Associations Between Carpal Kinematics and Carpal Ligament Damage: A Quantitative Dynamic MRI Study

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Introduction: Carpal instability, resulting from acute trauma or sustained wear of the wrist, impedes the daily activities of an estimated 15 million Americans [1,2]. This condition is primarily characterized by misalignment and movement abnormalities of the carpal bones. Accurate diagnosis of carpal instability is challenging due to the wrist's complex structure and the shortcomings of traditional radiography and magnetic resonance imaging (MRI) techniques, which only provide static views. These methods fail to capture the complex joint dynamics that are essential for a comprehensive clinical assessment of joint instability. As compared to other dynamic imaging modalities, dynamic MRI (dyMRI) offers time-resolved 3D imaging without the need for ionizing radiation and is therefore an appealing choice for dynamic wrist assessment. This exploratory study aims to investigate the association between dyMRI metrics and ligament health in a cohort of participants with and without wrist injury.

Methods: *Participants:* The study included 34 participants: 20 with wrist injury and 14 without a history of wrist injury. All participants provided written consent into an IRB-approved study. *MRI Acquisition:* MRI scans were conducted on clinically utilized 3 Tesla scanners (Premiere, GE Healthcare, Waukesha, WI). The dyMRI protocol, based on methods by Zarenia et al [3] and Sharafi et al [4], first acquires a static high-resolution image to provide a reference for the subsequently acquired rapid 3D 2-point Dixon MRI sequence (Fig. 1). The participants performed dynamic wrist motion during the rapid acquisition. Images were acquired with subjects freely moving their wrist in radial-ulnar deviation and flexion-extension. Visual guidance was provided to pace wrist movements. A standard morphologic clinical MRI series was also acquired to assess the presence and severity of articular degeneration and ligament tears [5].
Dynamic Metric Derivation: As detailed in prior studies [3,4], dyMRI carpal kinematics were derived using deep-learning bone segmentation, followed by a point-cloud-based registration within a radius-based coordinate system (Fig.1). Final dyMRI metrics were then computed through polynomial fitting of capitate-referenced kinematic profiles of the scaphoid and lunate. This produced 120 metrics for each subject (as reported in Sharafi et al [4]), detailing the motion of the scaphoid and lunate relative to the capitate, spanning radial-ulnar deviation and flexion-extension motions.
Carpal Ligament Health Classification: An orthopaedic radiologist evaluated 10 wrist ligaments from the static clinical MRI. Four extrinsic and six intrinsic ligaments were assessed. Each ligament was classified as 'damaged' or 'normal' .
Statistical Analysis: Associations between dyMRI metrics and ligament health were explored using Mann-Whitney U-tests. Twenty key metrics, showing stability in cohorts with minimal damage, were used in initial assessments. Additionally, multi-variate logistic regression and principal component analysis (PCA) were employed, with PCA reducing the dyMRI metrics to a set achieving over 90% explained variance.

Table1 Notable Mann-Whitney U-scores and associated p-values for tests of dynMRI metrics against binary ligament damage classifications. Cohen's D effect sizes and predictive model AUC scores are also provided for each comparison. Targeted ligaments (Lig.= SL: Scapholunate, DSTL: dorsal scapholunotriquetral, DICL: dorsal intercarpal ligament), principle movement direction (Mov.=[RUD: Radial-Ulnar Deviation, FE: Flexion-Extension), dynMRI measurement (Meas.=[T: translation, A: angle]), metric direction (Dir.=[rotation axes for angles - RU: radial-ulnar, SP: supination-pronation, FE: flexion-extension and direction for translations - RU: radial-ulnar, VD: volar-dorsal, DP: distal-proximal]), and fit component (Comp=[m/l for mth polynomial component of lth order fit]) are provided.

Lig.	Mov.	Meas.	Dir.	Bone	Comp	p	D	AUC
SL	RUD	T	DP	S	2/0	0.001	1.19	0.84
DSTL	FE	T	DP	L	2/0	0.004	-1.06	0.81
DICL	FE	T	RU	L	1/0	0.005	-0.91	0.82

Results: Nearly 20% of the individual dyMRI metrics (23/120) displayed a significant, $p<0.05$, association with ligament damage. Of these identified associations, the three most significant associations with ligament damage are identified in Table 1. The strongest association was between scapholunate ligament damage and distal/proximal scaphoid positioning during radial/ulnar deviation movement. Performance metrics, including Cohen's D, AUC measures from ROC curves, and P-values from simple logistic regression modeling results, as shown in Table 1, underscore the strength of these associations.

Multi-variate logistic regression modeling of dyMRI metrics against ligament damage provided promising preliminary results of the proposed dyMRI methodology for identification of wrist pathology. Specifically, dyMRI metrics demonstrated an ROC AUC of 0.79±0.24 for scapholunate ligament damage classification. Figure 2 provides an illustrative case, where the clinical MRI evaluation depicted a tear in the scapholunate ligament and a near-absence of the dorsal scaphotriquetral ligament. Correspondingly, the computed dyMRI model delivered damage probability ratios of 0.71 and 0.65 for the scaphololunate and dorsal scaphotriquetral ligaments, respectively.

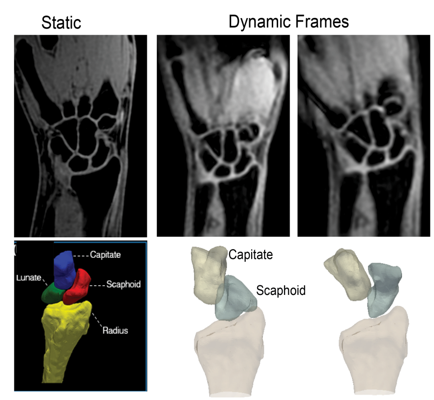

Figure 1: Top Row: A static image and dynamic images displaying ulnar deviation. Bottom Row: Bone surface meshes indicating capitate movement in a radius-based coordinate system.

Discussion: The strong associations observed between specific dyMRI metrics and damaged ligaments underscore dyMRI's capability to provide a more nuanced understanding of carpal instability. This approach has the potential to offer a more direct and potentially accurate method for assessing the health and function of wrist ligaments. Furthermore, the preliminary multi-variate modeling highlights a promising avenue for future research, hinting at the capability of comprehensive dyMRI metrics to quantitatively identify specific sources of instability-inducing ligament damage.

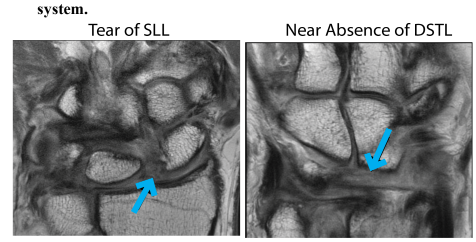

Figure 2: Example clinical MRI demonstrating ligament damage in a single subject.

Clinical Significance: The present study's findings emphasize the potential utility of dyMRI as a diagnostic instrument to accurately pinpoint specific ligaments responsible for carpal instability, which could lead to targeted treatments and reduce current trial-and-error based interventions. In addition, this non-invasive, non-ionizing imaging technique may provide a means to improve rehabilitation protocols and longitudinal monitoring of carpal instability.

References: [1] *Obrien et al, J. of Hand Therapy,31(3):282–286, 2018*, [2] *Ootes et al, Hand,7(1):18–22, 2012*, [3] *Zarenia et al, PlosOne, 17(6):e0269336, 2022* [4] *Sharafi et al, arXiv preprint arXiv:2305.16423, 2023* [5] *Hayter et al, Journal of Magnetic Resonance Imaging, 37(5):1005–1019, 2013*

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