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Optimizing Web-Based Viewer of 4D CT Scans for Clinical Assessment of Injured Wrists*

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Abstract— **Wrist injuries pose a unique challenge for patients and providers. Due to the complexity of the wrist, it is difficult to determine if a wrist injury is primarily a bone fracture or soft tissue damage. The scapholunate interosseous ligament (SLIL) is an important ligament in the function of the wrist, and it is also one of the most common soft tissue injuries in the wrist. Wrist arthroscopy is the gold standard for assessing injuries of the scapholunate joint; however, it is an invasive procedure. Recent advances in dynamic imaging with 4D Computed Tomography scans allow for the assessment of SLIL injuries non-invasively. Unfortunately, 4DCT scan data can be difficult to disseminate to clinical practitioners due to the large amount of data generated and the complexity in visualizing the data. A web-based application has been developed to interactively assess 4DCT scans of patients with suspected SLIL injury. Due to the magnitude of data and the diversity of hardware platforms used to visualize the data, the images are preprocessed with a rendering engine and presented in a pseudo-3D visualization paradigm where the user can interactively explore the 3D data without transmitting the entire dataset to the local computer. The technology has been used to assess 27 patients.**

I. INTRODUCTION

The wrist is one of the most complicated joints of the body consisting of eight small bones organized in two rows [1]. The large dynamic range of motion from the wrist is enabled by the intricate interaction of bones within the constraints of a network of ligaments. It is unsurprising that injuries of the wrist can be difficult to diagnose and manage given the topological and functional complexity of this joint [2]. Imaging, particularly dynamic imaging, allows clinicians to evaluate the structural and functional integrity of the wrist without directly intervening through invasive diagnostic procedures. Unfortunately, it can be challenging to acquire and distribute dynamic imaging datasets to clinicians in an out-patient environment. This paper describes the ongoing engineering effort to provide web-based presentation of dynamic imaging datasets to surgeons as part of the clinical evaluation process in diagnosing the severity of a wrist injury and planning the appropriate treatment strategy.

While traditional radiographic imaging is an excellent technology for the assessment of fractures, many wrist injuries will have some amount of soft tissue damage. Scapholunate ligament injury is the most common soft tissue injury of the wrist. The scapholunate joint is very important in ensuring a stable range of motion of the wrist. When the scapholunate interosseous ligament (SLIL) is injured, there is a well-established degradation of wrist function leading to instability, arthritis, and joint pain [3]. At present, the clinical standard for assessing an SLIL injury is wrist arthroscopy. Using arthroscopy, the SLIL can be directly visualized. Damage to the SLIL may be visible, however, it can still be challenging to determine the extent of damage. The Geissler's classification scale is a standardized assessment of the SLIL which considers both tissue damage and abnormal function (by looking at gapping between the bones) [4]. Although widely used, arthroscopy is an invasive procedure which has inherent risks and higher costs than non-invasive evaluations.

Traditional medical imaging technologies are not effective diagnostic platforms for soft-tissue injury of the wrist. Radiographs lack the necessary 3D context of the wrist, and soft tissue damage cannot be interrogated directly or indirectly due to the lack of image contrast. MR imaging does allow for soft tissue visualization, but the dynamic nature of SLIL injuries (i.e., the dynamic gapping between the scaphoid and lunate throughout motion) is difficult to visualize in the static MR scans. Four-dimension CT (4DCT) is now an established dynamic imaging technique [5]. Advanced multi-source, multi-detector CT scanners can dynamically acquire multiple volumetric datasets per scan. Because of the temporal resolution of these scanners, patients can complete wrist motions at a semi-normal continuous pace while data is acquired. The resulting dataset can be analyzed both spatially and temporally [6].

The ultimate end user of the 4DCT scan is the hand surgeon who is tasked with assessing the extent of damage to the wrist following a traumatic injury. While radiology workstations are well-suited for reviewing 4DCT image datasets, most clinical practices do not have these advanced workstations distributed into non-radiology departments in the clinic. Surgeons may only have basic visualization tools available to them during the clinical assessment of the images.

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To support the clinical adoption of 4DCT as well as several ongoing clinical research studies utilizing 4DCT, we have developed a web-based interface for the 4DCT which can be used throughout the clinical practice. The web app trades off functionality, performance, and resource availability within the Mayo Clinic environment. It allows clinicians to review the dynamic CT scans from any desktop or tablet device connected to the Mayo Clinic network.

