PASSIVE ELASTIC PROPERTIES OF THE RAT ANKLE

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INTRODUCTION

Passive elastic properties of muscles and tendons help create realistic musculoskeletal models and influence postural control. Muscles and tendons are often assumed to be “slack” – contributing zero passive torque – at certain joint angles in simulations [1], but this assumption has not always been verified experimentally. Passive joint properties also create a constant rest posture for the joint. Hooper et al [2] has shown that animals with large ratios of muscle passive force capacity to limb size exhibit constant, gravity-independent leg postures that occur within the range where passive force magnitudes of the flexor and extensor muscles overlap. The current work measured passive elastic torques at the rat ankle, a joint that allows the muscle groups to be easily severed and their relative contributions to ankle torque distinguished. Also, passive properties are especially significant at the rat ankle since a constant rest posture was observed.

Previous studies that measured passive rat hindlimb tension and torque have suggested the importance of extensor (a.k.a. “plantarflexor”) contributions to total passive ankle torque. Gillette and Fell [23] found that the extensors gastrocnemius, soleus, and plantaris contributed 29% of the passive tension of the entire hindlimb. Ochi et al [4] observed a statistical correlation between the passive resistive torque of the ankle joint and the passive tension of the gastrocnemius muscle. However, these studies did not measure joint torques directly and examined only flexion (a.k.a. “dorsiflexion”) positions. They also used behaviorally unrealistic knee postures, and measurements of musculotendon contributions to ankle torques may have been confounded by gravitational forces on the foot. The current study has implemented methodological improvements and measured passive torques across the ankle range of motion.

METHODS

Passive rat ankle torques were measured before and after cutting the extensors to find over what joint angles they have an effect or go slack. Measurements were taken at five ankle positions, including “zero” position where the foot was orthogonal to the tibia. Joint positions greater than the zero position were considered flexion positions. Flexion torques, which move the foot towards flexion positions, were also greater than zero.

Two female Sprague-Dawley rats were used for the experiments. The animals were anesthetized with ketamine xylazine and the left hindlimb deñervated by severing the sciatic and femoral nerves. The protocol was approved by the Northwestern Univ. Institutional Review Board.

Figure 1: Experimental setup. A brushless servo motor (Galil Motion Control) rotated a reaction torque sensor (Interface Force), a coupler to the rat foot, and the foot, all attached rigidly in series. A linear stage allowed precise alignment of the center of rotation of the apparatus with the rat ankle. The ankle was mechanically isolated by fixing the tibia and femur with bone screws with the knee at 90 degrees. The animals were placed so that ankle torques were not affected by gravity.
The experimental apparatus rotated the rat ankle to desired joint positions and measured torque and angular position. The motor controller (Galil Motion Control CDS-3310) was commanded by a host computer that ran the experiment protocol. Torque data was recorded at 10 kHz with a resolution of $8.33 \times 10^{-5}$ Nm through an external DAQ board (Measurement Computing 1208FS) connected to the host computer. The motor encoder recorded position with a resolution of $1.57 \times 10^{-3}$ radians at approximately 500 Hz, and position data was synchronized to torque data in post-processing.

The experimental procedure consisted of: 1) stress relaxation at zero position, 2) slow movement at 0.40 radians/s to a non-zero position, 3) stress relaxation at the non-zero position, and 4) slow movement back to zero position. This sequence of events occurred for each of the four non-zero ankle positions. In some sequences, pseudo-random perturbations about a mean ankle position occurred between events 3) and 4), and the data will be used for system identification in the future. The return to zero position ensured that joint torques at each non-zero position had the same history. The presentation of all four non-zero ankle positions was repeated twice for the intact ankle and after the extensors triceps surae and plantaris were severed at the Achilles tendon. Stress relaxations lasted two minutes to allow ankle torques to stabilize, and the last 30 s of data was used to calculate passive torque for that position. The slow movement data was also analyzed and showed similar trends to the stress relaxation data. Future studies will also examine flexor contributions to ankle passive elastic torque.

RESULTS AND DISCUSSION

A constant, gravity-independent rest posture was observed in the passive rat ankle, and the posture was restored after external perturbations to the foot. The ankle ROM was also much larger in extension than flexion, as measured relative to zero position - where the foot was orthogonal to the tibia.

Passive torques across the range of motion shifted towards greater flexion torque, and the zero-torque ankle position shifted towards flexion after cutting the triceps surae and plantaris (fig. 2). Since extensors exert passive extension torque in flexion positions, the decrease in magnitude of extension torques in flexion positions after tendon cuts is not surprising. However, the result that flexion torques for extension positions increase in magnitude after tendon cuts shows that triceps surae and plantaris have an effect throughout the range of motion and oppose the action of the flexors in the passive intact ankle. The shift of the zero-torque ankle position towards flexion after tendon cuts further supports that the rest posture of the ankle is created by the balance of flexor and extensor passive torques and not by slack in the muscle groups.

![Figure 2: Passive ankle torque for ankle intact (blue) and after triceps surae and plantaris were severed (red). Solid markers show data points, circle denotes estimate of equilibrium position, and black lines denote zero torque and zero position.](image)

CONCLUSIONS

The current study measured passive elastic joint torques across the range of motion for the intact rat ankle and after severing the primary extensors. Passive torques across the range of motion shifted towards greater flexion torque after extensors were severed, showing that extensors exert passive torque across the range of motion. The shift of the zero-torque ankle position towards flexion after cutting extensors is further evidence that the rest posture of the ankle is created by the balance of passive ankle flexion and extension torques. These results challenge the common assumption that muscles and tendons go slack within a joint’s range of motion, and support previous work [3] that found a constant rest posture exists in animals with small limb sizes relative to muscle force capacity.

REFERENCES