Self-righting in squirrels during unexpected falls: towards the crucial function of bushy tails in arboreal mammals

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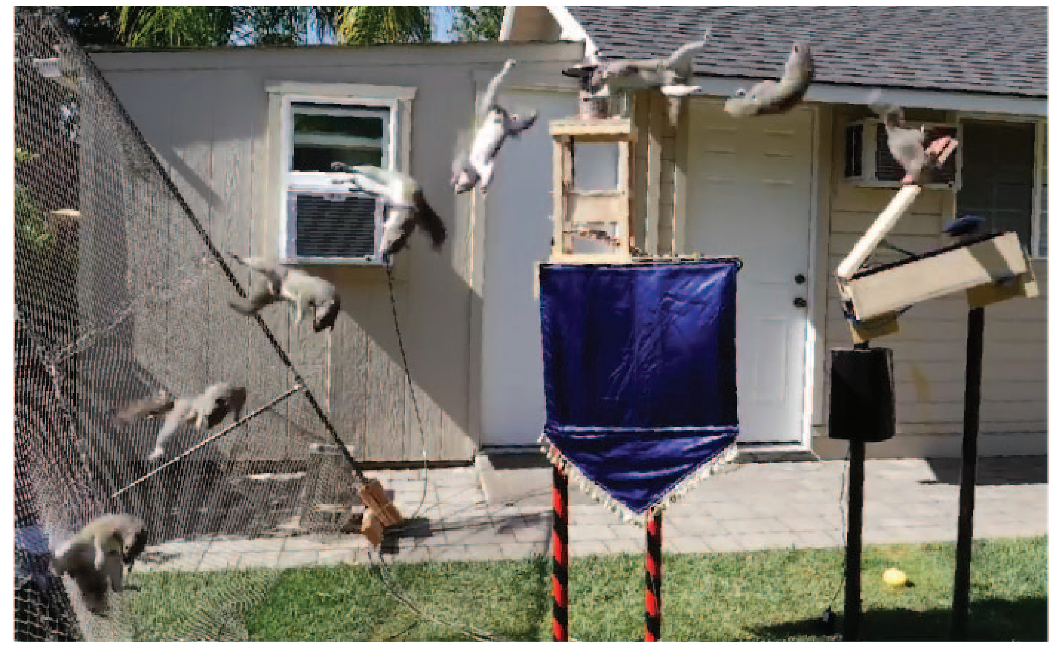
Introduction

Squirrels are widely observed to be among the most maneuverable arboreal animals. In a recent online video, unsuspecting squirrels were catapulted while attempting to reach a feeder. Their body rotation was initially uncontrolled, but they skillfully rotate their tail and stabilize their body, finally landing with stable posture [1]. Previously, aerial righting reflexes have been described in various animals such as cats, rats, geckos, and stick insects using inertial control [2]. However, their ranges of movement were principally in one plane. e.g. cat free-fall: 0 – 180° in coronal plane, gecko jumping: ±45° in lateral plane.