II. METHODS

A. Data collection

Under an ongoing IRB approved study, patients with suspected wrist injury are recruited into the study. After a subject is identified as a viable candidate and consented into the study, the subject is asked to partake in a 4DCT examination. The subject places one wrist into the CT scanner. All scans were obtained using a Siemens SOMATOM Force CT scanner [7]. During acquisition, the subject is asked to complete a full range of motion flexion-extension (F-E) maneuver [8]. The desired constant rate of motion is guided by feedback cues to the subject. This maximizes the extent of data collection, ensuring that the full range of motion is capture in 15 volumes. After the F-E data collection, a second scan is completed using a radial-ulnar deviation (R-U) motion [8]. Fifteen volumes of data are obtained. After completing one wrist, the other wrist is scanned in the similar manner. The Siemens Br44 soft tissue kernel is used for reconstruction.

B. 4DCT Preprocessing

The purpose of the web-based image viewer is to delivery 4DCT data to surgeons and clinical researchers throughout the Mayo Clinic campus. A wide variety of endpoint computer devices are used at Mayo Clinic including Windows and Apple desktop computers, thin clients, laptops, tablets, and mobile phones. The technical specifications of these devices vary greatly ranging from large memory, Xeon processor workstations, to mobile phones with limited memory and local storage. Additionally, various network connections, from 10Gbit ethernet down to 802.11 a/b/g Wi-Fi, are used through the campus. For these reasons, it is intractable to deliver the full 4DCT dataset to the end users. To address this limitation, it is necessary to pre-process the raw images into the high-valued rendered images which are presented to the end user.

Subject datasets are exported from the institutional clinical PACS as DICOM image. The images are loaded into a local DICOM database and sorted into their respective DICOM series. Mayo Clinic Analyze is used to preprocess the image data [9]. To do so, individual series are loaded into 3D volumes and subsequently concatenated with the other 3D volumes of the DICOM study. The resulting 4D volume is used for all subsequent processing. The 4D volume is rendered using parallel geometry volume compositing algorithm [10]. A standard CT alpha map is used to enhance the presentation of bony structures. Renderings are generated at predetermine rotations around the z-axis and x-axis. The process is repeated for each timepoint. All renderings are combined into a high-dimensional array before they are serialized into an indexed 3D volume. Figure 1 shows the rendering and serialization process. The process is completed for both arms and both motions (F-E and R-U).

C. Web Application for Viewing 4DCT scans

The web application is built on HTML5 using PHP on the backend. Processed image datasets (i.e., the rendered volumes) are loaded on the server immediately following the automated rendering script. Once a subject is selected, the pre-processed dataset is loaded into the browser memory across the network. To accommodate the different end-user devices, the web application was designed to be highly configurable. Images can be presented in a 1-,2-, or 4-panel configuration. When multiple panels are shown, the panels are synchronized, allowing the user to visualize both arms and both motions at the same time. Rotations can be achieved using a keyboard, mouse, or touch display. Additionally, precision controls are included to allow the user to specify pre-determined viewpoints. Figure 2 shows the different GUI components of the web application.

