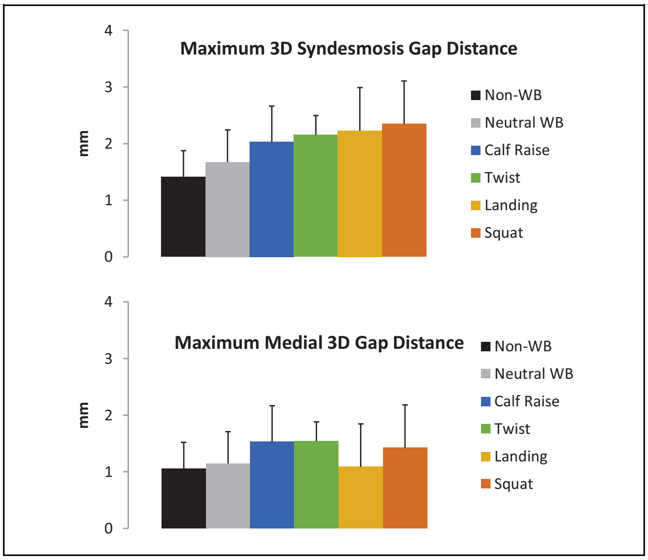


**Figure 6.** Maximum syndesmosis gap (top) and medial clear space (bottom) distance shown for all activities.

## Results

### *Tibiofibular (Syndesmosis) and Tibiotalar ROM*

Changes in fibular and talar positioning relative to their initial nonweightbearing neutral locations showed no significant difference across static poses. Average ROM of the tibiofibular and tibiotalar joints are compared across the dynamic activities in Table 2. During the dynamic activities, squatting imposed the least amount of rotational ROM in the fibula (Table 2), whereas the twist and box jump activities caused the most change in internal-external rotation with 8.8 ± 2.5 degrees and 9.3 ± 3.5 degrees, as well as the greatest ranges in anterior-posterior translation with 3.3 ± 2.2 mm and 3.2 ± 1.0 mm, respectively. The box jump activity also displayed the largest range overall in superior-inferior translation (2.5 ± 0.9 mm).

Maximum dorsiflexion and plantarflexion and anterior-posterior ROM of the tibiotalar joint occurred for calf raise (34.7 ± 12.9 degrees and 16.3 ± 7.1 mm) (Table 2). The torso twist exhibited the greatest range in internal-external rotation (15.0 ± 3.4 degrees). Generally, there was little variation and similarly small magnitudes of ROM in inversion-eversion, medial-lateral, and superior-inferior across all activities.

### *Syndesmosis Gap (Lateral Clear Space)*

Syndesmosis gap measurements during static poses illustrated distinct effects of the ankle positioning on the overall distraction of the fibula from the tibia. Although joint distraction in the neutral stance showed little change with weightbearing (Figure 6), the dorsiflexed foot caused the greatest amount of gap in the syndesmosis (1.8 ± 1.2 mm), and a plantarflexed foot caused the greatest amount of compression and smallest gap distance in the syndesmosis (0.7 ± 0.5 mm).

**Table 3.** Minimum and Maximum Clear Space Distances of All Dynamic Activities for Syndesmosis and Tibiotalar Joints.

| | Minimum, mm | | Maximum, mm | |
|---|---|---|---|---|
| | Mean | SD | Mean | SD |
| Lateral (syndesmosis) clear space | | | | |
| Calf raise | 1.1 | 0.6 | 2.0 | 0.6 |
| Squat | 1.3 | 0.8 | 2.3 | 0.9 |
| Torso twist | 0.9 | 0.3 | 2.2 | 0.7 |
| Box jump | 1.1 | 0.8 | 2.2 | 1.0 |
| Medial (tibiotalar) clear space | | | | |
| Calf raise | 1.8 | 1.3 | 2.7 | 1.2 |
| Squat | 1.2 | 1.2 | 1.7 | 1.3 |
| Torso twist | 1.2 | 0.8 | 2.0 | 0.8 |
| Box jump | 1.0 | 1.0 | 1.9 | 1.4 |

During the dynamic activities, the calf raise and squat activities caused opposing movement of the fibula (Table 3). Beginning at a neutral stance (0% completion) to then maximum plantarflexion (100% completion) of the calf raise, there was a significant decrease ($P = .001$) in syndesmosis gap distance from 2.0 ± 0.6 mm to 1.1 ± 0.6 mm. Conversely, the single-leg squat showed a significant increase ($P < .05$) in the syndesmosis gap from neutral (1.3 ± 0.8 mm) to maximum dorsiflexion (2.3 ± 0.9 mm). Minimum (0.9 ± 0.3 mm) and maximum (2.2 ± 0.7 mm) clear space distances observed during the torso twisting activity were also measured to be significantly different ($P < .05$).

