TD-SLIP: A Better Predictive Model for Human Running

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1 Introduction

Simple spring-mass systems, such as the Spring-Loaded Inverted Pendulum (SLIP) model, are widely accepted in the literature both as accurate descriptive dynamical models for animal locomotion [3, 5] as well as the basis for numerous robots capable of dynamic locomotion [7, 11]. Most existing literature, however, focuses almost exclusively on telescoping leg models with only radial actuation, overlooking possible uses of hip torque actuation for running behaviors.

Previous studies have demonstrated that center-of-mass kinematics and ground-reaction-force (GRF) data are reasonably consistent with the predictions of the SLIP model in many animals [3,5]. However, a recent qualitative comparison of GRF data from running animals to those generated by the SLIP model reveals structural discrepancies in horizontal force predictions [17]. Here, we investigate the Torque-Actuated Dissipative SLIP (TD-SLIP) model, which incorporates both damping and hip torque actuation [2], in an effort to overcome the structural deficits in the SLIP model pointed out by Srinivasan and Holmes [17]. Following a similar approach, we show that TD-SLIP indeed is both qualitatively and quantitatively more accurate than the ideal SLIP model in predicting GRF profiles of human running.

The lossless SLIP model is extensively presented in the literature and consists of a point mass attached to a massless compliant leg alternating between flight and stance phases during locomotion. In contrast, the TD-SLIP model [2], illustrated in Fig. 1, introduces viscous radial damping on the leg, and incorporates a controllable ramp torque acting on the leg, parameterized by its value at touchdown and vanishing at liftoff. To achieve this, the specific torque used in the TD-SLIP model [2] takes the form

$$\tau(t) = \tau_0 \left(1 - \frac{t}{t_f}\right), \qquad (1)$$

where $t = 0$ and $t = t_f$ corresponds to touch-down and lift-off instants respectively. We explore two other forms of this torque profile in this paper.

Our comparison of these two models—SLIP and TD-SLIP—supports the hypothesis that damping is a significant factor in modeling human running and the use of hip torque actuation might have an important role for such behaviors as well. This extended model is also more realistic from an implementation point of view, as evidenced by the successful use of similar actuation mechanisms in a number of robotic platforms [10, 15, 16].

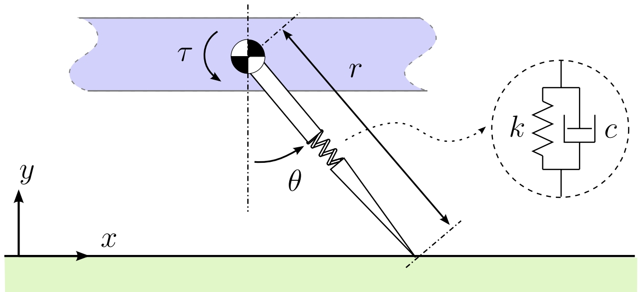

Figure 1: TD-SLIP : Planar, dissipative spring-mass hopper with rotary hip actuation [2]

2 Fitting SLIP and TD-SLIP Models to Experimental Human Running Data

Our comparison of model effectiveness is based on GRF data obtained from human running experiments at different speeds, obtained from [9] for a single human subject running at 3 m/s and from [8] for 4 m/s, 5 m/s and 6 m/s with normalized force data averaged over 10 human subjects for each speed. Using standard filtering techniques in biomechanics ensuring periodicity of motion and the average locomotion velocity, we extracted COM trajectories through integration. We then found model parameters (stiffness, damping, and torque profile parameters) and system initial conditions for both the SLIP and TD-SLIP models that satisfy important trajectory constraints such as matching average speed, stance and flight times and ensuring periodicity of motion while minimizing mean squared errors (MSE) between predicted and observed GRF profiles. MSE of a prediction on a data set can be calculated using

$$MSE = \frac{1}{N}\sum_{k=1}^{N} ||\mathbf{F}^*(k) - \mathbf{F}(k)||_2^2,$$

where N is the number of samples and $\mathbf{F}^*(k)$ is the prediction of the force vector at k^{th} sample.

As in [17], we fixed the body mass to $64.5kg$ and the leg length to $1m$ for both models, normalizing experimental force measurements whenever necessary. In order to ensure that the number of parameters was the same between the two models, we also extended the ideal SLIP model by including radial damping (but no hip torque) and piecewise constant stiffness (effectively adding radial actuation). For both TD-SLIP and damped-SLIP models, we enforced the condition that successive apex states must have the same energy, since both are actuated, dissipative models. Given practical limits on parameter values, our fitting simulations converged on unique solutions.

