STABILIZATION OF LOCOMOTION BY A MUSCULOSKELETAL MODEL OF CAT HINDLIMBS WITH HILL-TYPE ACTUATORS

Alexander N. Klishko[1] and Boris I. Prilutsky

Georgia Institute of Technology, Atlanta, GA, USA
[1]Permanent address: Institute of Mathematical Problems of Biology, Puschino, Russia
E-mail: aklishko3@gatech.edu, Web: www.ap.gatech.edu/prilutsky

INTRODUCTION

Animals during locomotion are able to withstand sudden external perturbations (Jindrich and Full, 2002). This could be achieved by both reflex responses and intrinsic mechanical properties of the musculo-skeletal system (Jindrich and Full, 2002). The contribution of the latter to locomotion stabilization is difficult to assess experimentally. The aim of this study was to investigate inherent stabilizing effects of a musculoskeletal model of cat hindlimbs with Hill-type actuators (no short-range stiffness) using forward dynamics simulations.

METHODS

For forward dynamics simulations we used a 2D, 10-DOF model of cat hindlimbs with the trunk (for details see Ivashko et al., 2003). Each hindlimb was actuated by 9 muscles with the force-length-velocity properties and pennation of the muscle fibers and the force-length properties of the tendon and passive parallel structures; these data were taken from the literature. Muscle dynamics was described by a Hill-type model similar to one of He et al., 1991. Muscle force was computed as a function of muscle activation, fiber length, velocity, acceleration, and pennation angle. The ground reaction forces were computed from horizontal and vertical displacements of the feet contact points on the ground which was modeled as a viscoelastic material.

In order to simulate normal, unperturbed cat locomotion, we used as input low-pass filtered EMG profiles of 9 hindlimb muscles during walking recorded and/or published previously. The equations of hindlimb motion and muscle dynamics were integrated over one complete walking cycle using the second-order Runge–Kutta method with a constant 0.025-ms step starting with recorded (Prilutsky et al., 2005) generalized coordinates and velocities at the beginning of left leg swing. To minimize the difference

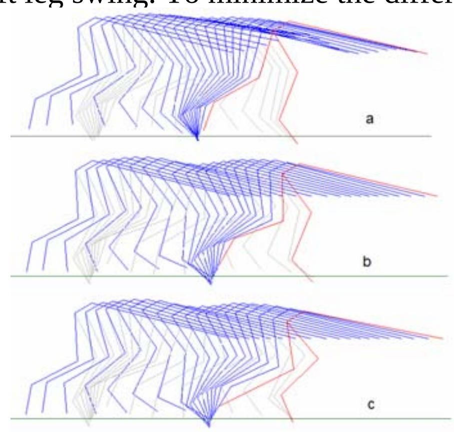

Figure 1: Stick-figures of experimental non-perturbed walk (**a**), simulated non-perturbed walk (**b**), and simulated perturbed walk (**c**; perturbation: t=0%, Δt=7.5 ms, F=0.1 N); the maximum deviation of the hip vertical coordinate from unperturbed hip trajectory (D2) was 14% (considered unstable walk).

in joint angles and ground reaction forces between the experiment and simulation, we used a simulated annealing optimization algorithm to adjust the muscle excitation patterns by tuning three pattern parameters per muscle until the difference between the experimental and simulated kinematics and ground reaction forces was within 10% (e.g. Neptune and Sasaki, 2005). Such a solution was found (see stick-figures in Fig. 1b and compare them with the experiment, Fig. 1a). Normal walking was perturbed by applying a single rectangular force impulse to the left leg in either horizontal or vertical direction. The impulse was defined by 3 parameters which were varied in simulations: onset time (t: 0-90% cycle), duration (Δt: 0-37.5 ms) and magnitude (F: 0.01-10 N). The ability of the model to resist perturbations was estimated using 2 measures D1 and D2. D1 was the mean normalized deviation of the generalized coordinates from those of simulated unperturbed walking, computed over 15 ms from perturbation onset. The model was considered to loose balance if the deviation of the hip vertical coordinate one cycle after the perturbation (D2) was 14% or higher (Fig. 1c).

RESULTS AND DISCUSSION

Perturbations with durations up to 37.5 ms, applied at the cycle onset, destabilized locomotion (D2$\geq$14%) if perturbation magnitude exceeded 0.02 N for vertical impulses (Fig. 2, left), and 0.01 N for horizontal. The two measures of stability (D1 and D2) were closely related for perturbations at cycle onset (Fig. 2, right).

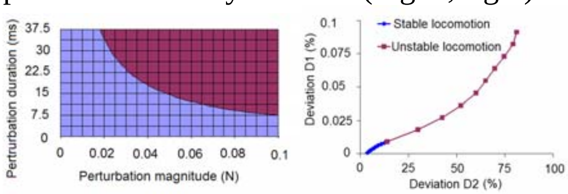

Figure 2: Left: Areas of stable (D2<14%; blue) and unstable (D2$\geq$14%; brown) walking after vertical perturbations (Δt=0-37.5 ms, F=0-0.1N) at cycle onset (t=0). **Right**: Relationship between stability measures D1, D2 after above perturbations.

Thus the model was considered to loose balance if D1 $\geq$ 0.01% which corresponded to D2$\geq$14%. Vertical impulses of Δt=7.5 ms, for example, applied at any cycle instance, did not destabilized locomotion (D1<0.01%)

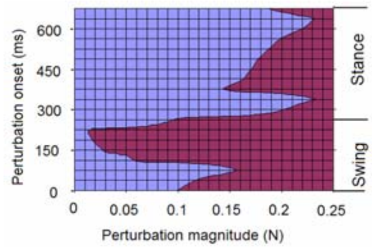

Figure 3: Areas of stable (D1<0.01%; blue) and unstable (D1$\geq$0.01%; brown) walking after vertical perturbations (t=0-37.5 ms, Δt=7.5 ms, F=0-10N).

if F< 0.01 N (Fig. 3). The model was substantially more resistant to destabilizing perturbations in vertical direction compared to horizontal and during stance than in swing (Fig. 3). The most destabilizing effects had perturbations applied at 75% of the swing phase (Fig. 3).

SUMMARY/CONCLUSIONS

Overall, this musculoskeletal model with Hill-type actuators seems unable to withstand even small perturbations applied to the foot during locomotion. Thus, reflexes and short-range stiffness should be taken into account to explain locomotion stabilization in animals.

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