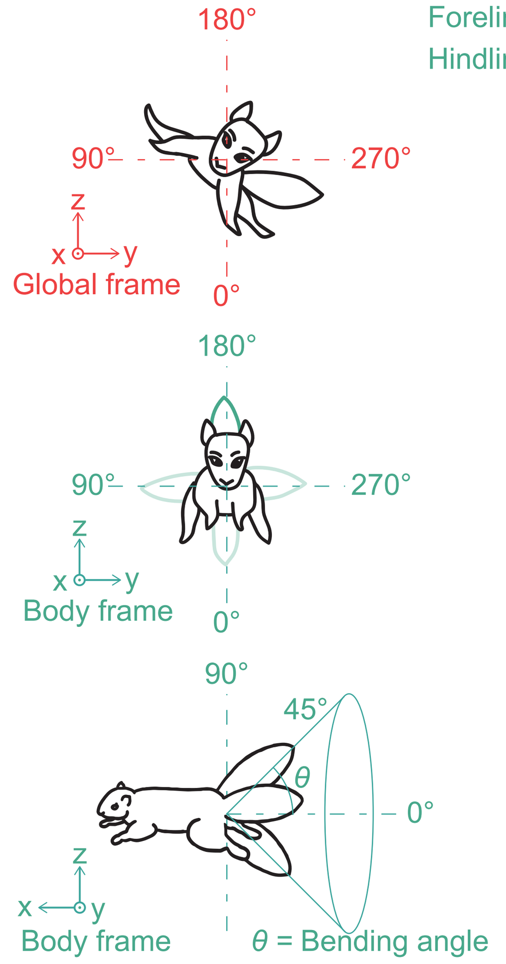


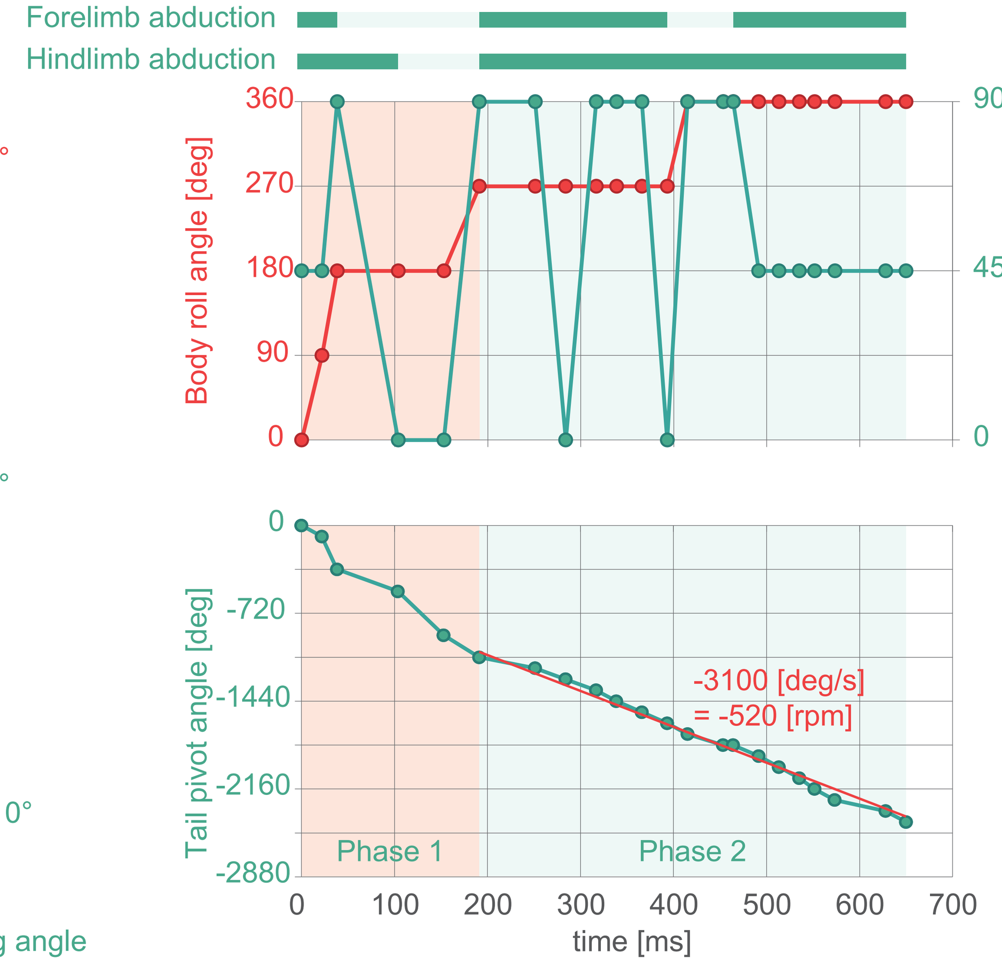
The sequential photo was clipped out from the YouTube video "Building the Perfect Squirrel Proof Bird Feeder" [1] authored by Mark Rober.

In the squirrel's righting maneuver, they move their bodies and tails in three-dimensions and the tail is spun multiple times in under a second. We analyze their motion and examine the righting mechanism.

Video Analysis

We analyzed the righting motion of the squirrels from the video clip. There were two cases of catapulted motion. In both cases the tail stayed very straight and spun in a plane which is orthogonal to the animal's main axis. First, the head and tail were uncontrollably rotated (phase 1), and the head was stabilized, then the body was also stabilized (phase 2).

