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Technical note

# Determining 3D scapular orientation with scapula models and biplane 2D images

Kristen F Nicholson[a,*], R Tyler Richardson[a], Freeman Miller[b], James G Richards[a]

[a] *Biomechanics and Movement Science Program, University of Delaware, Newark, DE, USA*
[b] *Nemours Alfred I. duPont Hospital for Children, Wilmington, Delaware, USA*

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ABSTRACT

This study evaluated a strategy for identifying 3D scapulothoracic orientation using bilateral X-ray scans and 3D scapula models. Both subject-specific scapula models and a scaled general model were utilized. 3D scapulothoracic orientations obtained from X-rays were compared to motion capture data. “Subjects” consisted of a skeletal model of a human torso and ten real bone scapulae. Retroreflective markers were placed on the scapulae and a three-marker triad was placed on the trunk. Marker positions were recorded using an eight camera motion capture system. A biplane X-ray system from EOS Imaging was used to collect two orthogonal 2D images of the skeleton and markers. Custom software was created for the 3D to 2D matching process. The results indicated that the matched orientations compared favorably to motion capture orientations, with RMSE errors ranging from 3.1° to 5.5° and a mean error of 3.9° The proposed strategy was shown to be accurate for both subject-specific models and a scaled general model.

## 1. Introduction

The research required to evaluate clinically applicable measures of dynamic scapular orientation has been hampered in part by the lack of a non-invasive “gold standard” that can be applied across all populations. Bone pins have traditionally been used as the reference standard for evaluating non-invasive approaches to the measurement of dynamic scapular orientation [1–3]. However, the invasive nature of bone pins severely limits their application to healthy adult populations, and prohibits their use altogether in pediatric populations. Additionally, there is reason to believe that scapula movement is constrained when pinned to the skin, which raises questions regarding the utility of using bone pins as a “gold standard” validation approach in-vivo [4].

Considering the issues surrounding bone pins, coupled with advances in radiographic imaging including improved resolution and lower exposure to radiation, biplane fluoroscopy might provide a more palatable option as a research “gold standard” for determining dynamic scapular orientation. Specifically, with motion-trial radiation exposure limited to that of a single chest X-ray or less, this approach could potentially be utilized to examine the accuracy of existing and future non-radiological, non-invasive approaches to the clinical measurement of scapulothoracic (ST) orientation.

Using dual-plane fluoroscopy to determine the orientation of underlying skeletal structures requires an approach that enables identification of specific landmarks or alignment of similar geometric shapes. The landmarks typically consist of radio-opaque beads that are implanted in skeletal structures, which limits this approach to special circumstances. A technique referred to as model-image registration is capable of estimating 3D orientation by matching 3D segment models with 2D radiographic images [4–11]. Both single and dual plane radiographic model-image registration techniques have been used. While the single plane radiographic image technique is accurate for in-plane motion, it loses its accuracy as the bone moves out of the viewing plane [11]. Using this technique with dual-plane radiographic images improves accuracy [5,8,10,11].

Previously described strategies for model-image registration vary from manually matching the model to the radiographs [10], matching digitally reconstructed radiographs (DRRs) to the actual radiographs [4,8,9,11,12], and using frequency domains to match the model to the image [13,14]. The most common technique is to match DRRs to actual radiographs. The DRR matching technique has typically been used on knees, which primarily move in the sagittal plane. The scapula, however, has six degrees of freedom and moves between 20° and 40° in protraction/retraction,

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*Abbreviations:* ST, scapulothoracic; DRR, digitally reconstructed radiographs; TS, trigonum spinae; IA, inferior angle; AP, acromion process.

[*] Corresponding author.

*E-mail addresses:* kristent@udel.edu (K.F. Nicholson), trich@udel.edu (R.T. Richardson), freeman.miller@nemours.org (F. Miller), jimr@udel.edu (J.G. Richards).

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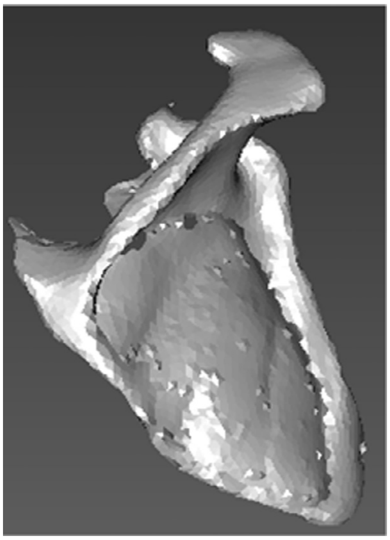

**Fig. 1.** Example of one 3D model created from a real bone scapula.

**Fig. 2.** Torso model with two real bone scapulae attached.

internal/external rotation, and posterior/anterior tilt [15]. The triaxial motion of the scapula would require a large library of DRRs, making this technique computationally impractical.

