Vault Reconstruction System Assessment in Patients with Glenohumeral Shoulder Implants: Prospects in Fluoroscopic Image Processing For 3D Motion Analysis

Undergraduate Research Opportunities Program

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1. Introduction

This research project was aligned with the beginning of the long-term Zimmer Biomet study, a critical evaluation of reverse shoulder arthroplasty procedures utilizing the vault reconstruction system. Reverse shoulder arthroplasty is an alternative to traditional joint replacement, based on custom implant insertion with a metal ball affixed to the glenoid fossa and a socket attached in place of the femoral head. This approach allows for effective intervention even in instances of severe osteoarthritic bone loss or gross rotator cuff damage. The VRS, as the first commercially available patient-matched glenoid system, offers unique capacities for creating highly individualized implants, tailored to each patient's anatomy and unique clinical needs. While technologies for reverse shoulder arthroplasty became available in 2006, the first VRS implantation didn't take place until ten years later. At this time, with the described patient-specific implant insertions creating more opportunities to take on increasingly complex cases, an in-depth assessment is crucial for procedural revision and optimization. Through this study, the University of Minnesota Rehabilitations and Biomechanics Laboratory undertakes the first comprehensive evaluation of VRS reverse shoulder arthroplasty on such a scale. This project aims to determine whether any differences exist in implant position, orientation, and screw trajectory of the VRS relative to the manufacturer's preoperative planning guide. Recognizing the unique challenge of conducting 3D motion analysis on the base of fluoroscopic imaging acquired through biplane radiography, optimizing image processing techniques towards input specifications of the software has been a key objective. Realization of these required a combination of multiple programs specializing in 3D analytics. The primary motion analysis platform was C-motion, with particularly relevant extensions Orient3D and X4D. The latter is capable of processing x-ray images with an automatic algorithm and adjustable parameters; however, this is not specific to unique requirements imposed by each set of radiographic data and therefore pre-processing of the images would allow for greatly improving accuracy in characterizing joint kinematics in this type of investigations.

2. Experimental Design and Protocol

The study is set to involve ten participants, while the scope of the current project was focused on finalizing the standardized procedure for the first, model subject. Guidelines for patient recruitment specified the 18-75 age group, having undergone surgery at least 6 months prior to involvement. An additional requirement for participation was to demonstrate nonrestrictive shoulder mobility, marked by a minimum of a 120° range of arm elevation.

To collect data on the patient, techniques of dynamic fluoroscopy were implemented. The subject's arm elevation was recorded using a mobile c-arm fluoroscopic acquisition unit supplied by Philips Medical Systems. Optimal parameters for data collection were established as 99.5 cm source to image distance, image resolution of 1024x1024, a 30 cm field of view, as well as a sampling frequency of 25 Hz. To complete data acquisition, all necessary preoperative imaging was obtained from the VRS manufacturer. A detailed representation of planned trajectories for the implant system's screws was also provided. The CT imaging of the patient's 3D-reconstructed scapula and humerus, created before the procedure, required reformatting in 3-matic software. Materialise 3-matic was the 3D modeling program utilized for design modification and optimization of the scans. The software contains elaborate functions for surface processing and smoothing and is an excellent platform for rescaling 3-dimmensional design components before further modification.

Processing of the fluoroscopic images representing the sequence of shoulder motion through arm elevation was carried out in MATLAB, utilizing functions of the image processing toolbox. The primary focus was improvement of edge detection, enhancing differentiation between outlines of the implant and distinct bones of the shoulder. Another demanding aspect was fine-tuning intrinsic parameters of the image set such as contrast, thresholding for pixel discrimination and removal of noise characteristic to contributions from soft tissue in radiographic scans. Requirements for these parameters varied between the anterior and posterior representations of the shoulder as well as throughout the phases of arm elevation.

It became apparent that the processing steps performed in MATBLAB required close coordination with the automatic processing algorithm internal to X4D of the C-motion package. In X4D precise tracking of bones is dependent upon the X-ray and DRR (digitally reconstructed radiograph) image processing parameters within the program. The accuracy of motion characterization showed high dependence on how well the input image characteristics matched the preferential parameters of the image analysis software. Multiple iterations of processing within MATLAB were performed in order to find modifications providing the optimal outcome both at the surface-level visual assessment as well as the final product viewed inside C-motion. To assure holistic compatibility images representing the beginning, middle, and end phases of arm elevation were first individually tested under the finalized MATLAB code.

