Shoulder Instability as a Cam-follower Mechanism

Laurent B. Willemot, M.D. 1, Andrew R. Thoreson, M.S. 1, Ryan B. Breighner, Ph.D. 1, Alexander W. Hooke, M.A. 1, Kai-Nan An, Ph.D. 1, Olivier Verborgt, M.D., Ph.D. 2.

1Mayo Clinic, Rochester, MN, USA, 2University Hospital of Antwerp, Antwerp, Belgium.

Disclosures:

Introduction: Traditional experimental studies investigating concavity-compression in shoulder (in)stability, have either measured translational force during displacement or measured displacement after applying a predetermined translational force. In 2003, Oosterom et al.(2) published a mathematical model allowing the prediction of translational stiffness of the replaced shoulder joint. The authors described three positions and two regions of instability along the humeral track. Namely, the regions described in progression are centered (pos. 1), stable sliding (reg. 2), glenoid rim (pos. 3), subluxation (reg. 4) and dislocated (pos. 5). It is our hypothesis that the interaction between humeral head and glenoid surfaces during instability can be adequately modeled as a cam follower mechanism. Thus, humeral head trajectory during dislocation should be predictable. In this study we attempted to prove the accuracy of such a prediction by analyzing the behavior of a custom-molded idealized shoulder model.

Methods: An axisymmetric cup with a 39.6 mm radius and a depth of 17.5 mm functioning as idealized glenoid was molded from a semi-rigid casting resin. Two different Delrin® spheres of 25.4 mm and 38.1 mm radius were sequentially used as humeral heads. The spheres were mounted to a polycarbonate rod simulating the humeral shaft. The articulating surfaces were lubricated with silicone lubricant. The testing device consisted of a 4-axis load cell mounted onto a programmable, stepper-motor controlled x-y table allowing motion in the superior-inferior and anterior-posterior directions. The rod was mounted at a 60° angle to a sliding stage connected to a pneumatic cylinder, which was used to apply a 50-N compressive force. Translation was initiated from the center of the glenoid at 2 mm/sec and continued over 100 mm along the y-axis. Each test condition was run twice, with mean values used for analysis. We used the formulas reported by Anglin et al.(1) and Oosterom et al.(2) to predict peak force (force at pos. 3) and distance to peak force (reg. 2). Additionally, our calculations consisted of two functions describing the humeral track as derived from the glenoid and humeral head geometry. The first function defined the track from the center to position 3 (Fig. 1), while the second described position 3 until dislocation. This allowed for the prediction of lateral displacement (y-axis) throughout this motion. All formulas assumed spherical objects in a frictionless and non-deformable condition.

Results: The error between predicted and observed peak force was 7.1 N (percentage error = 9.9%) for the 25.4 mm sphere and 9.0 N (percentage error = 12.9%) for the 38.1 mm sphere. The errors between predicted and observed distance to peak force were 1.4 mm (10.6%) and 1.9 mm (57.6%) for the small and large spheres, respectively (Fig. 2). The error in subluxation region was confirmed to be linearly related to deformation. Preliminary regression analysis of the lateral displacement data demonstrated an acceptable fit between predicted and observed trajectories.

Discussion: In this experiment, we aimed to establish that humeral head and glenoid interaction during mid-range instability is essentially governed by cam-follower mechanism kinematics. As our results indicate, simple, but accurate, predictions can be made solely on the basis of the geometrical properties and the compressive forces applied to the translating surfaces as far as non-deformable bodies are tested. Unlike previous publications, we propose that the entire humeral track can be predicted by the material and geometrical properties of the glenoid and the humeral head, expressed as mathematical equations. Analyzing spherical objects simplifies the mathematical calculations, but non-circular surfaces can be analyzed in a similar fashion. The mismatch between observed and predicted values can be explained by friction and deformation of the resin during loading. More encompassing models, i.e. finite element analysis tools, are required to incorporate these factors in the model to yield more accurate predictions.

Significance: This study confirms that the gleno-humeral joint behaves according to cam-follower mechanism kinematics during instability. Applying modeling techniques will limit the need for cadavers and other scarce and valuable resources, which can be reserved for other studies in future research.

Figure 1. Geometrical illustration of humeral head motion from center to position 3. Full circle = humeral head at centered position; dashed circle = humeral head at position 3; dotted line = tangent at point of contact; f(x) = function describing glenoid surface; g(x) = function describing center of humeral head track; θ = constraint angle; d = depth of glenoid; a = distance traveled by center of humeral head along y-axis.

Figure 2. Humeral head (HH) translational force observed vs. predicted. Green = 25.4-mm HH, triangles = observed data, line = predicted; orange = 38.1-mm HH, squares = observed data, line = predicted. Relevant positions and regions are indicated with colored brackets.

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References:

Figure 1.

Figure 2

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