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Technical note

A method for carpal motion hysteresis quantification in 4-dimensional imaging of the wrist

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ABSTRACT

Introduction: Carpal bones motions exhibit hysteresis that is dependent on the direction of wrist motion, which can be seen during 4-dimensional (3D plus time) imaging of the wrist. In vitro studies have demonstrated the phenomenon of carpal hysteresis and have reported that hysteresis area increases with carpal instabilities. However, their techniques required implantation of bone markers and thus cannot be used clinically. The objective of this study is to use noninvasive 4-dimensional computed tomography (4DCT) technique to quantify carpal hysteresis, and to determine the reliability of this method.
Method: A cadaveric wrist mounted on a custom motion simulator was imaged using a dual-source CT scanner while undergoing periodic radioulnar deviation. Ten image phases of this motion was reconstructed through retrospective cardiac gating. The rotational angles of scaphoid, lunate and triquetrum in each phase were derived through manual registration using Matlab after segmenting the bones in Analyze 8.1. These angles were then plotted against global wrist positional angles to produce the hysteresis curves and the area was calculated. The image segmentation and measurements were repeated by 2 raters to derive intra- and inter-rater reliability assessments.
Results: The hysteresis area was found to be larger in the lunate (96.5 deg^2) followed by triquetrum (92.3 deg^2) and scaphoid (67.5 deg^2). The measurement of the total hysteresis area of the scaphoid had the highest reliability with intra- and inter-rater reliability of 95.5% and 95.4% respectively.
Discussion: We have demonstrated that our approach of using 4DCT imaging can be used to assess and quantify the hysteresis of the carpal motion with good reliability.
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1. Introduction

Dynamic or predynamic carpal instabilities of the wrist [1] only demonstrate abnormalities during motion. This would explain the lack of observable pathologies in static radiographic in patients with wrist pain. Currently, real-time fluoroscopy is the only imaging modality that can be used to detect dynamic abnormalities in these patients [2]. However, fluoroscopy suffers from several drawbacks such as low image resolution, images limited to 2-dimensions, and the inability to objectively quantify any abnormalities if present. Radiation exposure is another drawback in fluoroscopy as well as CT scan. However, as the wrist is not a radiation-sensitive body part, the effect of radiation exposure is not so significant.

Previous studies by Tay et al. [3,4] and Neo et al. [5] have shown the feasibility of using CT imaging to achieve dynamic real-time or 4-dimensional computed tomographic (4DCT) imaging of the moving wrist joint. Several other studies have also reported various techniques using 4DCT imaging to investigate the kinematics of the wrist joint [6–9]. However till date, there has been no report on using noninvasive 4DCT method to assess and quantify hysteresis of the carpal bones. Investigating the hysteresis phenomenon exhibited by the carpal bones during motion could be one of the methods to identify changes to the carpal motion due to the ligament injuries that may be present. Such phenomenon has been demonstrated in other in vitro carpal kinematics studies, and in these studies they have reported that the total carpal hysteresis area is dependent on the integrity of the ligaments [10,11]. It was shown that the hysteresis area increases with carpal instabilities. However, the techniques used were invasive and required the implantation of bone markers

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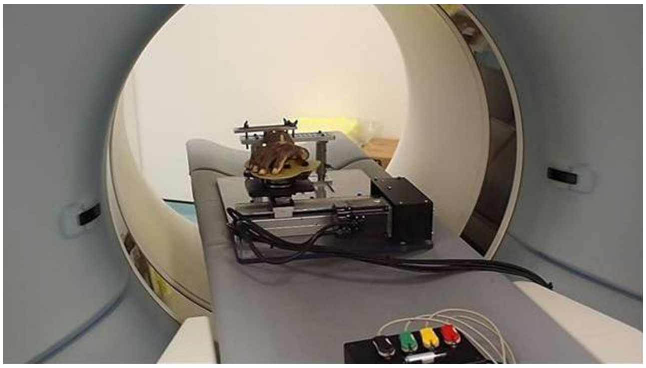

Fig. 1. Cadaveric forearm on the motion platform.

which cannot be used clinically. 4DCT scanning, on the other hand, is noninvasive and has potential for direct clinical translation.

In this paper, we report on a method using 4DCT imaging to dynamically scan the cadaveric wrist joint during periodic radioulnar motion, and to quantify the carpal hysteresis effect that was exhibited by the wrist.

2. Materials and methods

2.1. Equipment setup

With the approval from our Institutional Review Board, the study was performed using cadaveric forearm with no history of wrist injury and instability.