The DRR matching technique also relies heavily on the bone model and image being the exact same shape, requiring a subject-specific bone model. The creation of a subject-specific bone model is typically performed using CT or MRI scans, and the reconstruction of individual bones, especially bones that are relatively thin such as the scapula, is a laborious and costly process. The ability to utilize a scaled general model in place of a subject-specific model without loss of accuracy would reduce both cost and labor, and consequently, would be highly beneficial.

The purpose of this study was to determine the accuracy associated with estimating 3D scapular orientations from biplane radiographic images. The primary goals of this study were: (1) to determine whether low-level radiation sources such as EOS or fluoroscopy could be used to accurately determine 3D scapular orientation using 2D to 3D image registration, and (2) to determine whether a scaled general scapula model could be used to achieve the same level of accuracy as a subject-specific model.

## 2. Materials and methods

Three dimensional scapula models were created from 12 (six left and six right) real bone scapulae with a FaroArm Fusion with ScanArm V3 attachment (FARO, Lake Mary, FL). Each scapula was scanned and a 3D point cloud was exported to Geomagic Studio (3D Systems, Rock Hill, SC) (Fig. 1). Each 3D model was saved as a VRML model and loaded into custom software to establish coordinate systems that matched recommendations of the International Shoulder Group [16]. These models served as idealized forms of patient specific models built from CT or MRI scans. Ten of the models were used as subject-specific models, while the other two models served as the generic scapula models.

A life-size skeletal model of a human torso (rib cage, sternum, spine, clavicles, and humeri) and ten of the scanned scapulae were used as subjects in this study. The skeleton torso was placed in the viewing volume of the motion capture system. A triad of three 7 mm spherical retroreflective markers was placed on the sternum. All three markers were affixed to a solid plastic plate in a triangular configuration. The plate was affixed to the sternum so that the top triad marker was over the suprasternal notch. Retroreflective 2D markers 6 mm in size were placed on the trigonum spinae (TS) and inferior angle (IA) of all ten scapulae. A 6 mm 3D marker was placed on the flattest/broadest portion of the acromion process (AP) of each scapula. Two scapulae (one left, one right) were attached to the humeral heads in positions that appeared anatomically feasible. An eight camera motion capture system (Motion Analysis Corporation, Santa Rosa, CA) operating at 60 Hz was used to collect 3D motion capture data.

After 3D coordinate data were recorded with motion capture, the torso, with attached scapulae, was moved into an EOS (EOS Imaging, Cambridge, MA) scanning volume. The torso was positioned with the bottom ribs resting on a pedestal at approximately a 45° angle to the X-ray beams (Fig. 2). This orientation resulted in the right X-ray beam being approximately perpendicular to the left scapular plane, and the left X-ray beam being approximately perpendicular to the right scapular plane.

Following the EOS scan, the torso was moved from the EOS volume back to the motion capture volume. The scapulae were repositioned into new anatomically feasible orientations. Three-dimensional coordinate data were recorded, and the torso was returned to the EOS volume, where a second set of X-ray images was collected. This process was repeated three times for each set of scapulae. This resulted in a total of 15 motion capture data collections, and 15 corresponding sets of orthogonal X-ray images. Each set of X-ray images and motion capture data had both a left and a right scapula, for a total of thirty unique scapula orientations. Each set of 15 scapula positions approximated the typical scapular range of motion.

Custom software was used to define the scapula and trunk coordinate systems from the motion capture data. Coordinate systems for the scapulae followed the recommendations of the International Shoulder Group [16]. The trunk's coordinate system was created using the three triad markers: transverse axis from bottom left triad marker to bottom right triad marker; anterior axis perpendicular to the plane defined by all three triad markers; vertical axis orthogonal to the transverse and anterior axes. The measured angles between the trunk's motion capture orientation and scapula's motion capture orientation were calculated using the helical approach described by Woltring [17]. This orientation was regarded as the true scapula orientation.

Image registration was performed as follows: orthogonal X-ray views of each scapula obtained from the EOS system were analyzed in pairs. Three-dimensional viewing windows were super-