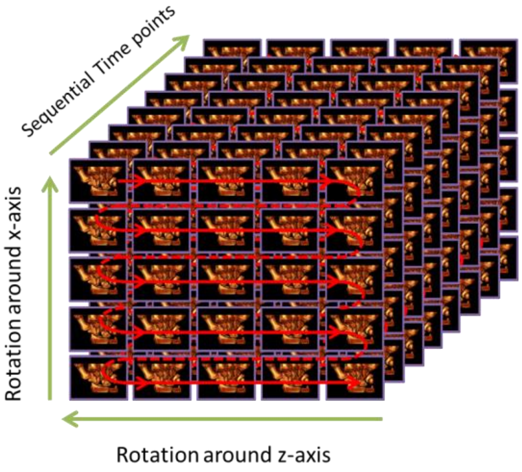
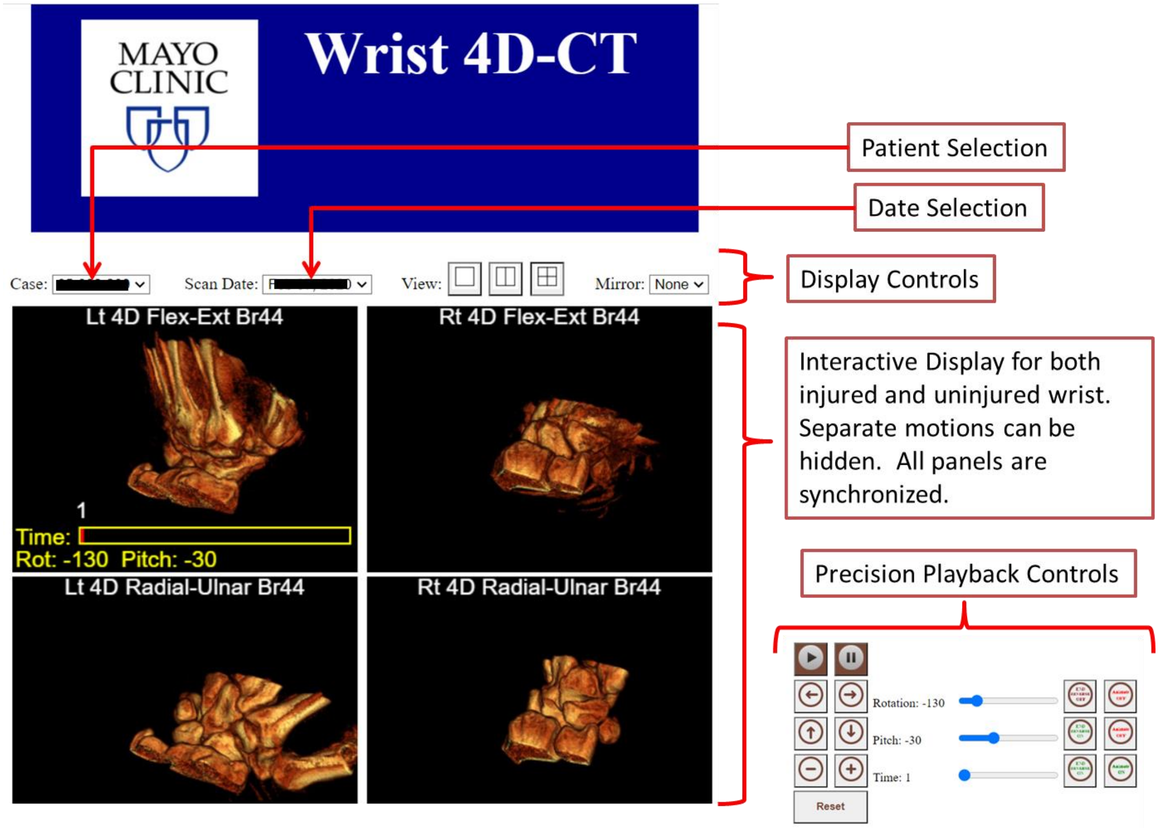


Figure 1: Rendering and serialization of volume rendered 4DCT scans for efficient delivery to remote devices. The backend rendering engine creates a 3D matrix of rendered images. All images are then serialized into a stack of rendered images.

III. RESULTS

To date, 27 subjects have been enrolled in the study; 10 subjects have completed both pre-surgical and post-surgical evaluations. The average age of participant is 42.7 (range 21-69 y.o.). Five subjects are female, and 12 subjects are right-handed. The median Geissler score for the cohort was 4 (range 2-4). The size of each DICOM study ranged from 20,000 and 23,000 images, required 9 to 11 Gb of storage. After processing, the final rendered volumes require 250Mb to 312Mb of storage. The web application requires an average of 77 Mb to operate (as tested in Google Chrome build 89.0.4389.128).

The majority of datasets were processed and loaded into web application without user intervention; some datasets didn't conform to the acquisition protocol and required minor manual intervention. Due to the size of the raw data and the need to export the data out of the clinical PACS system, the pre-processing of the data takes nominally 2 hours to complete. Network connectivity is the primary bottleneck, followed by the time required to load all the DICOM images into 3D volumes. The rendering engine is multi-thread and



Case: [redacted]

Scan Date: [redacted]

Mirror: None

Rot: -130 Pitch: -30

Rotation: -130

Pitch: -30

Time: 1

Patient Selection

Date Selection

Display Controls

Interactive Display for both injured and uninjured wrist. Separate motions can be hidden. All panels are synchronized.

Precision Playback Controls

Figure 2. Web interface for interactive assessment of wrist injury using 4DCT scans. Surgeons can select patient cases, review longitudinal dataset, and interactively interrogate the images. Future capabilities may include measurement of joint spacing.

can take advantage of server class hardware to accelerate the processing of the data.

IV. DISCUSSION

The web application has been used by clinical collaborators and research staff to investigate SLIL injuries. By collecting data on both the injured and uninjured wrist, comparisons can be made. Figure 3 shows one such example. The left column shows 3D renderings of the injured wrist during F-E and R-U maneuvers; the right column shows the normal wrist at the same points during the motion cycle. A large gap can be seen between the scaphoid and lunate which is indicative of an SLIL injury. In the actual application, the operator is able to interactively rotate the renderings to view the gap from different angles. The playback mode shows the changing of the gap throughout motion.

