An Automated Registration Framework for Reducing Alignment Error in Syndesmotic Instability Detection using Bilateral Weight-Bearing CT

Kareem Omran[1], Cesar de Cesar Netto[2,3], Nacime Mansur[2,4], Grayson Talaski[2], Kepler Carvalho [2,3], Kevin Dibbern[1,2]
[1]University of Nebraska Medical Center, Omaha, NE, [2]University of Iowa, IA, [3]Duke University, Durham, NC, [4]Union Memorial Hospital, Baltimore, MD
Email: komran@unmc.edu

Disclosures: C. de Cesar Netto: 6; Paragon28. K. Dibbern: 6; Paragon28. Et alia: None.

Introduction: Subtle syndesmotic instability presents significant diagnostic difficulties with standard of care X-ray and CT imaging frequently yielding inconclusive results. This presents a serious problem when undiagnosed as untreated patients may develop persistent pain and degenerative ankle joint changes. Emerging research has demonstrated the potential of bilateral weight-bearing CT (WBCT) imaging for subtle instability detection by using reference measures from the uninjured contralateral ankle. Historically, studies have indicated that clinically significant fibular translation can be as low as 2 mm under stress, but recent work evaluating syndesmotic widening in subtle injuries has reported instability at less than one millimeter in magnitude, emphasizing the importance for highly precise alignment methodologies [1,2]. Advances in automated anatomical coordinate systems (ACS) have been shown to reduce variability of measurement [3]. However, given the minute scale of displacement following injury, segmentation variability, imaging artifacts, and subtle variation in coordinate system definitions may introduce measurement errors of similar magnitude to the clinically meaningful displacement signals being detected. This technical limitation carries direct diagnostic and surgical implications: contralateral referencing approaches that fail to account for such systematic errors and anatomical variability in the contralateral reference risk compromised diagnostic accuracy and may provide misleading guidance for intraoperative reduction procedures. To overcome these challenges, an automated bilateral tibiofibular registration pipeline was developed and validated that combines ACS initialization with iterative closest point (ICP) refinement algorithms to minimize registration errors and accurately isolate true pathological displacement patterns. The primary objective of this study was to create a standardized, automated analytical framework for syndesmotic injury characterization from routinely acquired bilateral WBCT datasets of the foot and ankle. Secondarily, it sought to quantify how subtle anatomical differences in contralateral limbs influence variability in positional information derived from anatomical coordinate systems.

Methods: This IRB approved study evaluated thirty-six fresh-frozen through-the-knee cadaveric specimens (22 Male), which underwent bilateral weight-bearing CT imaging with 356 N of axial loading in a custom loading frame. Initial imaging was performed with intact ligamentous structures, followed by repeat scanning after sectioning syndesmotic stabilizers (anterior inferior tibiofibular ligament (AITFL), interosseous ligament, the distal 3 cm portion of the interosseous membrane, and posterior inferior tibiofibular ligament (PITFL)). The deltoid ligament complex, lateral collateral structures, and superior peroneal retinaculum remained undisturbed to create an isolated syndesmotic injury model. Tibial and fibular geometries were segmented from each scan and aligned utilizing an automated ACS toolbox to define consistent mediolateral, anteroposterior, and superoinferior reference axes[3]. The injured-side tibia underwent rigid coregistration with its contralateral counterpart using ICP. The ICP derived transform was applied to the injured fibula to maintain its original spatial relationship to the tibia but now within the same contralateral reference frame. Direct ICP registration from the control to the transformed injured fibula yielded injury-specific displacement parameters, with transforms decomposed into Cardan angles and summarized by translation magnitude (L2 norm) and rotation magnitude (quaternion-derived).Root mean square error (RMSE) of both tibial and fibular registrations was quantified. To quantify anatomical variation between limbs, repeated scanning of individual specimens (pre- and post-destabilization) was utilized to provide ground-truth assessment of residual ACS misalignment from scanning and segmentation variability and the ability of ICP refinement to correct it (Figure 1).