During the box jump, the foot began in a near-neutral position during the flight phase (Pre) then plantarflexed in preparation for initial contact with the surface to mark the toe-strike phase (Figure 3). Average syndesmosis clear space was smallest at initial toe-strike contact (1.0 ± 0.9 mm). On landing and heel-strike, the ankle rapidly dorsiflexed, causing maximum distraction of the syndesmosis joint of 2.0 ± 0.9 mm.

### *Tibiotalar Gap (Medial Clear Space)*

Gap distances between the tibial malleolus and talar dome in the neutral stance decreased 0.3 mm with weightbearing, indicating only slight compression of the joint to support loading (Figure 6). Maintaining the foot in a weightbearing dorsiflexed pose showed no change in medial clear space (1.8 ± 1.5 mm), whereas a plantarflexed position caused slight distraction of the joint (2.1 ± 1.3 mm).

During the dynamic activities, minimum medial clear space was observed at the highest point of the calf raise activity (1.8 ± 1.3 mm) (Table 3). Single-leg squatting illustrated a general pattern of decreasing clear space from neutral standing to maximum dorsiflexion, with the minimum tibiotalar gap distance occurring at the deepest point in the squat (1.3 $\pm$ 1.6 mm), although this overall change in medial clear space was only 0.4 mm. There were no significant differences in joint space distances during torso twisting, with an overall change of 0.8 mm measured throughout the task. Tibiotalar clear space throughout the box jump showed a general decreasing trend in which the absolute minimum (1.0 $\pm$ 1.4 mm) occurred at the maximum ground reaction force.

## Discussion

The results of this study indicate that during static activities, there was no significant change in fibular or talar positioning relative to the tibia. However, during dynamic activities, notable changes in rotational and anterior-posterior translation occurred. Internal and external rotational change and superior-inferior shifts of the fibula were greatest during the twisting and box jump activities. These same activities also resulted in the largest ROM of the fibula relative to the tibia in the anterior-to-posterior direction. No dynamic athletic activity caused a lateral shift of the fibula relative to the tibia beyond the commonly accepted 2 mm threshold; a diagnostic threshold for identifying a widened or mal-reduced syndesmosis.[8,10,22,26]

The syndesmosis gap experienced narrowing during plantarflexion of the foot as the movement of the talus allowed for compression of the tibiofibular space. As the foot moved into dorsiflexion, the syndesmosis widened, but not beyond the 2-mm threshold for a clinically intact syndesmosis. Weightbearing proved to have an impact on the medial clear space, by decreasing the space in response to ground reaction forces. Furthermore, both static and dynamic movements for the single-leg squat and the box jump decreased the medial clear space.

These results support the hypothesis that an increase in lateral and medial clear spaces occur during dynamic weightbearing activities. The directional components of this shift were mostly rotational, anterior-posterior, and superior-inferior, not medial-lateral. This indicates that the syndesmosis does not naturally "widen" in the classic uniplanar sense of medial-lateral translation, which is of primary focus during 2D radiographic evaluation. Instead, the motion of the syndesmosis during the most common injury mechanism (dorsiflexion and external rotation) is largely that of external rotation and posterior shift of the fibula relative to the tibia.

The findings of this study provide clinicians and scientists with a better understanding of the physiology of the syndesmosis and medial clear space in healthy athletes during static and dynamic movements. It is also possible that current means of evaluation and surgical management do not take into account or attempt to restore normal syndesmosis mechanics. Ultimately, there may be a need to advance the understanding of fibular movement during syndesmotic injuries to include the impact of in vivo kinematic results on clinical decision making and suggest ideal constructs for the operative management of syndesmotic disruption based on that kinematic behavior.