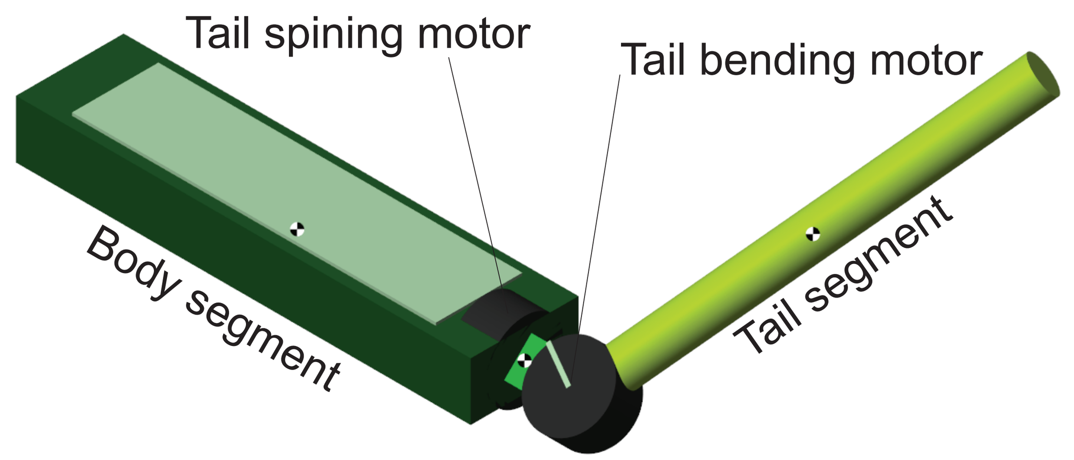




The squirrel cordially controlled the body and the tail to recover from the uncontrolled rotation (phase 1) and continuously spun the tail to stabilize the head and the body (phase 2)

Modeling

Segment	Length [mm]	Width [mm]	Mass [g]
Head	72	38	27.0
Body	164	56	235.0
Tail	215		11.0
Left forelimb	136		8.4
Right forelimb	139		9.9
Left hindlimb	178		25.0
Right hindlimb	171		24.3
Total			340.6



To model the squirrel's righting, we anatomically measured a squirrel's body dimension and mass. Then we made a three dimensional physical model via Simscape Multibody. Body and tail segments were connected by two rotational joints which were for the tail bending and the tail spin. Dimension, mass and inertia of the model were set based on the anatomical investigation.

Simulation Study

To investigate the righting mechanism, we explored optimized tail behavior using the model via genetic algorithm.

