PROXIMO-DISTAL DISTRIBUTION OF MECHANICAL WORK AND CAPACITY FOR ELASTIC ENERGY STORAGE IN THE LIMB JOINTS OF RUNNING GOATS

David V. Lee, M. Polly McGuigan, and Andrew A. Biewener
Concord Field Station, Harvard University
email: dvlee@fas.harvard.edu, web: http://www.oeb.harvard.edu/cfs/

INTRODUCTION

The legs of running animals generally shorten during the first half of stance and lengthen during the second half. In a multi-segment limb, this basic pattern requires flexion (or closing) followed by extension (or opening) of at least some the joints, thus presenting opportunities for storage and return of elastic strain energy via springs.[1] The Equine metacarpo-phalangeal (MCP) joint provides an elegant example of such a springy joint, the flexion of which is linearly related to the ground reaction force at the foot.[2] In fact, the long digital flexor tendons acting about this joint have almost no capacity to actuate the joint, due their extremely short muscle fibers. Nevertheless, joints proximal to the MCP (or MTP in the hindlimb) lack these anatomical constraints and are often actuated by muscles with longer fibers and shorter tendons. Here we investigate the joint mechanical work that is done by actuators and that which may stored and returned. Forelimb (elbow, wrist, and MCP) and hindlimb (knee, ankle, and MTP) joints were measured in running goats and a simple model was used to identify spring and actuator components of joint work. Distal joints were predicted to have greater capacities for elastic energy storage and return than more proximal joints.

METHODS

Three goats were run at various speeds across a pair of force platforms in series and ground reaction forces were recorded at 2,400 Hz. Concomitantly, an infrared motion capture system tracked joint and trunk positions at 240 Hz. Joint angles were determined from motion capture data and joint moments were given by the cross product of joint position and ground reaction force vectors. Joint work was determined by integrating the product of joint angular velocity and moment over the stance time of a given footfall. Using measured joint angles and moments, a simple model comprising an in-series rotational actuator and rotational spring was implemented to examine the potential for elastic energy storage and return. This was done by manipulating the spring constant and constraining the actuator to match the experimental joint angles while the experimental joint moments were applied. Searching the parameter space produced a spring constant that minimized positive + negative actuator work. Expressing this rectified actuator work as a fraction of rectified joint work provides a useful index of the actuator work contribution.

RESULTS AND DISCUSSION

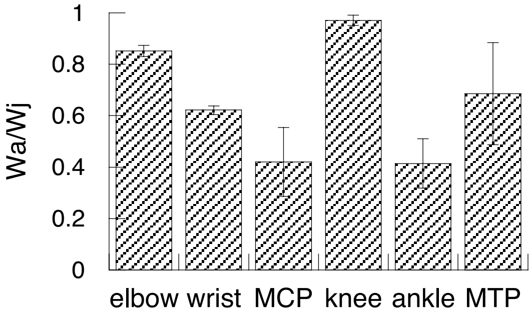

Figure 1: Ratio of rectified actuator work to rectified joint work in three forelimb and three hindlimb joints. Smaller values indicate greater spring contributions. Error bars show 95% confidence intervals.

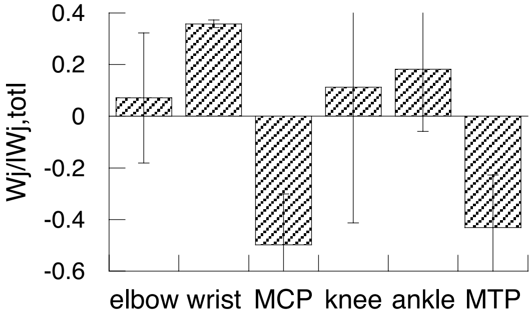

Figure 2: Ratio of joint work to the sum of joint work magnitudes across the three joints of the forelimb or hindlimb. Error bars show 95% confidence intervals.

As expected, the proximal most joints investigated (i.e., the elbow and knee) showed the greatest actuator contributions (values > 0.80) (Figure 1). The MCP and ankle showed the smallest actuator contributions (approximately 0.40), indicating substantial elastic energy storage and return (Figure 1). Surprisingly, similarly low values were not observed in the MTP, the distal most hindlimb joint. The wrist and MTP showed intermediate actuator contributions between 0.60 and 0.70 (Figure 1). This may be due in part to the function of the MTP as a damper, although the MCP also shows substantial negative net work (Figure 2). In contrast, the wrist shows substantial positive net work, while the elbow, knee, and ankle do little net work (Figure 2).

CONCLUSIONS

Greater actuator contributions were found at the more proximal joints. Although the joints with the greatest capacity for elastic energy storage were a distal (MCP) and a mid (ankle) joint, the predicted proximo-distal pattern generally held.

REFERENCES

1. Alexander, R. McN. (1984) *Elastic Mechanisms in Animal Movement*. Cambridge: Cambridge University Press.
2. McGuigan, M. P. & Wilson, A. M. (2003) *J. Exp. Biol.* **206**,1325-1336.