We evaluated the fitting performance of each model first quantitatively through the mean squared force error, and then qualitatively through the "effective footprint" concept introduced by [17]. The latter criterion is a visual method based on the intersection of the GRF direction passing through the COM with the ground plane and helps emphasize the evolution of the force direction throughout stance. For an ideal SLIP with a central force profile, the footprints must all meet at a single point, an inescapable structural feature of SLIP. However, when more complex effects such as foot slippage, rolling contact or hip torque actuation are present, the footprints may not all coincide within a single stance. Investigation of these footfalls for experimental data as well as the SLIP and TD-SLIP models reveals important discrepancies and helps identify the relative importance of different model features and parameters.

3 Results and Conclusion

As a result of our fitting analysis, the damped-SLIP model mentioned above converged to a conservative model for all speeds, implying that the added parameter does not improve the fit. For the TD-SLIP model, the ramp torque profile provided a better fit for all speeds than constant and sinusoid torque profiles whose amplitudes were considered as parameters for fitting. Consequently, we have chosen the conservative SLIP model and the TD-SLIP with a ramp torque profile for our comparisons. Prediction errors in GRF profiles between fitted models and experimental data presented in Table 1 show that TD-SLIP model has better predictive performance compared to the damped-SLIP model. Mean squared errors of the SLIP model are 2 to 4 times larger than those of the TD-SLIP model. Table 1 also provides root mean square errors (RMSE) which give the quadratic mean of the prediction errors. Quadratic mean of an "error signal" is a more intuitive quantitative result than MSE.

Investigation of associated effective footprints also shows that the TD-SLIP provides a better qualitative fit to experimental data, reproducing the rear-facing ground reaction forces at the beginning of stance rather than the single-point predicted by the ideal SLIP model (e.g. Fig. 2). This qualitative match, illustrated in Fig. 2 for speeds 3 m/s and 4 m/s, between the TD-SLIP model and experimental data is observed for all speeds and is consistent with observations described in [17].

We believe that both the quantitative results in the form of prediction errors in GRFs and the qualitative results that we observed using the graphical tool by [17] provide evidence towards both the presence of significant damping, and the use of hip torque actuation as an additional source of energy used by human runners, improving the predictive accuracy and utility of dynamic models of running.

Table 1: Prediction Errors (MSE and RMSE) in GRF Profiles

	MSE $[N^2]$		RMSE $[N]$	
Speed	SLIP	TD-SLIP	SLIP	TD-SLIP
3 m/s	44657	12424	211.3	111.5
4 m/s	48584	22413	220.4	149.7
5 m/s	68065	29960	260.9	173.1
6 m/s	87664	32837	296.1	181.2

4 Open Questions

How well can TD-SLIP describe animal locomotion for animal morphologies that closely match the TD-SLIP like models (e.g. guineafowl [4], ostrich [14])?

Can TD-SLIP capture transient behavior in animal (including human) running? What are the extensions necessary to handle the transients in human running?

TD-SLIP model ascribes all passive dynamics to the radial direction and active components to the angular direction. Should this assumption be relaxed, and how might we identify the most appropriate configuration of passive and active components in animal running? How can TD-SLIP-like simple mechanical models be used in understanding neural control mechanisms [6]?

Many scientific studies indicate that simple low dimensional models can describe complex animal behaviors [6,12,13]. Is this a byproduct of different neuromechanical control rules? Or is this a control target that might simplify control, e.g. facilitating a two-step control policy [1]?

Can TD-SLIP and other models be useful in improving interventions for rehabilitation?

References

[1] M. Ankarali and U. Saranl. Control of underactuated planar pronking through an embedded spring-mass hopper template. *Autonomous Robots*, 30:217–231.

[2] M. M. Ankarali and U. Saranli. Stride-to-stride energy regulation for robust self-stability of a torque-actuated dissipative spring-mass hopper. *Chaos*, 20(3), Sep. 2010.

[3] R. Blickhan and R. J. Full. Similarity in multilegged locomotion: Bouncing like a monopode. *J. Comp. Physiol., A*, 173(5):509–517, Nov. 1993.

[4] M. A. Daley and A. A. Biewener. Running over rough terrain reveals limb control for intrinsic stability. *Proc Natl Acad Sci U S A*, 103(42):15681–15686, Oct. 2006.

