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# Multibody Dynamics for Planar Peristaltic Locomotion of Metameric Earthworm-like Robots

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## Abstract

Earthworms, stand out for their remarkable mobility in confined spaces and challenging terrains, inspiring the development of numerous prototypes [1–3] that mimic earthworm planar locomotion. However, the lack of dynamic analysis of the planar peristaltic locomotion of multi-segment earthworm robots leads to notable disparities between theoretical predictions and experimental outcomes, notably regarding slippage [3–5]. This motivates the authors to formulate a comprehensive and precise multibody dynamic model for the planar peristaltic locomotion of the metameric earthworm-like robot. Specifically, a simplified model of the robot is constructed, incorporating rigid bodies and connectors, guided by the robot's configuration and locomotion mechanism (Figure 1a). In this model, each rigid body experiences a combination of propulsive and frictional forces, consistently adhering to the constraints of an isosceles trapezoidal shape throughout deformation. On the one hand, proportional-derivative (PD) controllers are developed to replicate the propulsive force and torque generated by servomotors (Fig. 1b). The PD controllers function within three degrees of freedom—$x$, $y$, and $\theta$—constantly assess the variance between the measured process variable (PV) and the desired setpoint (SP), i.e., continuously correcting distances along with the pinch angle between the two adjacent rigid bodies. On the other hand, the anisotropic friction force on each segment is transferred from the bristle structures to the center of mass (CM) of the rigid body (Fig. 1c), incorporating the hyperbolic tangent function to characterize the impact of segment deformations on friction. Furthermore, the friction model is refined as the head segment is elevated during locomotion, thereby reducing lateral friction and augmenting sliding. Leveraging the aforementioned setup, the dynamic model of the $i$th rigid body can be deduced as:

$$\begin{aligned} m\ddot{x}_i &= f_{i,x} - h_{i,x} + h_{i-1,x}, \\ m\ddot{y}_i &= f_{i,y} - h_{i,y} + h_{i-1,y}, \qquad (i = 1, 2, \cdots, N+1). \\ J\ddot{\theta}_i &= Mf_i - M_i + M_{i-1}, \end{aligned} \tag{1}$$

Here, $m$ and $J$ denote the mass and inertia of each rigid body, respectively. $(x_i, y_i)$ represents the global coordinates of the CM of rigid body $i$, while $\theta_i$ signifies the angle between rigid body $i$ and the global $x$-axis. The subscripts '$x$' and '$y$' of $h_{i,x}$, $h_{i,y}$, $f_{i,x}$, $f_{i,y.}$ indicate the projection of the propulsive force and frictions in the global $x$ and $y$ directions, respectively. For the specificity of the head and tail segments, Mark $h_{0,x} = h_{0,y} = h_{i+1,x} = h_{i+1,y} = 0$ and $f_{N+1,x} = f_{N+1,y} = 0$, to indicate the special positions of the head and tail.

Simulations and experiments involving fifty discrete gaits are conducted on the proposed dynamic model and a six-segment earthworm-like robot. Additionally, the previously introduced kinematic model's [3] results during discrete gaits are presented for comparison. Locomotion performance metrics, depicted in Fig. 2, are obtained for all gaits in kinematics, dynamics, and experiments. The results indicate that the dynamic model provides accurate quantitative and qualitative predictions for discrete gaits. Qualitatively, the metrics derived from the dynamic model exhibit significant alignment with kinematic estimates and experimental validation. Quantitatively, Fig. 2 illustrates that the dynamic model-based simulation results align more closely with experimental findings than those of the kinematic model.

Furthermore, we experimentally demonstrate the dynamic model's comprehensive capture of the robot's slippage and in-situ oscillatory gaits, achievements that the kinematic estimation fails to accomplish. Additionally, the correction of head friction is proven to significantly enhance the accuracy of predicting trajectory radii and locomotion velocities for specific circular gaits. These findings collectively affirm the accuracy, validity, and comprehensiveness of the proposed multibody model.