The appropriately reformatted structures exported from 3-matic along with the enhanced fluoroscopic imaging were imported into the main motion analysis platform, C-motion, creating the complete subject file. Two main extensions within C-motion were utilized to complete information for the file and to perform the final data analysis. Orient3D was used to prepare objects for tracking, loading surface models and performing calculations with respect to anatomically significant reference frames. X4D was the platform where tracking of implant components and bones took place in the x-ray space. The general organization of C-motion is outlined in Figure 1.

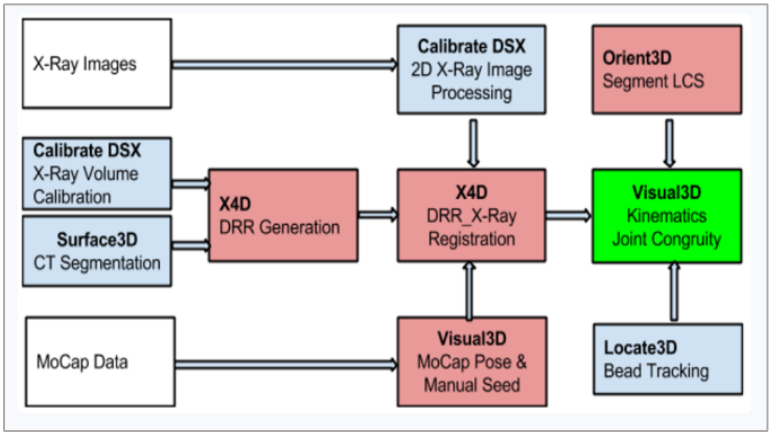

Figure 1. Schematic illustrating components of C-motion software utilized in the kinematic analysis. X-ray images are specified as a required system input. Figure retrieved from C-motion.com

With this set up reference frames from initial, middle and final stages of shoulder motion were chosen for preliminary shape matching. The goal for this critical stage of data analysis was to superimpose the outlines of the processed 3D trackable objects onto the 2D x-ray images representing kinematic events over multiple frames.

3. Data analysis and Results

The operations performed in processing implant and bone elements resulted in a functional set of trackable objects required to manually trace the patient's glenohumeral and scapulothoracic kinematics. Provided below in *Figure 2* is an exemplary frame from the biomechanical analysis, prior to input of rescaled and surface processed elements and prior to pre-processing the x-rays. All pre-processing operations for the fluoroscopic images were achieved within MATLAB. Utilizing the convolution operator in conjunction with a fast Fourier transform resulted in the effect of sharpening contours of the bones. The contrast adjustments and image thresholding proved to be problematic in terms of C-motion's response. The parameters which worked best upon exporting directly from MATLAB did not translate into significant improvements when input into X4D. Adjustments were made to accommodate to this, opting for contrast and thresholding parameters, which initially appeared to provide intermediate improvements while ultimately proved to optimize overall image clarity and specific edge enhancement within C-motion.

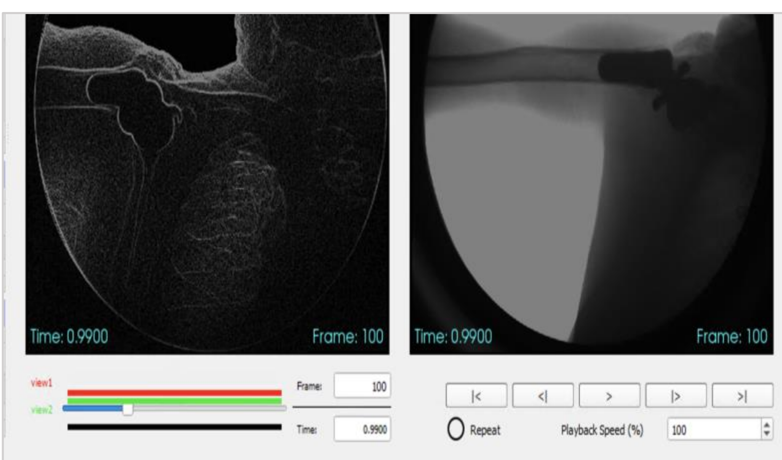

Figure 2. Select frame captured during arm elevation as viewed within X4D of the C-motion suite. Displayed on the right is the original x-ray in the posterior view. The corresponding frame on the left is the processed x-ray in the anterior view, obtained upon selecting the automatic x-ray processing function within the software. Pre-processing is to be implemented with the purpose of improving the resolution of individual elements in the implant/anatomical system.