### *Clinical Relevance: A Paradigm Shift*

Syndesmotic injuries are traditionally diagnosed through 2D radiography by examination of the medial-lateral tibiofibular space. Widening of this syndesmotic gap, beyond a 2-mm threshold, represents the instability of the ankle joint and disruption of the normal joint mechanics.[14] However, rotational changes of the fibula and talus are not readily visualized on 2D radiography, nor static 3D imaging. A study by Krahenbuhl et al demonstrated that radiographs could not reliably predict syndesmotic injuries because of this shortcoming in traditional imaging techniques.[21] The same group also reported that although magnetic resonance images have a sensitivity and specificity near 100%, the results do not directly correlate to clinical findings, since magnetic resonance imaging is a static study and dynamic instability patterns following syndesmotic injuries are complex and multifactorial.[21]

The shortcomings of 2D radiographs lie in the rotational nature of fibular displacements that occur during normal activities. Therefore, understanding the rotational and translational changes of the fibula during static and dynamic activities in healthy individuals is essential to providing care to the injured athlete. By considering these changes during dynamic activities, clinicians gain more perspective on the subtle changes that can occur at the distal tibiofibular joint when instability is not grossly apparent to indicate severe injury to the syndesmosis. Treatment of such injuries could be improved with a better understanding of the necessary rotational and translational movements of the fibula that should be afforded during fixation.

Historically, the fibula was thought to translate in the medial-to-lateral plane during dynamic maneuvers. As was observed with injury to the surrounding ligaments, compromising physiologic restraint of the joint. Instead, this study has shown that in the healthy uncompromised joint, the fibula primarily rotates internally and externally, while also translating in the anterior-posterior and superior-inferior directions during dynamic activities; medial-to-lateral translation of the bone was minimal. Twisting and box jump movements resulted in the most change in internal and external rotation of the fibula relative to the tibia and produced the greatest range of movement in the anterior-to-posterior direction. The degrees of change seen during the twisting and box jump movements resulted in 8.8 $\pm$ 2.5 degees and 9.3 $\pm$ 3.5 degees, respectively, of internal and external rotation. Box jumps also caused movement of the fibula in the superior-inferior plane, moving in a range of 2.5 $\pm$ 0.9 mm.

The goal in the clinical management of syndesmotic injuries is to restore the natural position of the fibula within the incisura and allow healing of the ligamentous structures, but not necessarily to directly repair or reconstruct the surrounding ligaments. Surgical repair intends to allow restoration of normal joint mechanics, but this does not appear to occur following current fixation constructs such as rigid fixation (eg, screws), flexible fixation (eg, suture buttons), and hybrid methods.[5] These current methods of repairing syndesmotic injuries and assessing stability focus on the reduction of the distal tibiofibular joint space to prevent widening and ankle instability. However, the natural rotational changes of the fibula after syndesmotic injury are likely not adequately addressed when using current constructs because none of them re-create the normal, functional kinematic environment of the joint.

The biomechanical study of Clanton et al compared current techniques for syndesmotic repair in which they randomly performed screw fixation, single suture-button fixation, and divergent suture-button repairs on cadaveric specimens.[5] The results showed that the fibula externally rotated significantly in all of the repair groups when compared to the intact state.[5] The 3 repair techniques provided torsional stability to the injured syndesmosis, but none restored rotational stability to the healthy intact state of the distal tibiofibular joint.[5] It is likely that anatomical repair strategies that more effectively approximate normal kinematics and allow for accelerated on-field rehabilitation and return to sport will be advantageous in the management of syndesmotic injuries.

Another cadaveric analysis by Clanton et al evaluated the weightbearing kinematics of intact cadaveric syndesmosis specimens.[6] Their study revealed, under simulated full body weight, that the fibula has 4.3 degrees of total rotation in the axial plane and translates a total of 3.3 mm in the sagittal plane.[6] Although the in vivo measurements presented in this study were less than the values shown by Clanton et al, adding internal and external rotation to the physiologic load of their cadaveric specimens resulted in rotational and translational changes to the intact syndesmosis similar to those measured in the dynamic torso twisting movement of this study.[6] Internal rotation increased 1.5 $\pm$ 0.7 degrees, whereas external rotation increased 2.8 $\pm$ 1.2 degrees. Similarly, increases in internal and external rotations of the fibula were also accompanied by 0.7 $\pm$ 1.7 mm and 2.6 $\pm$ 1.5 mm of anterior and posterior translation, respectively.