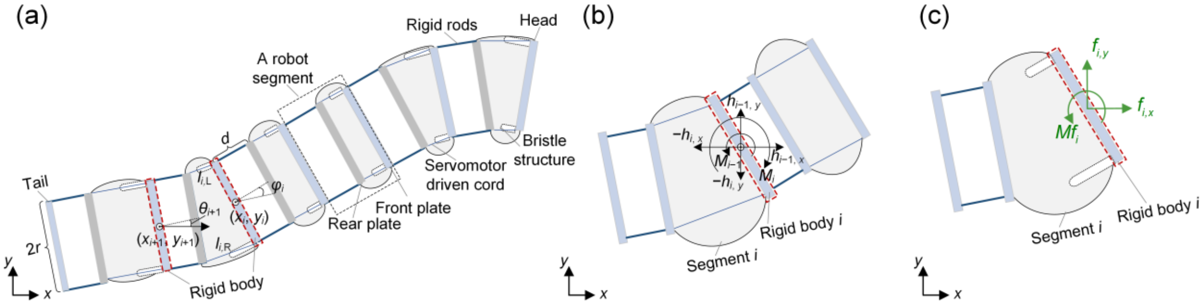

Figure 1: Schematic description of the Earthworm-like robot engaged in peristaltic planar locomotion(a) General configuration of an $N$-segment earthworm-like robot. (b) Propulsive forces and torques exerted on the $i$-th rigid body. (c) Friction forces and torques exerted on the $i$-th rigid body.

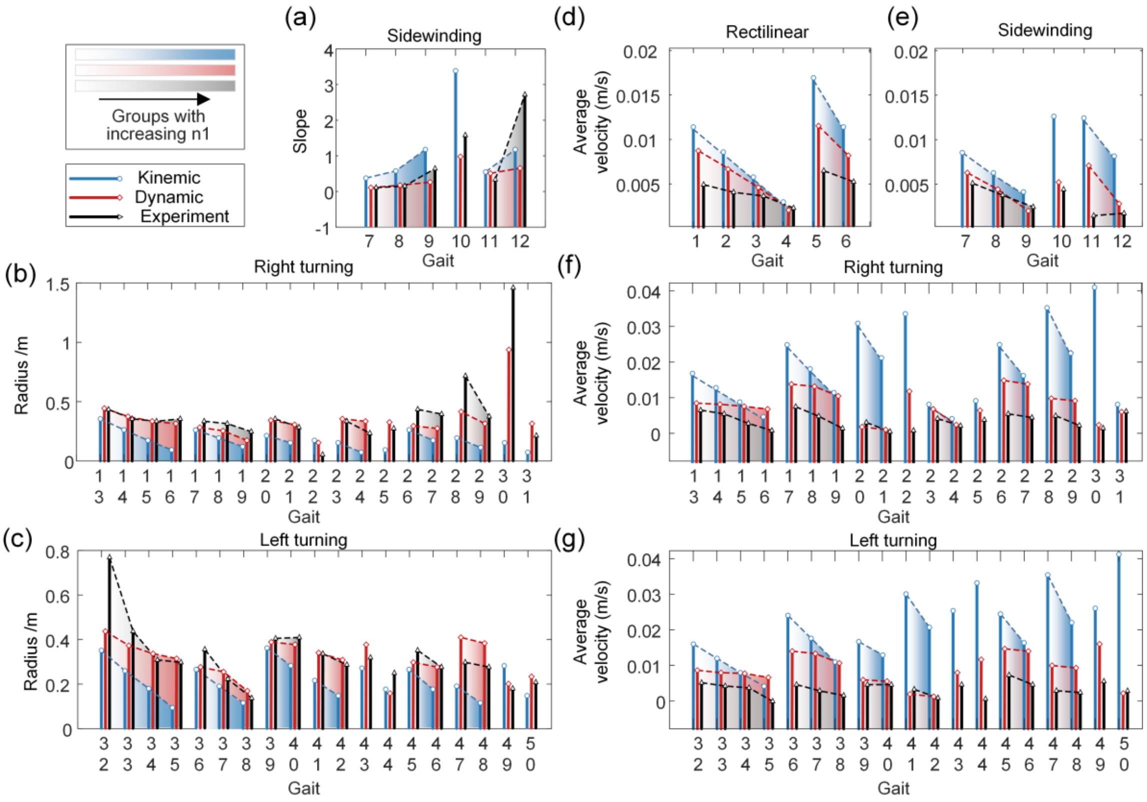

Figure 2: Comparison of kinematic, dynamic, and experimental results of locomotion metrics, comprising (a) slope of sidewinding locomotion, (b) radius of right-turning circular locomotion, (c) radius of left-turning circular locomotion, (d)-(f) average velocity of rectilinear locomotion, sidewinding locomotion, right-turning circular locomotion and left-turning circular locomotion, respectively.

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