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Impacts Versus Non-Impulsive Muscle and Joint Loads in a Two-Segmented Model of Hopping

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EXTENDED ABSTRACT

1 Introduction and hypothesis

The dynamic analysis of legged locomotion, in general, is a complex problem. A possible analysis direction is developing controlled multibody models whose control imitates the pattern generation and balancing process of natural pedal locomotors [1–4]. These controllers may be optimized and there is a wide range of choices for the related cost function. In some approaches a particular goal is the reduction of the ground-foot impact intensity [5], which is a particularly important issue in human running biomechanics [4,6,7]. From the literature, it can be deduced that the ground-foot impact intensity is highly affected by the motion kinematics.

The reduction of impact intensity in case of runners seems to be twofold. Foot plays the role of a shock absorber and utilizing the shock absorbing capabilities of the foot is good for the upper parts of the leg and hip. The drawback is that the foot may have a high loading particularly because of shock absorbing. For instance, paper [8] concludes that the risk of hip and knee injuries is higher in case of rear-foot strike pattern, when the shock absorbing role of the foot is not utilized. On the other hand, injuries related to the ankle and the foot are more probable in case of runners with fore-foot strike pattern [6, 8]. These observations suggest that an optimum between the loading of the foot and the loading of other tissues of the leg exists.

Similarly to the issue of foot strike pattern, the knee flexion may provide both benefits and drawbacks in case of running and hopping locomotion. Large bent knee helps in the reduction of impacting loads; however, it may increase the post-impact loading of muscles and tendons. Our hypothesis is that an optimum of knee flexion exists, which minimizes a certain linear combination of the impacting loads and the post-impact muscle efforts.

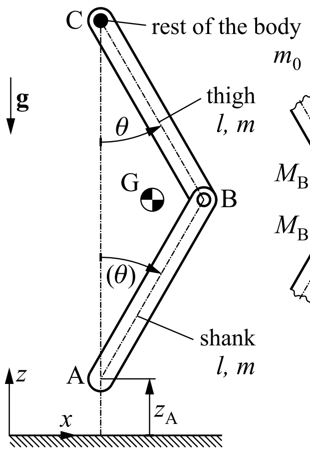
2 Methods

In order to understand the effect of knee flexion, we define a mathematical model of vertical hopping. The 2DoF planar model consists of two homogeneous bars of mass m connected by a frictionless pin joint and a particle of mass m_0. The upper and lower bars play the role of the thigh and the shank, respectively. The point mass m_0 represents the unmodeled body parts. For the sake of simplicity, point foot is considered. Point A, B and C denotes the tiptoe, the knee and the hip, respectively. As the left panel of Fig. 1 shows, the general coordinates z_A and θ allows the vertical motion of the model and the bending of the knee. Horizontal motion and the tilting of the model is not possible. The tiptoe is fixed to the ground by a frictionless revolute joint in the ground phase. The control, which maintains uniform hopping height, is an inseparable part of the model. The control action is achieved by the torque M_B applied in the knee. The time invariant control guarantees the prescribed apex height by means of a feedback loop, which modifies the control parameters stride-to-stride.

When the stable periodic motion, i.e. hopping, is achieved, we analyse the following two measures. **1)** The first measure is the norm of the effective mass matrix $\mathbf{M}_\mathrm{eff}$, which indicates the impact intensity [7, 9]. The effective mass matrix is calculated at the time instant of ground-foot impact as $\mathbf{M}_\mathrm{eff} = \mathbf{P}_\mathrm{c}^\mathrm{T}\mathbf{M}\mathbf{P}_\mathrm{c}$, where $\mathbf{M}$ is the mass matrix and $\mathbf{P}_\mathrm{c}$ represents the projection into the motion space that is constrained by the ground foot contact. A certain part of the kinetic energy, which is called *constrained motion space kinetic energy* (CMSKE) [7] is absorbed due to the impact. **2)** The second measure is related to the post-impact muscle loading and indicates the non-impulsive muscle and joint loading. The kinetic energy, which is not absorbed by the impact and which is related to the vertical downwards motion, has to be absorbed by the muscles. Then the body has to be accelerated upwards. The second measure is created by the combination of the mechanical work W_{M_B} and the peak value $\hat{M}_\mathrm{B}$ of torque M_B.

