The energetic effect of swing leg control

Jian Jin[1], Dinant Kistemaker[1],
Jaap van Dieën[1], Andreas
Daffertshofer[1,2], Sjoerd M.
Bruijn[1,2,3]

[1]*Department of Human
Movement Sciences
Faculty of Behavioural and
Movement Sciences*
Amsterdam, The Netherlands

[2]*Institute of Brain and Behavior
Amsterdam*
Amsterdam, The Netherlands

[3]*Orthopaedic Biomechanics
Laboratory
Fujian Medical University*
Quanzhou, Fujian, PR China

I. INTRODUCTION

In human walking, power for propulsion is generated mainly by the ankle and hip muscles. Using the simplest walking model, Kuo, (2002) showed that impulsive push-off applied just before heel-strike is four times less costly than hip powering, and the addition of a ‘passive’ hip spring is more economical than using only toe-off impulse (Kuo, 2002). However, the spring-like tendon forces at the hip are not ‘free’, as they come from human muscles producing active forces and expending energy (Doke et al., 2005), with different energetic efficiencies of doing positive work and negative work (Margaria, 1968), in addition to costs associated with muscle activation (Umberger et al., 2003). To investigate the energetic effect of swing leg control (with both hip swing and retraction), we simulated a planar flat-feet walker model with varying ankle elasticity and hip spring stiffness at different walking speeds. We aimed to find out whether the prediction that the addition of a hip spring is energetically beneficial is still valid when considering an estimate of ‘metabolic cost’, and if so, what the optimal hip spring stiffness is at various speeds. Our modeling study sheds light on how ankle and hip coordination during human walking may achieve higher energy economy.

II. METHODS

Model. The model we used consists of four rigid segments (with inertia) representing two legs and flat feet, connected in three frictionless hinge joints representing the hip and two ankle joints. This walker model allows for a non-instantaneous double-support phase. The walker can be actuated at the ankle and/or hip joint. Similar to Zelik et al., (2014), the walker was actuated at the ankle by a passive spring in series with a constant (pulse-like) torque, activated from peak ankle dorsiflexion until toe-off. Swing leg control was modelled by a torsional hip spring between the legs. For both ankle and hip torques, the efficiency of doing positive work was set at 25% and at 120% for negative work; activation costs were neglected.

Simulations. We systematically varied non-dimensionalized speed from 0.15 to 0.5. For each speed, we solved the parameter optimization problem in Matlab using the fmincon (SQP): find the combinations of ankle spring stiffness, ankle pulse-like torque, hip spring stiffness and all segment angles/angular velocities as initial state that minimize the ‘metabolic’ cost of transport, subject to the constraint of the desired speed and a stable periodic gait. The Cost of Transport (CoT) was calculated as the sum of total positive and negative work multiplied by the inverse of corresponding efficiencies.

III. RESULTS

Fig.1 illustrates the numerator and denominator of CoT for a high speed (0.45): metabolic work and step length, as a function of hip spring stiffness. Increasing hip spring stiffness reduced the step length, collision loss and cost of transport, outweighing the extra metabolic cost involved. We found an optimal hip spring stiffness corresponding to the lowest cost of transport (Fig. 2), which compromises between metabolic cost due to large collision losses and due to small step lengths. We also found the optimal hip spring stiffness to be non-zero except for very low speeds, and to increase with speed to increase step frequency. In conclusion, even when accounting for the metabolic cost of doing hip work, the addition of a hip torque may decrease energetic cost of locomotion.

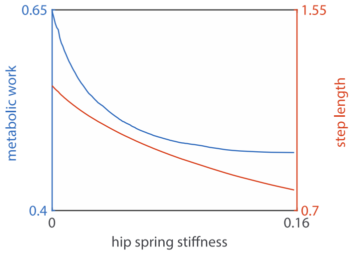

Fig.1

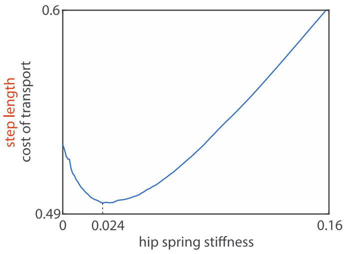

Fig.2

[1] Kuo, A. D. (2002). Energetics of actively powered locomotion using the simplest walking model. *Journal of Biomechanical Engineering*.

[2] Doke, J., Donelan, J. M., & Kuo, A. D. (2005). Mechanics and energetics of swinging the human leg. *Journal of Experimental Biology.*

[3] Margaria, R. (1968). Positive and negative work performances and their efficiencies in human locomotion. Internationale Zeitschrift Fur Angewandte Physiologie, 25(4), 339–351.

[4] Zelik, K. E., Huang, T. W. P., Adamczyk, P. G., & Kuo, A. D. (2014). The role of series ankle elasticity in bipedal walking. *Journal of Theoretical Biology.*

[5] Umberger, B. R., Gerritsen, K. G. M., & Martin, P. E. (2003). A model of human muscle energy expenditure. *Computer Methods in Biomechanics and Biomedical Engineering*, 6(2).

---

e-mail: j.jin@vu.nl. JJ and SMB are funded by a VIDI grant no. (016.Vidi.178.014) from the Dutch Organization for Scientific Research.