There are some limitations in the existing tool which should be noted. While best attempts are made to acquire data in a consistent manner (across motions and between wrists), there is variation in the acquisition process. There are two primary issues that arise from inconsistent acquisition. First, the noise and contrast characteristics change from subject to subject. As a result, the use of a fixed alpha map for rendering is limited. In some cases (such as Figure 3), the bony structures are rendered clearly. In other cases (such as the upper left image panel of Figure 2), soft tissue is visible and obstructs the view of some of the bones. A second problem with acquisition is maintaining consistent motion patterns across scans. Because the motion patterns are subject initiated (i.e., no mechanical intervention is used to control the motions), the subject may move at different rates. Additionally, an injured individual will likely have a different range of motion between wrists due to wrist pain.

Based on the known limitations of this tool as well as user feedback, there are several ongoing efforts to improve the user workflow and analysis pipeline. For example, the use of a z-buffer image (indicating the depth of each pixel in a rendered image) can be used to take 3D measurements from the 2D renderings. This will allow a surgeon to measure the gap between the two bones directly in the web application. Another approach to address the limitations of the current application is to adopt a polygonal model representation of the data. Currently, the raw CT data is directly rendered using a volume compositing approach. This approach is fast and doesn't require extensive processing of the data; however, it requires more memory/resources than other visualization techniques. Therefore, the rendering must be completed offline. Alternatively, OpenGL polygonal surface-based rendering requires minimal memory resources; however, all of the datasets must be segmented. As new deep learning approaches are developed to segment the bones of the wrist [11], the polygonal model approach will be adopted. An additional benefit of the model-based approach is that the bone motion can be interpolated allowing for pose reconstructions that occur between the individual scans.

Deployment of applications over the web is a well-established practice. It has been enabled by several technological factors including the advancement of the HTML5 standard, improvements in server-side coding frameworks, and optimization of the client-side browser engines. There are still limitations, however, to the networking infrastructure and local computational resources throughout the healthcare system. As such, analysis and visualization desktop applications can be difficult to virtualize to web-based applications. Care must be taken to optimize the processing pipeline to ensure a robust and interactive user experience.

V. CONCLUSION

The collection and analysis of high-resolution 4DCT scans may provide insights into SLIL injury without the need for an invasive arthroscopic evaluation. Due to the magnitude of data collected and the need for specialized visualization tools, it can be challenging to deploy this data into the clinical practice. Although technology (both desktop and mobile) continues to improve, it is still impractical to delivery the entire dataset to the end user. The use of web applications to delivery content in an optimized manner allows for the dissemination of knowledge with minimal impact to the infrastructure. The proposed web application allows surgeons and researchers to access the 4DCT data of patients shortly after the data is required. Even with the existing optimization in place, the process is not instantaneous and requires some amount of customization to support the ongoing needs of the clinic. Ongoing development activities will continue to enhance this capability with new quantitative features and more refined interactive tools.

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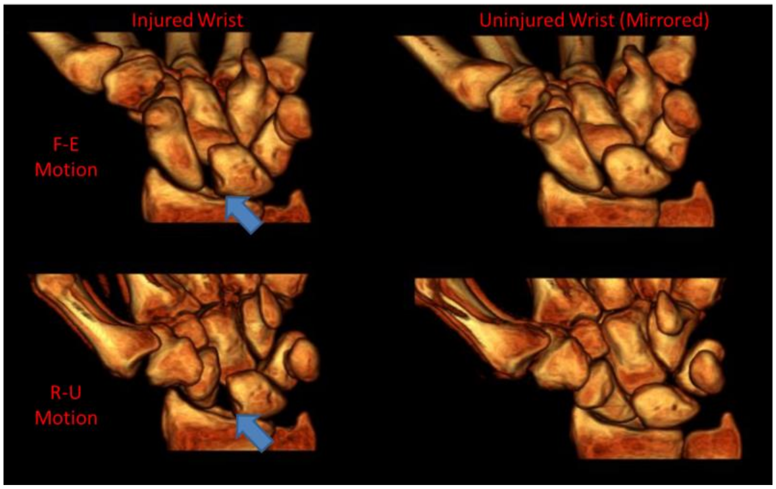

Figure 3. Example dataset generated from web application. The top two panels show the left and right wrist during a F-E motion; the bottom two panels show the same wrist during R-U motion. The injured wrist on the left shows a large gap (blue arrow) between the scaphoid and lunate which is indicative of SLIL injury.