3 Results

The effective mass $\mathbf{M}_\mathrm{eff}$ plotted on the right panel of Fig. 1 shows that falling on the ground with straight leg is the worst possible configuration, because the effective mass is equal to the whole body mass $2m + m_0$. The effective mass decreases monotonically with the flexion of the knee. Consequently, knee flexion is beneficial from the point of view of impact intensity: the more the leg is bended the lower is the impact intensity. We expect that the opposite is true for the non-impulsive muscle loading. The kinetic energy amount, which is not absorbed by the impact, is higher for higher values of θ. Therefore the work of the knee torque M_B and the peak value of the knee torgue M_B is expectedly higher. Both depend on the control algorithm.



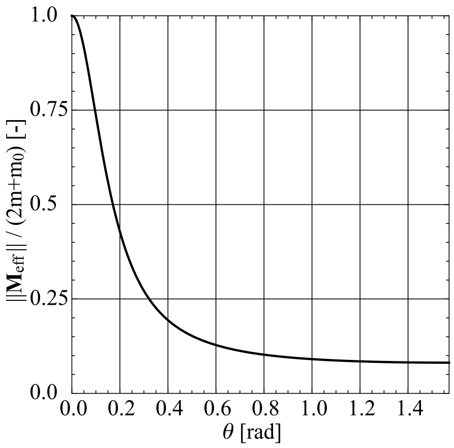


Figure 1: 2 DoF model of vertical hopping (left); The norm of the effective mass matrix (right)

4 Conclusion

In this work, we present a model of vertical hopping, which is used for the analysis of the effect of knee flexion on the ground-foot impact intensity and on the non-impulsive muscle and tendon loading. The model utilizes a controller, which ensures stable hopping with uniform apex height. We show that there is an optimal knee flexion, when a cost function, which is composed by the impact intensity and the work and peak value of the knee torque acting in the ground phase, is minimized.

5 Extensions after publication

Coordinates

Coordinates in the flight phase:

$$\mathbf{q} = \begin{bmatrix} z_{\mathrm{A}} \\ \theta \end{bmatrix} \tag{1}$$

$$\mathbf{q} = [z_{\mathrm{A}},\, \theta]^{\mathrm{T}} \tag{2}$$

and in the ground phase:

$$\mathbf{q} = [\theta] \tag{3}$$

Collision:

$$\dot{\mathbf{q}}^- \mapsto \dot{\mathbf{q}}^+ \tag{4}$$

Shooting method and monodromy matrix

Shooting:

$$\mathbf{F}(\mathbf{x}_0) = \boldsymbol{\phi}(t_{\mathrm{per}}, \mathbf{x}_0) - \mathbf{x}_0 \tag{5}$$

$$\mathbf{F}(\mathbf{x}_0) = \mathbf{0} \tag{6}$$

$$\mathbf{x}_0^* \tag{7}$$

Monodromy:

$$\tilde{\boldsymbol{\Phi}} = \mathbf{S}_{\mathrm{T2E}}\, \boldsymbol{\Phi}_{\mathrm{T}}\, \mathbf{S}_{\mathrm{L2T}}\, \boldsymbol{\Phi}_{\mathrm{L}}\, \mathbf{S}_{\mathrm{F2L}}\, \boldsymbol{\Phi}_{\mathrm{F}}\, \mathbf{S}_{\mathrm{E2F}}\, \boldsymbol{\Phi}_{\mathrm{E}} \tag{8}$$

Maintaining hopping height

The desired output is:

$$\sigma = \max_t (z_{\mathrm{A}}) - z_{\mathrm{A}}^{\mathrm{d}} \tag{9}$$

The desired output is maintained by tunig the desired knee angle right before foot touchdown:

$$\theta^{d+}_{\mathrm{grnd}} = \theta^{d-}_{\mathrm{grnd}} + P\sigma \,. \tag{10}$$

Note that increasing θ causes the decrease of the hopping height. The **optimal gain** P can be approximated if we take the hopping height in case of two different θ values. It gives and approximate linear on the θ versus $\max(z_\mathrm{A})$ plane or in other words θ–σ plane. The slope is P.

