Characterization of PMHS Shoulder Biomechanics Under Sub-Injurious Loading

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I. INTRODUCTION

Despite its crucial role in a variety of automotive collision scenarios (such as frontal belt loading, side impacts, and pedestrian impacts), the shoulder is one of the least validated structures within human body models (HBMs). Current validation studies focus primarily on high-speed impact response [1-2], without quantifying the internal biomechanics of the shoulder. This has resulted in unrealistically stiff joint models, which can lead to inaccurate prediction of arm positioning or of the interactions between the HBM and the seatbelt throughout an impact simulation. Previous attempts to quantify these mechanics were limited to only a few axial rotations, such as abduction or flexion, and utilized superficial palpation of volunteer subjects to capture the bone kinematics [3]. This study aims to generate new data, necessary for future HBM development, that define the relationships between the internal biomechanics and skeletal kinematics within the human shoulder in response to a variety of sub-injurious loading conditions that explore the entire joint space.

II. METHODS

Six mericut Post-Mortem Human Subject (PMHS) torsos (sans cephalus and amputated at the mid-humeri and mid-femurs) were procured through protocols approved by the University of Virginia Institutional Review Board – Human Surrogate Use (IRB-HSU) committee. Of these PMHS, three were approximately 50th percentile males (age = 53.0 ± 6.7 years, height = 176.1 ± 1.8 cm, mass = 77.1 ± 6.7 kg) and three were 5th percentile females (age = 61.0 ± 1.4 years, height = 163.4 ± 4.3 cm, mass = 45.2 ± 0.2 kg). The distal end of each sectioned PMHS humerus was embedded in a rigid fixture (i.e. potting cup) that was equipped with a six-axis load cell and a handle for manual manipulation. Further, reflective Vicon 3D motion tracking nodes were attached at various points around the potting cups to accurately record the motion of the humerus throughout testing. Additional Vicon instrumentation was installed on the remaining shoulder bones (left and right clavicles, scapulae, and the sternum) using minimally invasive procedures to limit disruption of the surrounding soft tissue. The sternum was equipped with a Vicon standoff plate, traditionally used in PMHS sled testing, while the scapulae and clavicles were each mounted with two 3D-printed, tree-like standoffs - one in a medial location and one in a lateral location. These duplicate mounts on the scapulae and clavicles ensured that the Vicon system always maintained line-of-sight with a minimum of three reflective nodes per bone for accurate tracking throughout testing and to reduce noise from data collection. The PMHS's spine was then rigidly mounted to a test fixture and positioned in a seated posture with a 15° seat pan angle [4]. A global coordinate system (CS) was defined based on each PMHS's spinal anatomy to counteract any postural differences between the subjects. For this global CS, positive X pointed forward, positive Y pointed to the right, and positive Z pointed downward [5]. Each shoulder bone was then assigned a local CS [6-7], and the position and orientation of each bone was recorded throughout testing.

Each shoulder was tested under manual manipulation, via the handle on the mid-humeral potting cup, to simulate shoulder abduction/adduction, flexion, extension, lateral flexion, and lateral extension. Three to six full loading-unloading motions were recorded for each case per shoulder, with varying input force. The lowest-force cases consisted of a rotation to the physiological range-of-motion (easily detected by a noticeable increase in joint resistance). Keeping within a low-to-moderate severity loading range, no test exceeded 60 N and 16 Nm of input load to the shoulder system. Bone kinematics were recorded for all tests via Vicon. To ensure that all shoulder motions were directly comparable, the data (position, orientation, force, and moment) from each left shoulder trial were mirrored into the right shoulder's CS, and the six-axis load cell data were transformed from the potting cup to the local humerus origin, located at the proximal humeral head [7]. Corridors of joint reaction force, joint reaction moment, bone displacement, and bone rotation were then generated by calculating the mean response (± 1 SD) for each metric across all comparable trials. Additionally, rigid body, prescribed motion simulations were generated using LS-Dyna to visualize the subject-specific bone kinematics for each test case.

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III. INITIAL FINDINGS

The prescribed motion simulations showed significant displacement and rotation within the humeral and scapular response to the abduction and flexion cases (Fig. 1). Similarly, the clavicle rotated with the humerus and scapula. However, while it displaced significantly on the lateral end (near the acromioclavicular joint), it barely moved on the medial-most end (near the sternoclavicular joint). This minimal response was also seen at the sternum, as it was the farthest bone from the applied rotation. Finally, the low range-of-motion in the extension case resulted in marginal rotation and displacement of all shoulder bones, with the magnitude of response increasing for the bones nearest the rotation (humerus > scapula > clavicle > sternum).