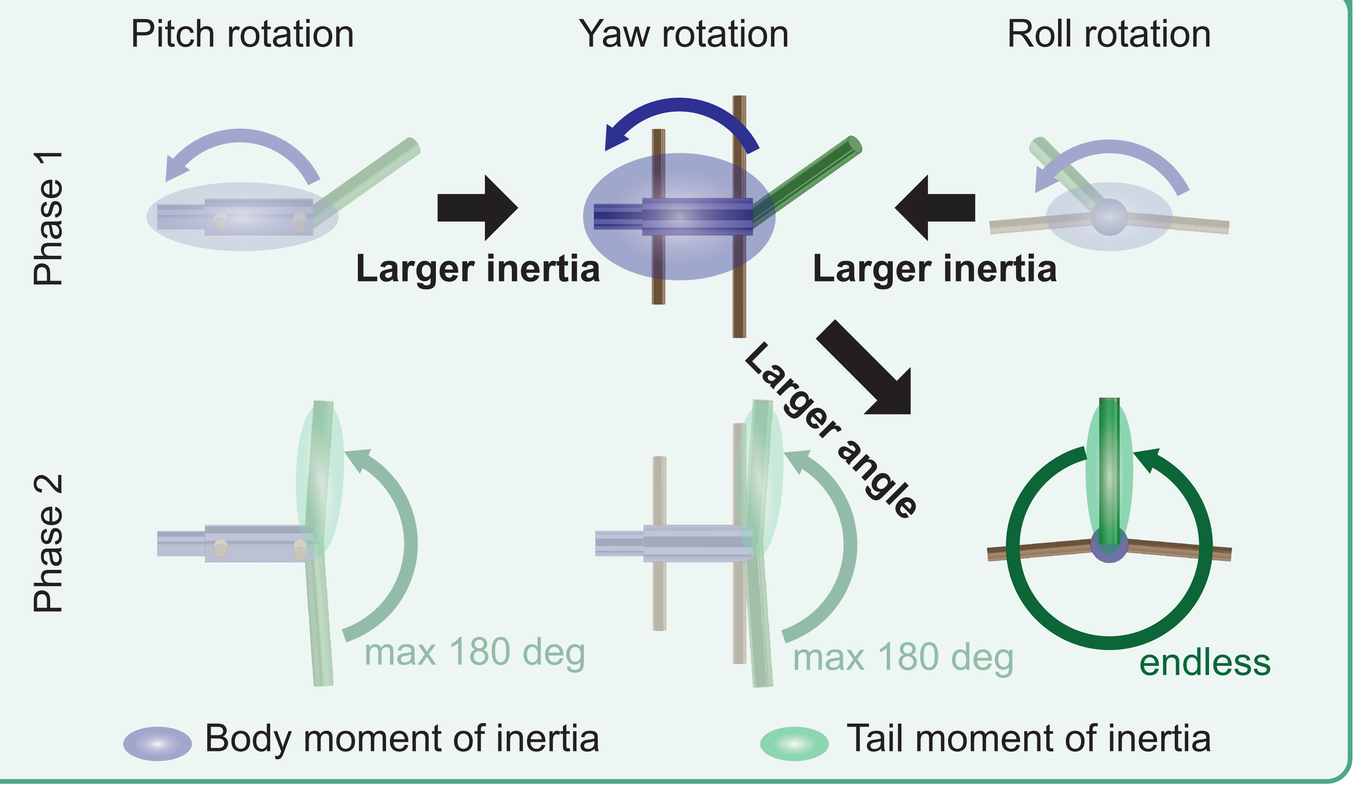
Simulation conditions

The model was initially given following angular velocities to emulate the unexpected launching. roll: -360 deg/s, pitch: -90 deg/s. Target values of the tail control were defined by some collocation points, which were used for gene representation in the with spline interpolation. Tail bending was controlled by rotational angle and tail spin was controlled by rotational speed. Fitness function to be minimized was defined as rotational kinetic energy of the body segment.

