Development of a Human Shoulder Simulator for Cyclic Testing

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INTRODUCTION: The shoulder complex, of which the glenohumeral joint is the main articulation, allows for a large range of motion. The rotator cuff muscles (supraspinatus, infraspinatus, subscapularis and teres minor) surround the joint and compress the humeral head into the glenoid fossa of the scapula to prevent dislocation. Injury is common and surgical therapies to repair tears of the rotator cuff often lead to unsatisfactory results[1]. The development of surgical repair methods and new treatments are limited by a lack of appropriate functional pre-clinical testing. There are very few pre-clinical natural shoulder simulators currently available and specifically the ability to operate over extended motion cycles and ranges of motion is lacking. To address this need, the aim of the study was to develop a novel cadaveric human shoulder simulator that is capable of repeated motions of activities of daily living.

METHODS: A new experimental shoulder simulator (Figure 1a) was developed which mechanically actuates the rotator cuff tendons of a cadaveric human shoulder to generate physiologically relevant motion cycles and measure the resultant force at each of these tendons. A pilot study involving a single human cadaveric shoulder (tissue used with consent for research under HTA license 12279), preserved using the saturated salt solution method[2], was dissected to isolate the glenohumeral joint. The humerus and scapula were retained and the clavicle removed at the acromioclavicular joint. The joint capsule was maintained whole with approximately 15 cm of the humerus attachments of the rotator cuff tendons (supraspinatus, infraspinatus, subscapularis and teres minor) and the anterior and middle deltoid tendons to provide attachment points for the mechanically actuated muscle system. The shoulder was kept under room temperature (25 C) and hydration was maintained by routinely spraying tissue with salt solution every 30 minutes. Braided polyethylene thread was secured to the six tendon ends via a modified finger-trap suture (Figure 1b). Eyelet screws were fixed into the scapula at the approximate insertion location of the six muscles to act as pulleys and maintain the line of muscle action. The braided thread was passed from the tendon end, through the respective pulley eye screw and secured to a stepper motor (NEMA 17). The simulator was used to generate cyclic movement of the shoulder by actuating the six stepper motors attached to the muscles to follow predefined motion trajectories. The required trajectory for each muscle was determined using a computational simulation of the motion (AnyBody). The resultant forces at each muscle were measured throughout the movement using load cells attached to the stepper motors. Movement of the humerus position was determined using video based motion analysis (MATLAB) to track the position of two coloured markers positioned on the bone. The shoulder simulator was evaluated by using the system to perform two movements whit 10 cycles: a) 0 - 40° abduction/adduction and b) 0-15° flexion/extension. Each movement was repeated three times to assess the repeatability of the simulator.

RESULTS: A cadaveric shoulder simulator was successfully developed that allowed the application of repeated motion cycles. The resultant force measured in each muscle through one abduction/adduction motion set is shown in Figure 2. Similar forces were observed between cycles in each muscle for each motion data set collected for both the abduction/adduction and flexion/extension motions. Evaluation of the resultant force observed in the supraspinatus muscle was consistent with literature and shows consistency across the movement (Figure 3).

DISCUSSION: The simulator provides opportunity to evaluate the contribution of the different muscles involved in the shoulder during motion. Considering the abduction/adduction motion (Figure 2), the supraspinatus muscles initiated movement with the deltoid muscles then supporting the final stages of the motion. This corresponds to Lam and Bordoni (2021) who stated that the primary muscle during the initiation of abduction was the supraspinatus followed by the deltoid muscle until 90° of abduction. Results from the flexion/extension movement are also in agreement, where the primary flexor was the anterior deltoid muscle[1]. The resultant force observed in the supraspinatus muscle was consistent across repeats of the movement, suggesting the simulation is appropriate for delivering repeatable cyclic testing. In all cases, the load measured in the muscles was higher during the initial cycles and then decreased and plateaued after 5 cycles. This is predicted to be a result of natural repositioning of the shoulder joint after being held in a steady state. Future work will look at the effect of increasing the number of cycles within a motion to consider extended movements. The simulator will then be used to assess the effect of rotator cuff tears and the resultant change in forces within the shoulder which occur, together with cyclic testing of different surgical repair method of the rotator cuff muscles.

SIGNIFICANCE/CLINICAL RELEVANCE: (1-2 sentences): A novel natural human shoulder simulator was created in order to produce cyclic motions representing activities of daily living in the glenohumeral joint, through active mechanical control of the shoulder muscles. The simulator measured the resultant muscle loads during movement. This will allow for cyclic testing of surgical repair methods of the rotator cuff muscles and the impact on rotator cuff tears on the forces within the shoulder.

REFERENCES: [1]Lam, J and Bordoni, B (2021). Anatomy, Shoulder and Upper Limb, Arm Abductor Muscles. Treasure Island, FL: StatPearls Publishing.
[2] Coleman, R and Kogan L (1998). An improved low-formaldehyde embalming fluid to preserve cadavers for anatomy teaching. J Anatomy. 192(Pt 3):443-6

IMAGES AND TABLES

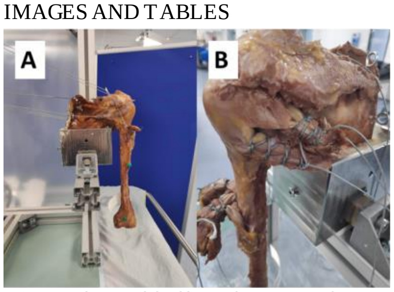

Figure 1 – The natural shoulder simulator setup. A: The natural shoulder simulator. B: Modified finger trap sutures connected the tendon ends to the braided polyethylene thread.

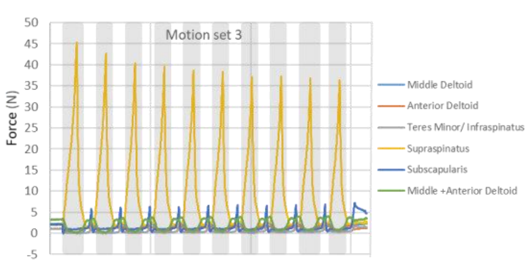

Figure 2 – The force required in each muscle through one motion set of abduction/adduction. The grey zones indicate periods of abduction and the white zones periods of adduction.

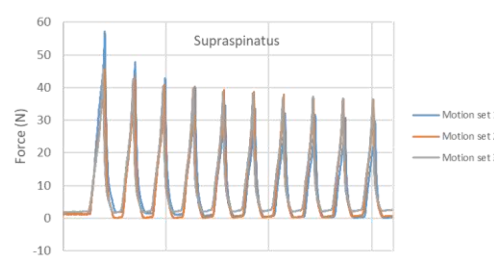

Figure 3 – The force required in the supraspinatus muscle for each motion set of the abduction/adduction motion.