Results: In the analysis of contralateral injury, ACS alignment alone produced mean tibial registration error of 2.14 ± 0.70 mm. Following ICP refinement, tibial RMSE decreased to 1.41 ± 0.56 mm, representing a 32.1% improvement ($p < 0.001$). Fibular alignment demonstrated a similar effect, with RMSE improving from 1.53 ± 0.50 mm after ACS alignment to 0.97 ± 0.26 mm after ICP (34.5% reduction, ($p < 0.001$). Overall, relative to the contralateral control tibia, the destabilized fibula translated by an average magnitude of 2.99 ± 1.64 mm relative to the contralateral tibia and rotated by 3.58 ± 1.69° across all specimens. Validation using repeated scans of the same limb confirmed that these improvements were not attributable to true anatomical differences between contralateral feet, but rather to residual ACS misalignment. In this setting, tibial RMSE improved from 1.56 ± 0.58 mm to 1.20 ± 0.50 mm after ICP (23.5% reduction, $p < 0.001$), and fibular RMSE decreased from 1.14 ± 0.46 mm to 0.739 ± 0.33 mm (32.8% reduction, $p < 0.001$)(Table 1).

Discussion: This study demonstrates that while ACS toolboxes reliably standardize bone axes, residual variability from segmentation and imaging distortion introduces small alignment errors that can be of similar magnitude to the signal of interest, in this case, syndesmotic injury. In both contralateral and same-limb experiments, pre-ICP registration errors were frequently greater than one millimeter, comparable to the magnitude of fibular displacement observed after syndesmotic destabilization. Without correction, such noise could mask true injury-induced changes. Incorporation of ICP refinement reduced alignment error by roughly one-third, which strengthens the validity that differences reflected ligamentous injury rather than technical variability. Contralateral analysis of fibular movement further reduces variability by removing error from replicated tibial coordinate system definition. After refinement, the destabilized fibula exhibited a reproducible pattern of inferior and posterior translation with associated external rotation, averaging a total of 2.99 mm of translation and 3.58° of rotation relative to the intact side. Same-limb validation confirmed that improvements were not purely attributable to true anatomical asymmetry between left and right ankles but also arose from accumulated variability in measurement from repeated ACS assignment. This distinction is critical, as it establishes that contralateral referencing can be made reliable provided that alignment distortion is accounted for. The implications extend beyond diagnosis. Intraoperatively, syndesmotic reduction is often judged visually or fluoroscopically. The ability to compare a destabilized fibula to a precisely registered contralateral reference introduces the possibility of patient-specific, three-dimensional surgical guidance. Without adequate understanding of this functionally loaded positioning, persistent malreduction rates are reported to range from at least 15 up to 50% and may be higher when quantitatively analyzed [4]. Future work should evaluate the impact of varying magnitudes of rotational and translational malreduction and residual instability on subsequent ankle degeneration.

Clinical Relevance: This automated bilateral registration pipeline enables clinicians to leverage routinely collected weight-bearing CT data for precise contralateral referencing, potentially improving both diagnostic accuracy for subtle syndesmotic injuries and operative reduction guidance in a clinical environment where malreduction rates currently range from 15-50%.

References: [1] J. R. Close, JBJS, vol. 38, no. 4, pp. 761–781, July 1956. [2]. De Cesar Netto et al., JBJS 107(4):p397-407. 2025 doi: 10.2106/JBJS.24.00199 [3] A. C. Peterson, K. M. Kruger, and A. L. Lenz, Front. Bioeng. Biotechnol., vol. 11, 2023, doi: 10.3389/fbioe.2023.1255464. [4]. Ray R, Koohnejad et al. GF Foot Ankle Surg. 2019 doi: 10.1016/j.fas.2017.10.005.

Table 1. Registration accuracy for same-limb tibia and fibula before and after ICP. *Total translation* = 3D displacement magnitude (L2 norm).All improvements were significant (*$p<0.001$*).

Bone	RMSE before[1]	RMSE after[1]	Mean reduction	Total Translation[1]
Tibia	1.56 ± 0.58	1.20 ± 0.50	0.37 mm (24%)	0.91 ± 0.66
Fibula	1.14 ± 0.46	0.74 ± 0.33	0.41 mm (33%)	2.37 ± 1.31

[1]Mean ± SD (mm)

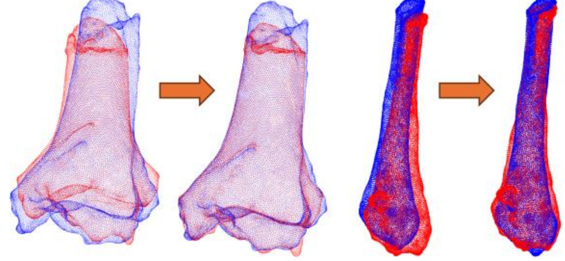

Figure 1. Example of same-side tibia and fibula alignment before (left) and after (right) ICP registration. The same fibula and tibia are shown in their control (blue) and destabilized (red) states, with tibial RMSE improving from 2.887 mm to 1.199 mm and fibular RMSE from 2.651 mm to 1.117 mm.