A custom-made motion simulator device powered by a servo motor (Mitsubishi Electric Corp, Tokyo, Japan) was used in this study. This device was similar to the device used in the previous studies [3–5]. The cadaveric specimen was securely mounted onto the linear slider of the motion platform and was set to move in periodic radioulnar deviation (RUD) at frequency of 37 cycles per minute (cpm) through a maximum arc of 30° (10° of radial deviation and 20° of ulnar deviation) (Fig. 1). The servo motor system was controlled using Twin-CAT I/O real-time driver software (Beckhoff Automation GmbH, Verl, Germany) (Fig. 1).

The moving wrist was scanned using a 64-slice Dual-Source CT scanner (Somatom Definition, Siemens Healthcare, Forcheim, Germany) with retrospective gated clinical CT protocol at pitch value 0.2, 60 mAs/rot, and 0.33 of rotation time. The motion frequency selected was calculated based on Ohnesorge et al. study [12], where the maximum pitch value was given by:

$$\text{Pitch} \leq \frac{M-1}{M}\frac{\text{Trot}}{\text{Tp}} \quad (1)$$

Using Eq. (1), for 0.2 pitch value the minimum motion frequency is 37.5 cpm. To avoid interpolation errors [12,13] a lower frequency of 37 cpm was selected.

2.2. Motion analysis

In order to measure the true dynamic motion of the wrist, the specimen was moved continuously in RUD direction for 10 cycles, with the first 9 cycles were used to pre-condition the specimen and the 10th cycle was captured and used for motion analysis. Data sets were collected and reconstructed at ten different phases of one full motion cycle with a slice width of 0.6 mm, 140 mm field of view, 512 × 512 pixel, a sharp reconstruction kernel of B20f and the voxel dimension was resized to 0.2 (x) by 0.2 (y) by 0.2 (z) mm. The phases refer to the volume image captured at different time points in a full motion cycles. In other words, at every one tenth of a cycle from radial deviation to ulnar deviation and back to radial, a volume image was reconstructed.

The contours of each proximal carpal bone (scaphoid, lunate and triquetrum) in every phase were then segmented from the CT volume images using Analyze 8.1 (Mayo Foundation for Medical Education and Research, Rochester, MN, USA). The segmentation of the carpal bones was performed by defining the area of interest on the rendered 3D images with minimum threshold of 175 through semi-automated segmentation process. Through this method, the

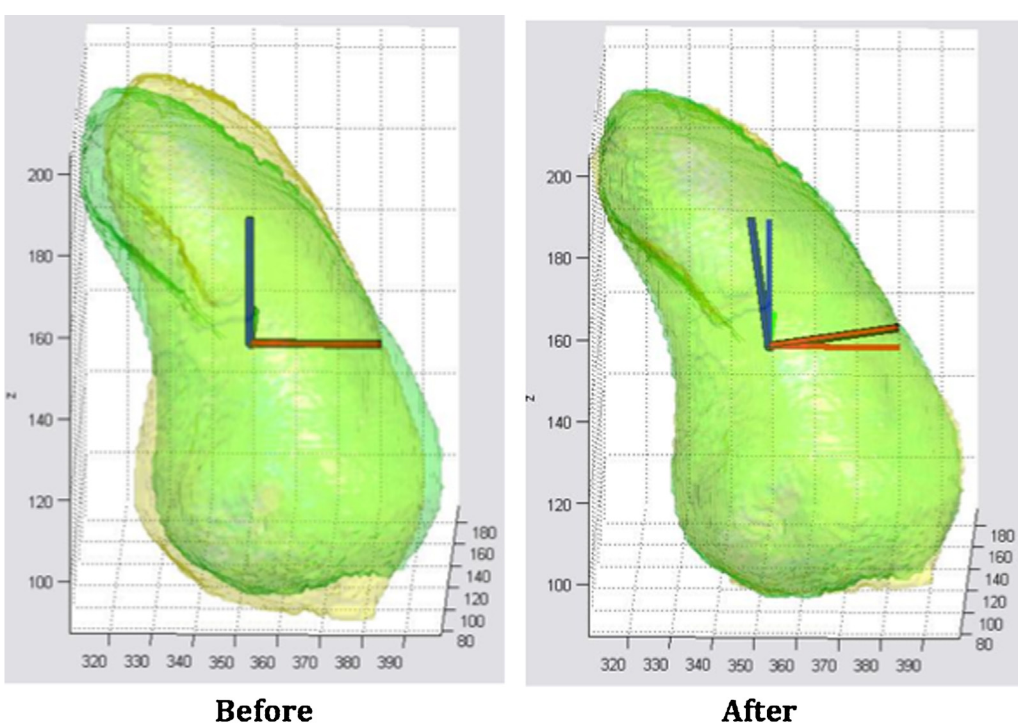

Fig. 2. Manual registration of the scaphoid (coded in Matlab) in Coronal view – before (left) and after (right) registration.

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