OpenSim Modeling of the Avian Downstroke

Team Members

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Description

Avian downstroke during flight is primarily powered using a single muscle, the pectoralis. The large power requirement for flight has spurred the adaptation of birds such that their pectoralis muscles make up 15-25% body weight and their chest bone, the keel, has been enlarged in order to form a broad attachment site for this now massive muscle. Dial even found that when the nerves to the wing of a pigeon were severed, preventing active muscle control, the birds were still able to fly (1). Due to this, the pectoralis has been a major muscle of interest for avian flight research and its work production during the wingbeat cycle has been characterized *in vivo* (2,3,4). While the strain and activation data is fairly reliable from these studies, acquisition of the *in vivo* force production has yet to be confidently estimated. The small size of most birds prevents direct measurement of the muscle force and instead a strain gauge is typically adhered to the bone adjacent to the pectoralis tendon insertion and a manual pull calibration is performed post mortem. This method has consistently underestimated the force required to power flight. Simulation of the avian downstroke could potentially capture the force production of the pectoralis and help to estimate a more accurate work loop.

Building the Model

Bone geometry and joint centers were based off of a CT scan of a parrotlet (*Forpus coelestis*). MeshLab was used to separate and clean the bones as individual meshes. The original mesh containing the entire wing was used to estimate joint centers as a single point by eye.
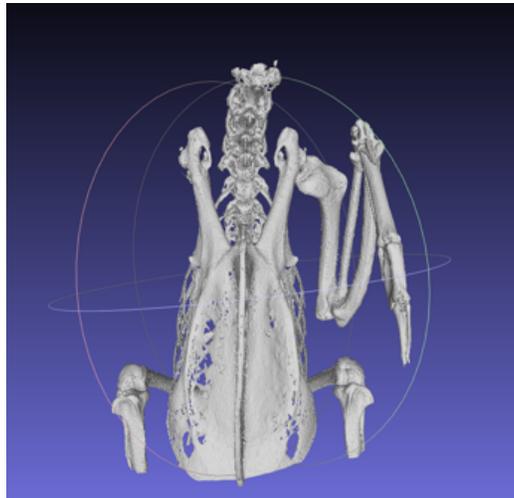

The pectoralis was modeled as four separate muscle-tendon units, representing anatomically significant regions (sternobrachial anterior, middle, and posterior regions; and the thoracobrachial region). The pinnation angle for each unit was based on a pigeon study (5). The optimal fiber lengths were scaled down to a parrotlet size from this study as well (5). The tendons are assumed to be rigid and a first guess at slack length was determined based on geometry. Wrapping surfaces were added to the humerus and keel in order to determine the path of the pectoralis muscles. See below for several views of the resulting model.
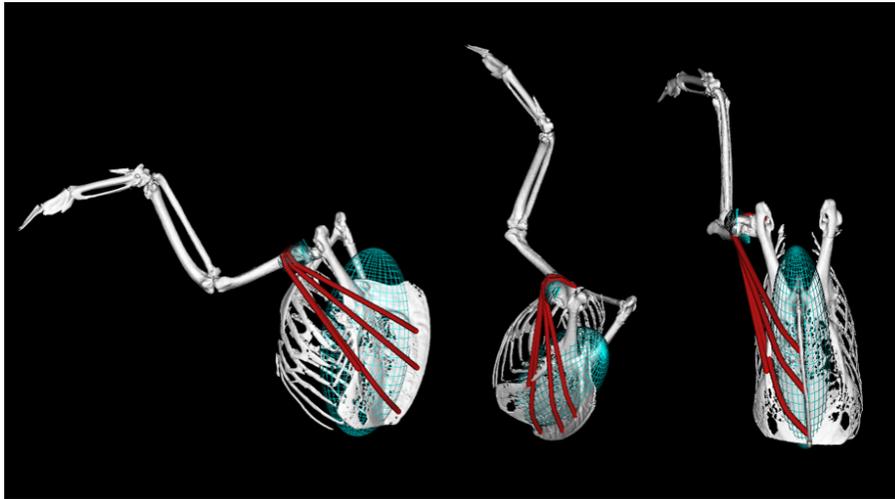
Model Simulations

Kinematics were based off of high-speed film of a parrotlet during level flight. Originally points were tracked manually throughout a single downstroke using a open source Matlab program (6). Markers were then rigidly attached to the bones in the model (see below). The elbow was constrained to a pin joint and long axis rotation of the carpometacarpus was locked in order to reduce the number of points tracked. Inverse kinematics was used to track the point locations for a single downstroke.
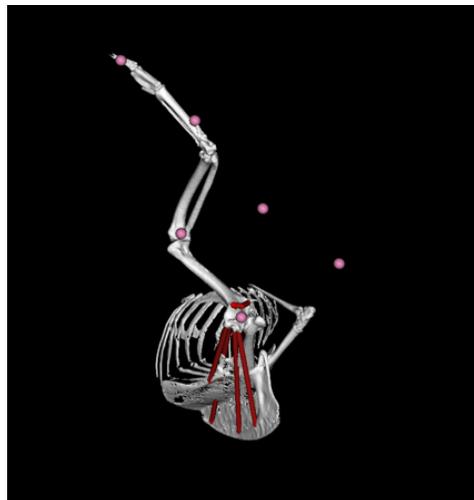