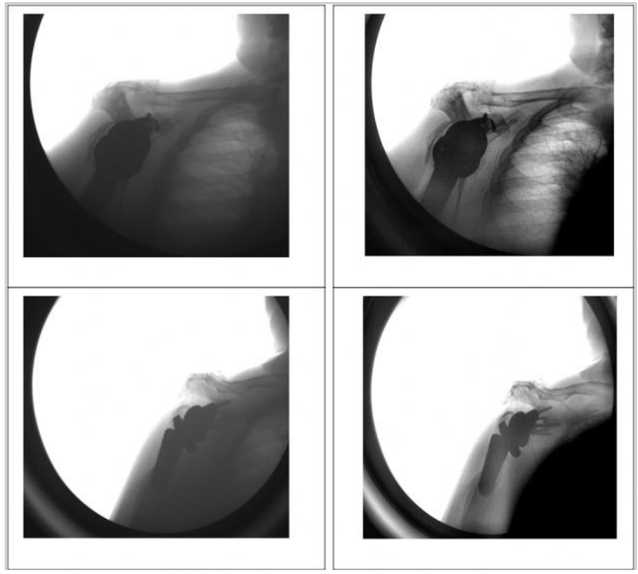

Figure 3. Image optimization performed on an example frame of the anterior (top) and posterior (bottom) view of the shoulder captured during the initial stage of arm elevation. The images on the right are the final result of pre-processing operations carried out in MATLAB.

Two consecutive frames for views from both cameras of the biplane radiography configuration were combined into a stack file, creating both edited and unedited versions of the same frames for direct side by side comparison. Emphasis was placed on studying the sensitivity of the software to each category of changes made in editing the fluoroscopic images. This allowed for finalization of the optimal set of parameters, keeping detailed documentation of the established protocol.

4. Discussion and Conclusions

Characterized in this report are the data collection and nearly completed data analysis processes established for the first subject in the assessment of VRS shoulder implants. The actions taken in this critical first phase of the study have provided insightful preliminary results, despite the yet to be concluded process of 2D/3D shape matching. The encountered challenges in working with raw fluoroscopic imagery prompted innovation and adjustment in the approach to kinematic analyses, suggesting significant advantages to conducting pre-processing on this type of scans through computer programming, with code specific to a given set of patient data. A key theme throughout this project has been recognition of the significant limitations to accurate interpretation of anatomical corelates in kinematic data, attributed to image quality. Despite optimization algorithms in place within motion analysis platforms, here X4D of C-motion, the distinct features of an input image can considerably affect accuracy of the 2D/3D shape matching process. One challenge to implementing an additional image modification series prior to the automatized processing are difficulties in matching the characteristics of the processed radiographs to input requirements imposed by the program. The process may require substantial trial and error to find optimal values for the code, depending on the initial image quality. Despite this, it is a worthy investment of time as removing the intrinsic noise in fluoroscopic imagery along with performing edge enhancements can significantly improve the efficacy and efficiency of the kinematic assay.

Considering evaluations of post-surgical orthopedics, achieving the greatest possible precision in data analysis is crucial. Any improvements made to the process directly translate into more informative results, providing insight into any beneficial interventions or possible rehabilitation practices. Future directions should further be focused towards assuring a more effective and synergistic workflow between processing medical imagery and performing operations on them within novel software available for motion analysis in order to maximize the potential of these technologies. As the possibilities for surgical treatment of complex shoulder disfunctions continue to expand, it is imperative that the techniques of biomechanical analyses evolve concurrently in order to advance research and innovate patient treatment.

Completion of this study will provide information essential for the purposes of seeking procedural optimization for reverse shoulder arthroplasty via the VRS and advance close coordination between the prosthesis manufacturer and surgeon. These findings will also open up more possibilities for expanding the established evaluation techniques towards different cases of implant systems. Utilizing the created pre-processing algorithm for all remaining study participants is expected to provide meaningful advantages in the process of data analysis.

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