Balancing stability and mobility during overhead motion: Lessons from the bat shoulder
Iden Kurtalija, Jennifer Kunes, Shicheng Li, Lynn Ann Forresterb, Michael Rowley,1,2, Sharon Swartz,2, Guy Genin, Stavros Thomopoulos1
1Columbia University, New York, NY; 2Brown University, Providence, RI; 3California State University, Hayward, IN; 4Washington University, St. Louis, MO
ik2401@columbia.edu

Disclosures: The authors have nothing to disclose.

INTRODUCTION: Repetitive overhead motion in humans often leads to shoulder injuries, a consequence of an evolutionary trade-off in which the glenohumeral joint's bony anatomy provides minimal stability constraints, but placing greater stress on the joint's surrounding soft tissues. Traditional animal models used to study shoulder pathology are quadrupeds, and lack comparable capacity for overhead motion. In contrast, bats consistently engage in overhead motion during flight, subjecting their shoulders to substantial loading throughout their relatively long lifespan. Remarkably, the biomechanical demands placed on a bat's shoulder are estimated to exceed the cumulative shoulder loading endured by a competitive swimmer by 45-fold [1,2]. In this study we were inspired to study functional adaptions in the shoulders of bats, the only mammals that use overhead motion as a critical part of their function and share similar coracocromial arch anatomy with humans. We performed comparative anatomy studies of the bat shoulder compared to the mouse shoulder, a similarly-sized quadruped. We quantified the constraints imposed by the bony anatomy of bats to maintain joint stability and determined the adaptations of rotator cuff tendons that allow bats to sustain overhead motion in a high stress repeated loading environment.

METHODS: Sample preparation. All animal procedures were approved by the Columbia and Brown University Institutional Animal Care and Use Committees. Shoulders harvested from adult (12 weeks) C57BL/6J mice (n=6) and C. perspicillata bats (n=5) were dissected and fixed in three different positions: full shoulder extension (“P1”), intermediate (“P2”), and full shoulder flexion (“P3”). To consistently identify the angle between the scapular spine and the humerus for each fixation position, gait (mouse) and flight (bat) analyses were used. MicroCT Imaging: Samples were scanned at 55 kV peaks with 145 mA intensity, and 6.5 μm resolution (Skyscan 1272, Bruker). Following scanning, samples were preconditioned by being sinusoidally loaded from 0.05 to 0.2 N for 5 cycles then allowed to rest for 2 minutes, before being strained until failure in tension at 0.1%/s. Mathematical model: We developed a model of shoulder instability as a function of the glenoid and humerus curvature and insertion angle of rotator cuff tendons. To model response to destabilizing forces, a concentrated force F was applied quasistatically, until the humeral head became unstable. To calculate the resistance of the system to instability, the work U done by F up to the point of instability was calculated: U = ∫ F · dF, where dF is the increment of path length followed by the point of application of the force. Equations were solved using Matlab (The MathWorks). Statistical analysis was performed using paired t-tests with Welch’s correction (GraphPad Prism 7). The threshold for statistical significance was defined at p < 0.05.

RESULTS: Bony Anatomy: The scapular index and infraspinatus index were both significantly larger in bats than in mice, while the supraspinatus index did not differ (Fig. 1a). The supraspinatus outlet area was significantly greater in bats compared to mice (Fig. 1b). The glenoid was retroverted in bats and anteverted in mice (Fig. 1c). Glenoid curvature and arc length were significantly higher in bats than in mice (Fig. 1d). Tissue level mechanics: The supraspinatus tendon in bats had a significantly higher cross-sectional area (CSA) compared to those of mice. In contrast, for the infraspinatus tendons of the two species, there was no significant difference in CSA (Fig. 2a). Bat supraspinatus tendons showed significantly lower failure stress compared to mice, but bats infraspinatus tendons showed a significantly higher failure stress than mice (Fig. 2b). Bat supraspinatus tendons had a significantly lower modulus compared to mice, but there was no difference in the modulus of the infraspinatus tendons when comparing bats to mice (Fig. 2c) Bat supraspinatus tendons were significantly less resilient than those of mice, while their infraspinatus tendons were significantly more resilient (Fig. 2d). Modeling: The bat shoulder was stable over a dramatically larger range of angles compared to the mouse shoulder (Fig. 3).

DISCUSSION: The bat’s enlarged infraspinatus index suggests a larger role for the infraspinatus in the bat’s glenohumeral stability. This also implies adaptations to relieve stress on the supraspinatus. Similarly, the larger supraspinatus outlet in the bat provides more space for the supraspinatus to pass under the coracocromial arch to prevent supraspinatus shoulder impingement, commonly seen in overhead-throwing athletes [3]. The glenoid was anteverted in mice, whereas it was retroverted in bats, analogous to the retroverted glenoids reported in high-level overhead-throwing athletes [4]. The bat glenoid had a larger glenoid arc length and articulating surface area with the humeral head, thus providing more bony stability to the joint. Bat supraspinatus tendon cross-sectional area was significantly larger than that of mice, consistent with previous measurements of supraspinatus-acromion clearance and outlet area. While bat supraspinatus tendons were weaker when compared to mice, as indicated by significantly lower maximum failure stresses, stiffness and toughness, bat infraspinatus tendons were significantly tougher and more resilient. The energy needed to dislocate the humeral head of bats was substantially larger than that in mice and stability was seen for a larger range of shoulder angles. Taken together, these results suggest that evolutionary adaptions in bats led to reduced stress on the supraspinatus, thus reducing risk of catastrophic tendon rupture, while the infraspinatus compensated by playing a stabilizing role.

SIGNIFICANCE: Functional adaptations of the bat’s shoulder joint provide insight into developing new approaches to treat glenohumeral joint instability.


Figure 1. (a) Scapular, supra. and infra. indices (b) Supraspinatus outlet area (c) Glenoid version (d) Glenoid curvature and arc length

Figure 2. Material properties of bat and mouse supraspinatus (left) and infraspinatus (right) tendons

Figure 3. The energy barrier that resists shoulder instability (red) was substantial in bats (bottom) over a larger range than in mice (top).

ORS 2024 Annual Meeting Paper No. 2150