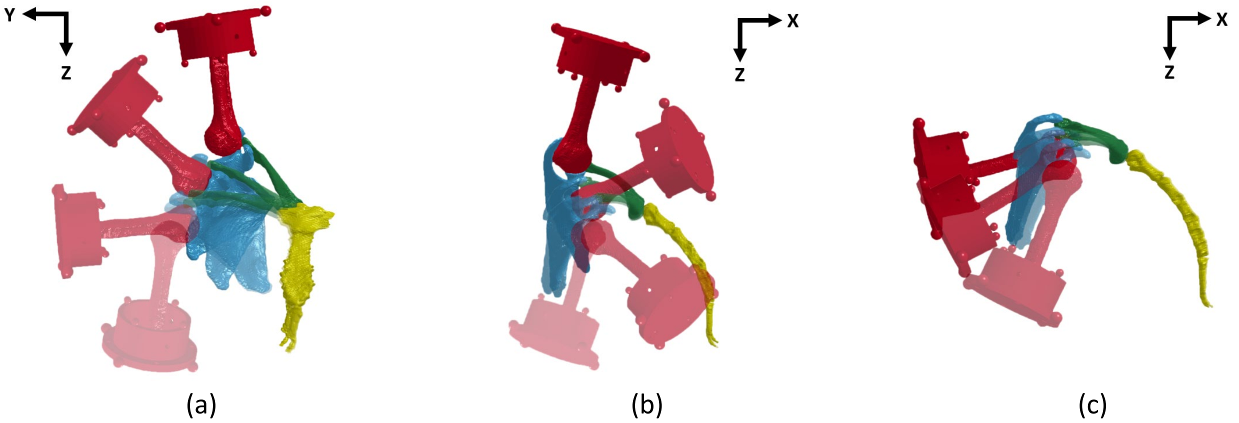

Fig. 1. An example of the bony kinematics of the shoulder joint based on reconstructions developed using subject-specific CT segmentations and the Vicon data for (a) abduction (front view), (b) flexion (lateral view), and (c) extension (lateral view).

Corridors of mean (± 1 SD) joint reaction moment were developed from all six PMHS for the abduction/adduction, flexion, and extension cases (Fig. 2). Each corridor demonstrated a non-linear relationship between the humeral rotation (abduction, flexion, or extension) angle and the applied moment. The abduction and flexion cases were comparable; both reaching a rotation angle of approximately 140–150° under an applied load of 0.5–5.5 Nm. The extension case was only capable of rotating to about 80° of extension in response to 0.5–4 Nm of applied load.

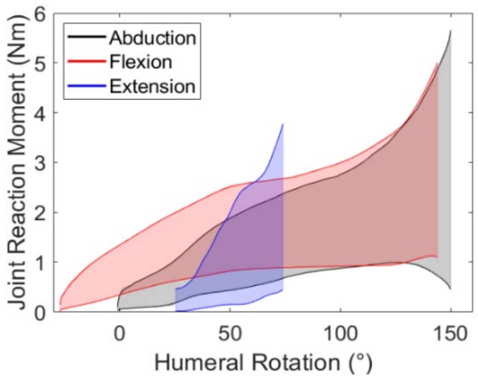

Fig. 2. Corridors of mean (± 1 SD) applied moment from all abduction/adduction, flexion, and extension trials.

IV. DISCUSSION

This study aimed to characterize the sub-injurious biomechanics of the human shoulder complex by measuring bone interactions and joint mechanics throughout various loading conditions. The data generated from experimentation will provide a direct comparison for improved validation of sub-injurious shoulder biomechanics and aid in the development of more life-like HBMs. Additionally, despite the low sample size (n=6), preliminary assessments found minimal difference between the shoulders of the 50th percentile male and the 5th percentile female. Similarly, no major differences were detected between left and right shoulders of an individual PMHS. Both comparisons warrant further study with an expanded sample size.

V. REFERENCES

[1] Park, *et al.*, *Ann Biomed Eng*, 2016.
[2] Koh, *et al.*, *Stapp Car Crash J*, 2005.
[3] Jackson, *et al.*, *J Biomech*, 2012.
[4] SAE Tech. Pap. 98316, 1998.
[5] SAE J1733, 1994.
[6] Wu, *et al.*, *J Biomech*, 2005.
[7] Drew, *et al.*, *Anat Rec* (Hoboken), 2019.