Results

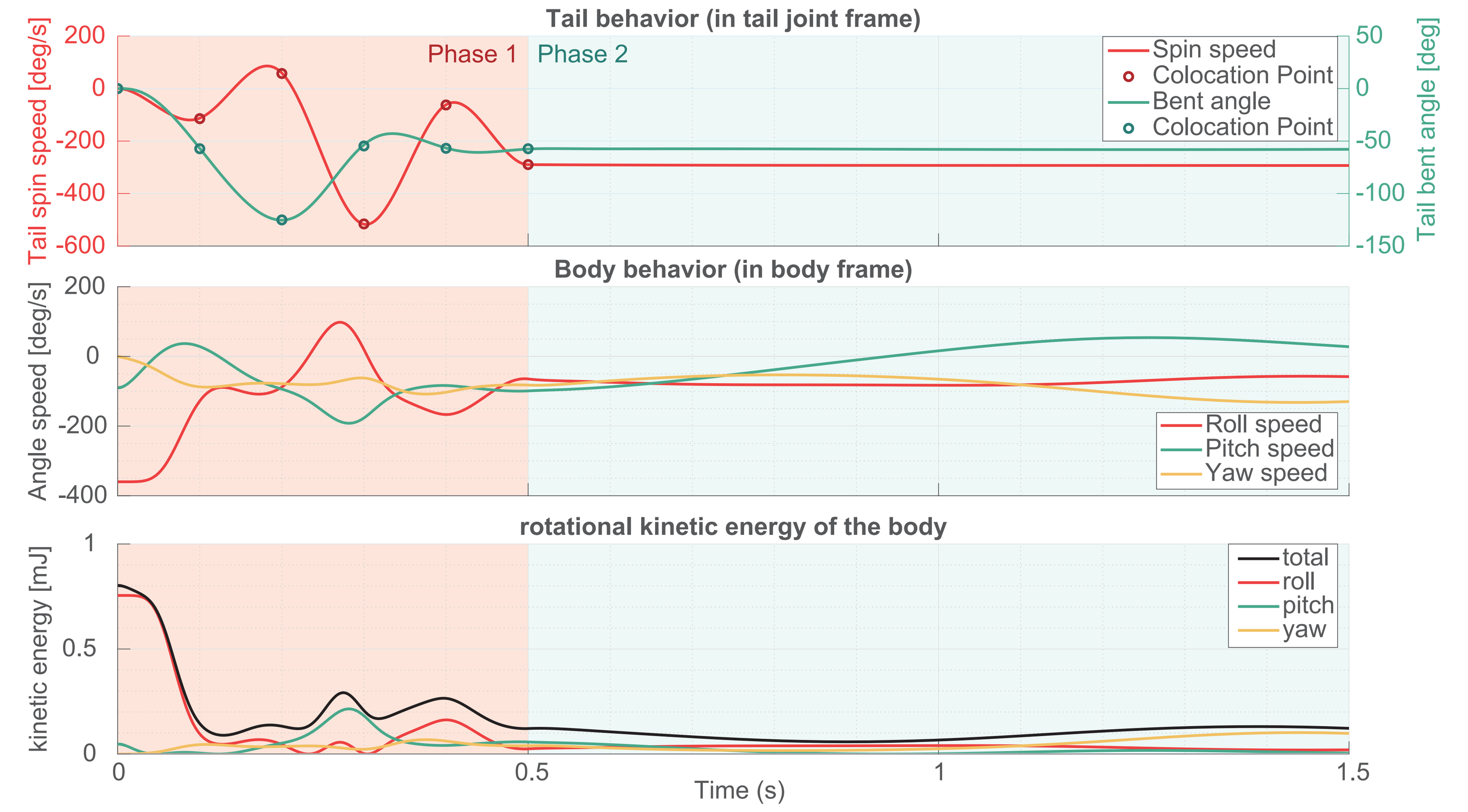
Phase 1:
Using tail bending, the model changed its rotational axis from roll and pitch to yaw to use larger moment of inertia.

Phase 2:
It changed the axis from yaw to roll again and at the same time spun the bent tail to reduce its body angular momentum: transfer body rotational kinetic energy to the tail.



Analysis

The body kinetic energy was reduced by 81 % (initially 0.802 mJ) by the tail motion and was transferred into tail kinetic energy (conservation of angular momentum). This optimized results showed squirrels have potential to transfer their body kinetic energy into the tail to stabilize their body. Additionally, in the real squirrel, they are able to control yaw moment of inertia by abduction and adduction of their limbs.



Conclusion & Discussion

We investigated the squirrel's righting mechanism from unexpected launching and presented effect of the enlargement of the body rotational inertia and continuous rotation of the tail.

This study ultimately will help us to better understand the mechanics of the tail during locomotion in a complex arboreal environment.

Aerodynamics effect

In this modeling, we ignored the aerodynamics effect. In the real world, we suppose the bushy tail can work as a damping element and help the kinetic energy to be dissipated. This mechanism could help stabilize the body more efficiently during locomotion maneuver.

Musculo-skeletal effect

In a musculo-skeletal body, a tail has elasticity which may help the rotational axis change in the phase 1. Also, the tail can have more DOFs instead of mechanical rotational joints. This insists a possibility to control its moment of inertia during spinning in the phase 2.

Squirrel robot

We developed a squirrel-like robot based on our simulation results. We will conduct robot experiments in the real world as well as additional behavioral observation from living squirrel individuals to explore new factors to be implemented further on in our model. To keep performing the hardware – simulation cycles would brush up the model and enable us to know animals more.

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[1] M. Rober (2020.05.24), "*Building the Perfect Squirrel Proof Bird Feeder*," Video on YouTube, URL: https://www.youtube.com/watch?v=hFZFjoX2cGgt=16m10s, [2] A. Jusufi, Y. Zeng, R. J. Full, R. Dudley, "Aerial Righting Reflexes in Flightless Animals," *Integrative and Comparative Biology*, Vol. 51, No. 6, pp 937–943, 2011.

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