Seven reasons to brake leg swing just before heel strike

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When walking (at moderate or fast speeds) or running, humans apply a burst hip torque to start leg swing and then again, at the end of the swing phase, to brake and reverse motion of their swing leg prior to heel-strike. The resulting rearward rotation of the swing leg, so called swing-leg retraction, is also observed in animal gaits. Why is this retraction a common feature of many walking and running animals? Previous studies have shown that swing leg retraction aids the robustness of walking three ways:

1) improves the stability (reduces eigenvalues) of periodic walking [1] and running [2],
2) increases the maximum tolerable disturbance in walking [1] and running [3], and reduces the recovery period from disturbance [1],
3) improves the state estimation by increasing the accuracy of the predicted time of heel-strike [4].

There are further possible energetic and stability benefits of active swing-leg retraction. For example, leg retraction can potentially reduce the collision loss by reducing the tangential (parallel to ground) foot speed at heel-strike. But this collisional saving trades off against the extra effort spent to brake and accelerate the leg. Another issue is the interactions between leg retraction and pre-emptive push-off (push-off just before heel-strike). Pre-emptive push-off is a key part of energy effective walking. But in a multi-body mechanism forces and/or torques at different joints are mechanically coupled. So the interaction between hip torque and push-off and their relative timing potentially influences the energetics. In particular is retraction beneficial, and if so, how does it's timing matter? Should it be just after, just before, or simultaneous with the pre-emptive push-off?

We address these questions with a mechanical model probed with analytic and numerical methods. The model is a 2D two-link biped whose rigid legs have distributed mass. The upper body is represented by a point mass at the hip. Based on observations of humans and previous numerical optimization studies, this biped is powered by a sequence of impulses: impulsive push-off just prior to collisional heel-strike, and two impulsive hip torques at the beginning and end of the swing phase. Gravity and ground reaction force are the only external forces acting on the system. Double-support is assumed to be instantaneous. For simplicity we ignore the small coupling of the light swing leg on the center of mass motion during smooth part of the gait cycle. We consider the full range of step lengths and average speeds for which walking gait is possible without ground suction (downward ground reaction force) and without multiple swing cycles (swing leg passes vertical only once).

The central results are these:

4) *Increased viability and controllability regions*: Allowing use of braking torque on the swing leg increases the maximum speed for which compass walking is possible. Without this torque, at high speeds the needed pre-emptive push-off lifts the hip and precludes heel-strike. In other words, the breaking hip torque guarantees that heel-strike, and thus support transfer, occurs after push-off. This support transfer is otherwise unobtainable at high walking speeds.
5) *Reducing the required push-off impulse*: The breaking hip torque decreases the required push-off impulse for periodic walking (coupling effect). The energy minimizing hip torque is then determined by the competing costs of push-off and active swing leg retraction.
6) *Possible improvement in energetic cost*: For a given late-swing *braking* hip torque (possibly applied for purposes 1-3 above), it is energetically favorable for it to be applied immediately after push-off and before heel-strike. This is consistent with observations from human walking, where leg retraction mostly follows push-off. However, in the model it is not always energetically optimal to apply late-swing hip torque, even if optimally timed. Whether or not retraction torque is energetically helpful depends on the relative costs of positive and negative muscular work and whether heel-strike has an energetic cost.
7) *Reducing the risk of slippage at heel-strike*: Although the required friction coefficient to avoid slippage at heel-strike is mainly dependent on the step length, the breaking hip torque slightly decreases it, reducing the risk of slippage.

References

[1] D.G.E. Hobbelen and M. Wisse, Swing-Leg Retraction for Limit Cycle Walkers Improves Disturbance Rejection, IEEE Trans Robotics, vol. 24, no.2, pp. 377-389, April 2008.
[2] A. Seyfarth, H. Geyer, and H. Herr, Swing-leg retraction: a simple control model for stable running, J of Exp Biol, no. 206, pp. 2547-2555, 2003.
[3] M. Haberland, J.G.D. Karssen, and S. Kim, M Wisse, The Effect of Swing Leg Retraction on Running Energy Efficiency, In Proc. of IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 3957 3962, 25-30 September 2011, San Francisco, CA, USA.
[4] P. Bhounsule, J. Cortell, B. Hendriksen, J.G.D. Karssen, C. Paul, A. Ruina, A robot that can walk far using little energy, accepted in Int. J. Robotic Research, 2012.