In the continuous phases, the state variable of the controller is constant:

$$\dot{\theta}^{d}_{\mathrm{grnd}} = 0\,, \tag{11}$$

$$\hat{\mathbf{x}} = \begin{bmatrix} \mathbf{x} \\ \theta^{d}_{\mathrm{grnd}} \end{bmatrix} \tag{12}$$

Monodromy with the united dynamics:

$$\hat{\tilde{\mathbf{\Phi}}} = \hat{\mathbf{S}}_{\mathrm{T2E}}\, \hat{\mathbf{\Phi}}_{\mathrm{T}}\, \hat{\mathbf{S}}_{\mathrm{L2T}}\, \hat{\mathbf{\Phi}}_{\mathrm{L}}\, \hat{\mathbf{S}}_{\mathrm{F2L}}\, \hat{\mathbf{\Phi}}_{\mathrm{F}}\, \hat{\mathbf{S}}_{\mathrm{E2F}}\, \hat{\mathbf{\Phi}}_{\mathrm{E}} \tag{13}$$

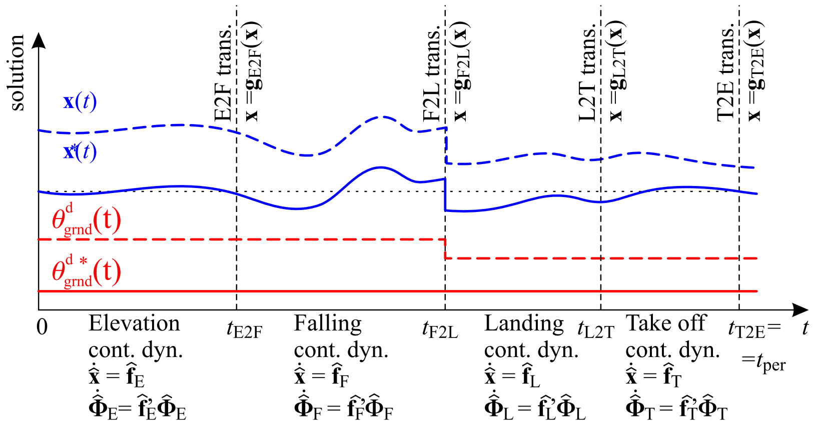


Figure 2: united dynamics for the state variables of the mechanical system and the state variables of the controller

Acknowledgments

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References

[1] P. Holmes, R. J. Full, D. E. Koditschek, and J. Guckenheimer, “The dynamics of legged locomotion: Models, analyses, and challenges,” *SIAM Rev.*, vol. 48, no. 2, pp. 207–304, 2006.

[2] Eric R. Westervelt, Jessy W. Grizzle, Christine Chevallereau, and et al., *Feedback Control of Dynamic Bipedal Robot Locomotion*, CRC Press, 2007.

[3] J. Rummel and A. Seyfarth, “Stable running with segmented legs,” *Intl. Journal of Robotics Research*, vol. 27, no. 8, pp. 919–934, 2008.

[4] A. Zelei, B. Krauskopf, and T. Insperger, “Control optimization for a three-segmented hopping leg model of human locomotion,” in *DSTA 2017 – Vibration, Control and Stability of Dynamical Systems*, Lodz, Poland, 11-14, December 2017, pp. 599–610.

[5] W. Blajer and W. Schiehlen, “Walking without impacts as a motion/force control problem,” *Journal of Dynamic Systems, Measurement, and Control*, vol. 114, pp. 660–665, 1992, doi:10.1115/1.2897738.

[6] D. E. Lieberman, M. Venkadesan, W. A. Werbel, A. I. Daoud, S. D’Andrea, I. S. Davis, R. O. Mang’Eni, and Y. Pitsiladis, “Foot strike patterns and collision forces in habitually barefoot versus shod runners,” *Nature, Biomechanics*, vol. 463, no. 7280, pp. 531–535, 2010, doi:10.1038/nature08723.

[7] J. Kövecses and L. L. Kovács, "Foot impact in different modes of running: mechanisms and energy transfer," *Procedia IUTAM*, vol. 2, pp. 101–108, Symposium on Human Body Dynamics, 2011.

[8] A. I. Daoud, G. J. Geissler, F. Wang, J. Saretsky, Y. A. Daoud, and D. E. Lieberman, "Foot strike and injury rates in endurance runners: A retrospective study," *Med. Sci. Sports Exerc.*, vol. 44, pp. 1325–1334, 2012, doi:10.1249/MSS.0b013e3182465115.

[9] K.-J. Chi and D. Schmitt, "Mechanical energy and effective foot mass during impact loading of walking and running," *Journal of Biomechanics*, vol. 38, no. 7, pp. 1387–1395, 2005, doi:10.1016/j.jbiomech.2004.06.020.