Unfortunately, the errors in tracked the points was too large due to few visible anatomic markers during late downstroke. This resulted in the humerus flipping about its long axis very rapidly at mid downstroke. In order to create a somewhat realistic kinematic profile, rotations about each bone's axis were prescribed based off of the experimental videos. The resulting motion is displayed in the graphs below.
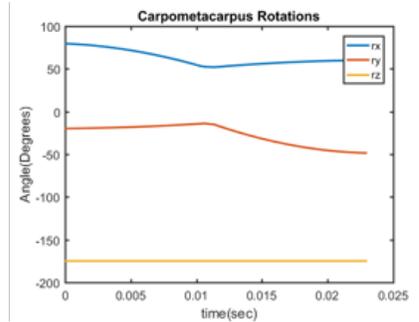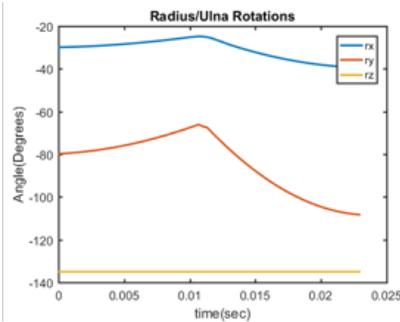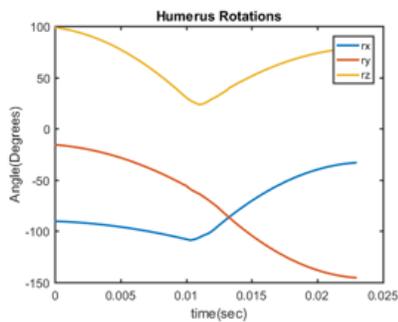
Muscle - tendon unit lengths during downstroke are described by the left graph below. By assuming a rigid tendon the muscle fiber length can be evaluated by subtracting away from the whole length. Based off of (7) the pectoralis should reach optimal fiber length around 3/4 of the way through downstroke. Tendon slack length for each muscle region was adjusted to best match this condition. Muscle fiber length normalized by optimal fiber length for a single downstroke is shown in the right graph below.
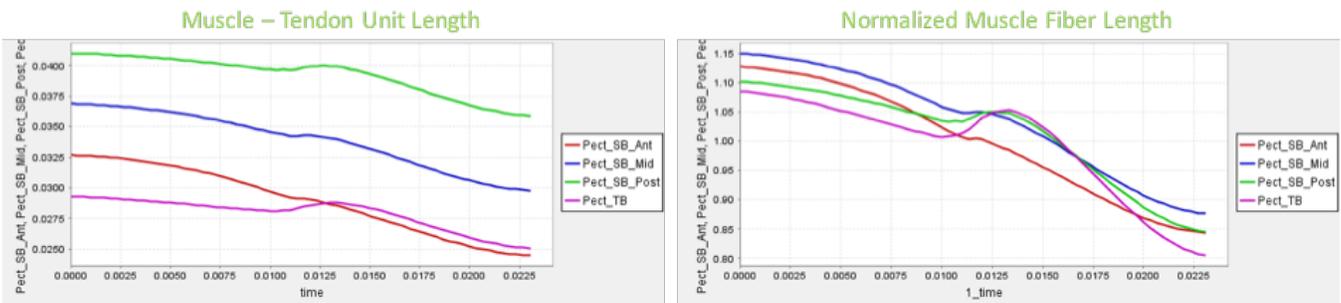
The total length change of the pectoralis found experimentally in cockatiels was about 30% (7), which agrees with my findings here. In the future I would like to obtain more accurate kinematics by tracking reflective markers on the bird wing automatically using a Qualisys System. Using these kinematics, along with experimentally obtained muscle activation (sample activation shown below), a forward simulation of the model can be used to estimate various muscle parameters during flight. Alternatively, torque and residual actuators can be introduced at the model's joint and external force measurements on the wing (see below) can be used to run a static optimization of downstroke. The resulting muscle parameters can then be compared to experimental data.
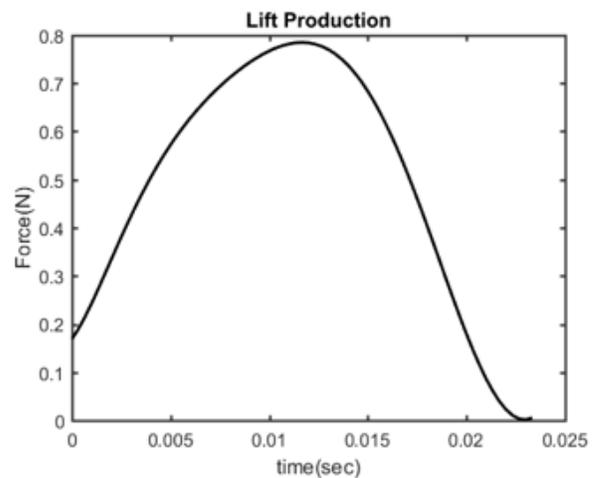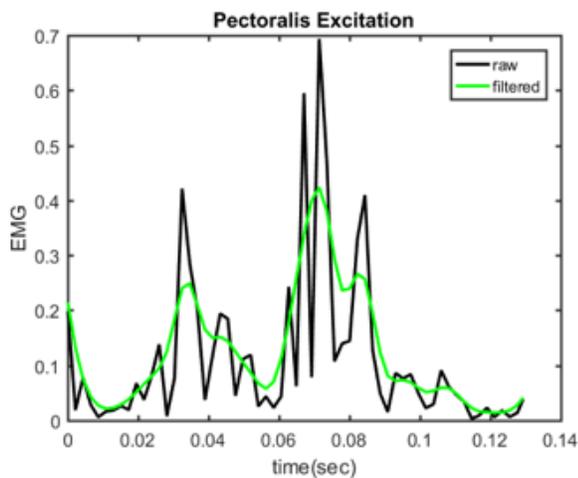
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