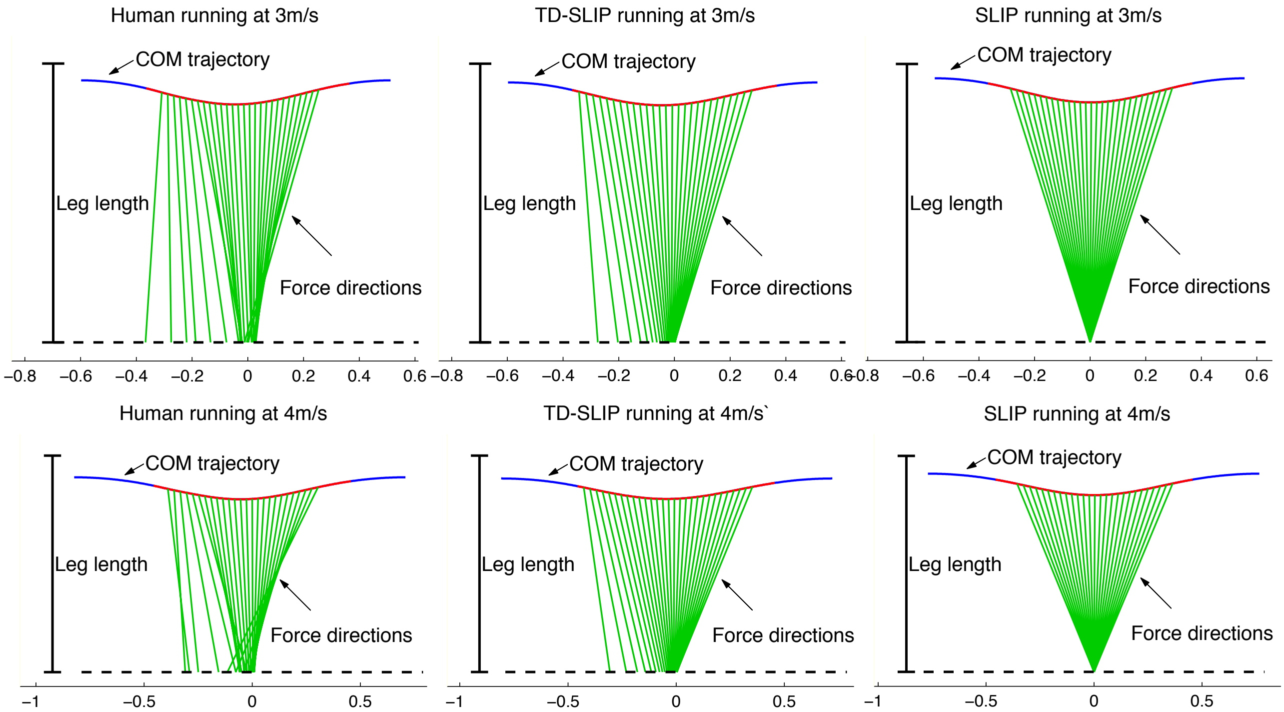

Figure 2: Center-of-mass trajectories and effective footprints of human, TD-SLIP and SLIP running at 3 m/s and 4 m/s. Green lines show the directions of GRFs as in [17].

[5] C. T. Farley, J. Glasheen, and T. A. McMahon. Running springs: Speed and animal size. *The Journal of Experimental Biology*, 185:71–86, 1993.

[6] R. J. Full and D. E. Koditschek. Templates and anchors: Neuromechanical hypotheses of legged locomotion. *The Journal of Experimental Biology*, 202:3325–3332, 1999.

[7] P. Gregorio, M. Ahmadi, and M. Buehler. Design, control, and energetics of an electrically actuated legged robot. *Transactions on Systems, Man, and Cybernetics, Part B: Cybernetics*, 27(4):626–634, August 1997.

[8] J. Hamill, B. Bates, K. Knutzen, and J. Sawhill. Variations in ground reaction force parameters at different running speeds. *Human Movement Science*, 2:47 – 56, 1983.

[9] R. Kram, T. M. Griffin, J. M. Donelan, and Y. H. Chang. Force treadmill for measuring vertical and horizontal ground reaction forces. *J. Appl. Physiol.*, 85(2):764–769, 1998.

[10] I. Poulakakis, J. A. Smith, and M. Buehler. Modeling and Experiments of Untethered Quadrupedal Running with a Bounding Gait: The Scout II Robot. *Int. J. Rob. Res.*, 24(4):239–256, 2005.

[11] M. Raibert. *Legged robots that balance*. MIT Press, Boston, 1986.

[12] S. Revzen. *Neuromechanical Control Architectures of Arthropod Locomotion*. PhD thesis, University of California, Berkeley, 2009.

[13] S. Revzen and J. M. Guckenheimer. Finding the dimension of slow dynamics in a rhythmic system. *Journal of The Royal Society Interface*, 2011.

[14] J. Rubenson, D. Heliams, D. Lloyd, and P. Fournier. Gait selection in the ostrich: mechanical and metabolic characteristics of walking and running with and without an aerial phase. *Proceedings of the Royal Society B: Biological Sciences*, 271(1543):1091, 2004.

[15] U. Saranli, M. Buehler, and D. E. Koditschek. RHex: A simple and highly mobile robot. *International Journal of Robotics Research*, 20(7):616–631, July 2001.

[16] A. Sato and M. Buehler. A planar hopping robot with one actuator: design, simulation, and experimental results. In *Proc. of the IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, volume 4, pages 3540–3545, Sept.-2 Oct. 2004.

[17] M. Srinivasan and P. Holmes. How well can spring-mass-like telescoping leg models fit multi-pedal sagittal-plane locomotion data? *J. Theor. Biol.*, 255(1):1–7, 2008.