## *Clinical Impact: Redefining Ideal Constructs*

The combination of these cadaveric and biomechanical studies suggests that current surgical fixation of the syndesmosis may not adequately address rotational motions of the fibula during rehabilitation. Clanton et al's biomechanical analysis showed that all 3 fixation constructs had significantly more external rotation compared with the intact state during physiologic load and external rotation testing.[5] Comparing the same group's cadaveric data to this biomechanical study reveals that an intact syndesmosis allows for 2.8 degrees of external rotation under physiologic load, leaving 4.3 to 6.9 degrees of external rotation unaccounted for during repair. As a result, the optimal construct would likely restore normal rotational and translational kinematics of the fibula in addition to serving as a tether to lateral displacement.

The ideal construct for the repair of the injured syndesmosis should focus on anatomic reconstruction of injured ligaments, reducing the distal tibiofibular gap, and restoring physiologic constraints to the joint. Depending on the grade of the injury, available suture anchor and tape constructs might serve to augment the associated ligaments and prevent extremes of displacement, and related hypertrophy, similar to the function for Brostrom augmentation.[31] Internal braces have been shown to act as secondary stabilizers of ligaments during reconstructive procedures of the anterior cruciate ligament, medial collateral ligament, and ulnar collateral ligament.[2,7] Support is growing for their use as a novel technique in foot and ankle, sports, and hand procedures, with some studies reporting a quicker return to activity and better outcomes in athletes.[1,4,11,19]

These data contribute to the growing body of literature suggesting that current surgical repair constructs for syndesmotic injuries, although effective, may not functionally restore the native biomechanical environment. The development and testing of alternative or adjunctive techniques for syndesmotic fixation has the potential to safely accelerate time to weightbearing, on-field rehabilitation, and return to play protocols. The model created by this study may translate well to an ex vivo biomechanical model to test various injury patterns and repair constructs, leading to optimal constructs.

## *Limitations*

Some limitations were inherent in this study. The sample size (n = 6) could be considered relatively small compared to other studies with published kinematic data. Investigations based on the collection and processing of stereoradiography are time and labor intensive in proportion to the number of subjects and activities. Provided a choice between collecting a larger number of subjects or activities, we chose a greater number of activities to more broadly investigate the activity dependence of dynamic ankle kinematics. Additionally, the high accuracy of the HSSR system and the closeness in anthropometric data among the subject cohort allowed us to keep the healthy participant population relatively small. To minimize deviations, a single person performed bone tracking to limit inter-tracker variability. Internal and external rotations proved to be the most variable measure of fibular kinematics, and this variability would unavoidably carry into the closest-point measurement of lateral clear space. Even so, values for fibular rotation were similar to prior in vivo work done by Beumer et al[3] and Wang et al.[25] Although the kinematics of the syndesmosis and tibiotalar joints varied across subjects and activities, the joint distraction measured in the medial and lateral sides was small and fairly consistent. The small values of clear space widening illustrate the stability the surrounding ligaments provide in limiting excessive separation of the bones and maintaining the integrity of the ankle joint. Overall, joint gap spaces did not exceed 2.3 $\pm$ 0.9 mm and 2.7 $\pm$ 1.2 mm for the syndesmosis and tibiotalar joints, respectively. These values fall well within the normal range of syndesmosis gap widening for a healthy ankle joint, as identified by clinicians via radiographic measurements.[16] Furthermore, gap measurements made during standing nonweightbearing were very close to values measured from the supine CT of each subject, providing confidence in the measured gaps during activities.

## Conclusion

Under physiological loading, most of the fibular motion was rotational and anteroposterior, rather than the lateral translation that causes widening of the syndesmosis. The talus also rotated significantly within the mortise, but the combination of joint load and ligamentous constraints of the healthy ankle limited large translational shifts of the bones that would otherwise detrimentally widen the medial clear space. Most assessments of syndesmosis fixation focus on lateral displacement of the fibula from the tibia in a 2D radiographic image. However, the physiologic movements of the ankle mortise during dynamic activities suggest far greater magnitudes of rotational motion, anteroposterior shifts, and inferior-superior shifts, rather than just syndesmotic widening in the lateral direction. These data support a potential advance in our understanding of fibular excursion during dynamic activities and how implant device constructs are designed to restore native mechanics. We believe the focus of stabilizing and rehabilitating syndesmotic injuries should shift from solely assessing the restriction of lateral translation and toward the restoration of normal physiologic movements of the fibula and ankle mortise in all degrees of freedom.

### Ethics Approval

Ethical approval for this study was obtained from the University of Denver Institutional Review Board. Approval #: 853976-4.

### Declaration of Conflicting Interests

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### ORCID iD

Jonathan Bartolomei, MS, https://orcid.org/0000-0001-9318-4870

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