Volumetric Dynamic Magnetic Resonance Imaging for Functional Kinematic Assessment of the Wrist

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INTRODUCTION: Static MRI examination of the wrist, as performed routinely in clinical practice, provides excellent spatial resolution and contrast for characterizing bone and soft tissue. However, initial stages of wrist instability often manifest only during active motion, for example with snapping or sudden changes in the intercarpal alignment, and do not show visible abnormalities on routine static examinations. Real-time MRI techniques have been proposed for the dynamic examination of patients experiencing pain during movement of the wrist [1,2]. However, the 2D nature of most real-time methods makes it difficult to capture out-of-plane translations or rotations of the carpal bones. Existing dynamic 3D MRI methods, on the other hand, do not reach the required temporal resolution and image quality to properly capture sudden and rapid motion abnormalities.
In this work, we describe a novel approach for rapid dynamic volumetric wrist examination, based on assembling 2D real-time MRI data into 3D snapshots.

METHODS: Coil and Platform Design: A custom-tailored wrist coil was created by repurposing a "blanket" coil that was built previously at our center[3,4]. The wrist coil was designed to wrap tightly around the wrist in the fashion of a medical support brace. The coil has eight high-impedance elements (ø = 6cm) that are geometrically overlapped and arranged in 2 rows of 4 elements. A support platform was designed with a 3D printer to guide the wrist movement over multiple repetitions. The platform includes an MRI-visible marker, used for automatic alignment of the 2D slices from each repetition (see below). The forearm is immobilized using Velcro straps and cushions, enforcing that only the wrist joint moves during maneuvers (Fig 1c/d). Two tubes were integrated into the moving part of the platform and filled with pineapple juice, whose bright MR signal (Fig 1b) was used to track the wrist position during motion.

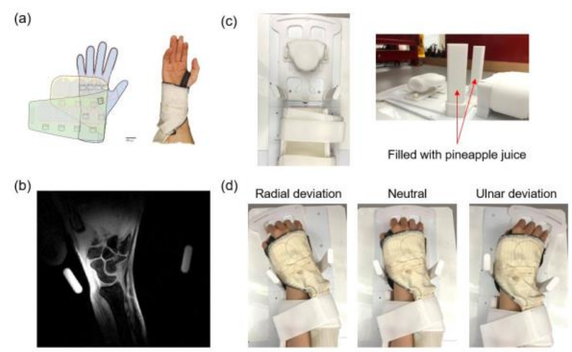

Fig 1: (a) 8-channel wrist coil. (b) Representative T1-weighted coronal image of the wrist. (c) 3D-printed support platform to guide the ulnar-radial deviation in a front (left) and side (right) view. Tubes filled with MRI-visible pineapple juice mounted on the platform move with the wrist and are used as marker for slice alignment. (d) Example of experimental setup during ulnar-radial deviation, showing both the wrist coil and platform.

Experiments: For technical development and demonstrating feasibility, we scanned healthy volunteers (after obtaining informed consent) on a clinical 3T scanner (MAGNETOM Prisma, Siemens Healthineers). Volunteers were asked to perform continuous ulnar-radial deviation during the acquisition. Dynamic data were acquired with an RF-spoiled 2D FLASH sequence, which uses radial sampling with interleaved acquisition order over five successive images[5]. Each interleave included 13 equidistant angular projections covering 360°. 30 slices were sequentially acquired in coronal orientation. The acquisition scheme was repeated 40 times for each slice to properly capture the continuous motion. Spectral fat suppression was performed prior to each repetition. Relevant parameters included: FOV 220x220mm^2, resolution 1x1mm^2, slice thickness 2mm, FA 4°, TR/TE 3.69/2.21ms, BW 500Hz/px, total duration 5:12min.

Image Reconstruction: Dynamic images were reconstructed slice-by-slice using the GRASP algorithm[6], which applies a total-variation constraint along the time dimension. 13 projections were combined into each image frame, resulting in a temporal resolution of 48ms/frame. To fuse the dynamic 2D images into a dynamic volume, the position marker was segmented in each image using a U-Net. The Jaccard similarity index was calculated for segmentation masks of each frame from the different slices. Frames with the highest similarity score were assigned to the same wrist position and stacked into a 3D volume.

RESULTS: Fig 2 shows the assembled dynamic volumes for different wrist angular positions, for a representative volunteer. After the alignment, the position markers remain in a consistent position for all slices. The carpal bones are properly aligned, as seen especially in the axial view, which demonstrates the accuracy of the proposed marker-based alignment procedure. In this way, we are able to obtain a smaller movement between the adjacent dynamic volumes, which has the potential to enable the detection of sudden abnormalities in wrist instability.

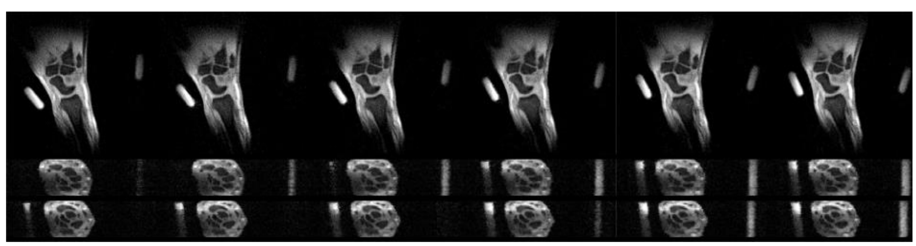

Fig 2: Selected frames of the assembled 3D dynamic wrist volumes at difference wrist angular position during ulnar-radial deviation, for a representative volunteer. The shown volume frames are 6 steps apart.

DISCUSSION: Here, we proposed a new approach to obtain dynamic 3D wrist volumes by acquiring 2D real-time images and fusing images from different slices into 3D volumes using auto-detected marker position. The approach uses a 3D-printed platform that can be positioned freely in the scanner to maximize patient comfort and does not require additional optical or electronic sensors. Ongoing work is focusing on extracting the trajectories of carpal bones during continuous movement to characterize pathology. Given the high contrast obtained with fat suppression and the low anisotropicity compared to previous approaches, individual carpal bones can be segmented in each dynamic volume using tools such as itkSNAP[7]. To improve the accuracy of the kinematic assessment, we plan to utilize a static high-resolution scan for generating a reference 3D model of the wrist bones, which can then be used as strong morphological prior for determining the shape and location of individual bones in the dynamic volumes[8]. To this end, the next step will be to find a poly-rigid transformation model for mapping the reference carpal bone shapes onto the dynamic volumes to obtain a dynamic series of binary segmentations for each carpal bone, which represent the kinematic motion to be analyzed.

SIGNIFICANCE/CLINICAL RELEVANCE: This work demonstrates the feasibility of obtaining real-time dynamic MRI volumes during continuous wrist motion and has the potential to be used for the quantitative analysis of carpal kinematics in order to detect and characterize wrist abnormalities.

REFERENCES: [1] Frahm J, et al, Invest Radiol 2019;54:757. [2] Shaw CB, et al, PloS one. 2019;14:e0222704. [3] Zhang B, et al, Nat Biomed Eng 2018;2:570. [4] Zhang B, et al, ICEAA 2019 p. 459-0464. [5] Zhang S, et al, JMRI 2010;31:101. [6] Feng L, et al, MRM 2014;72:707. [7] Yushkevich PA, et al, NeuroImage 2006;31:1116. [8] Abbas B, et al, Proc.SPIE 2019 vol. 10949.

ACKNOWLEDGEMENTS: This work was supported by NIH R21 AR080325.