Can Impacts Be Avoided in Stable Running?

[1,2] Yvonne Blum, [1]Susanne W. Lipfert and [1]Andre Seyfarth
[1]Locomotion Laboratory, University of Jena, Dornburger Str. 23, 07743 Jena, Germany
[2]Correspondig author, e-mail: Yvonne.Blum@uni-jena.de, web: www.lauflabor.de

SUMMARY

From a model based point of view, stable running can be provided by swing leg control. In this work linear adaptations of model parameters during swing phase are assumed. As foot point velocities of human data are translated into model relevant changing rates of kinematic parameters (leg rotation and leg length change), experimentally observed landing strategies of barefoot and shod running can be compared with predictions of the spring mass model.

INTRODUCTION

Different gaits, speeds, and morphologies in human and animal locomotion can be described by consistent spring like leg behavior [1]. In this work, the human leg is represented by the planar spring mass model [2]. Even though the spring mass model shows selfstable behavior for adequate leg parameter adjustments (angle of attack, leg stiffness and leg length) and sufficient speeds ($v_x > 3$ m/s) [3], the range of parameters providing stable running can be extended with additional control strategies. These model predicted control strategies and their influence on stability are observed in the landing strategies of barefoot and shod running [4].

METHODS

Spring mass running is characterized by alternating flight and stance phases. The body is represented by a point mass m supported by a linear spring with angle of attack α_{TD}, spring stiffness k and rest length L_0.

The stability of spring-mass running is analyzed using a one-dimensional return map of two subsequent apex heights. For stable running the absolute value of the slope s of the apex-return map has to be smaller than one in the neighborhood of a fixed point. In this work the criterion for stability is set to $s = 0.5$, which means that small perturbations are reduced to the half after each step.

By adjusting leg parameters during swing phase (i.e. without changing the energy), it is possible i) to stabilize periodic solutions that are unstable without control [5] and ii) to enlarge the region of stable running. Here, linear adaptations of the three parameters leg angle, leg stiffness and leg length are assumed.

Although the leg of the spring mass model is considered massless, the size of impacts a real leg would experience can be approximated. Higher foot landing velocities of with respect to the ground produce larger impacts at touch down. In these terms, *ground speed matching* (GSM) defines the qualitative magnitude of the impacts, as 100% GSM describes an absolutely smooth landing without any impact, while 0% GSM means a landing without kinematic control (leg angle and leg length are constant, foot moves with the same velocity as the center of mass).

Experimental data of 7 subjects running with shoes and barefoot on an instrumented treadmill at different speeds (v_x = 2, 3 and 4 m/s) were collected.

RESULTS AND DISCUSSION

Figure 1 shows the experimentally observed kinematic control strategies (leg rotation and leg length change) for both, barefoot (gray dots) and shod (black dots) running at one speed (v_x = 3 m/s) in comparison with model based predictions. Although barefoot running indicates better GSM, compared to shod running, the vertical components of the impacts are higher (with increasing distance perpendicular to the diagonal line, which indicates the absence of vertical impacts, the magnitude of vertical impacts increases as well). The model predicted region of stability (gray area) is shown for one stiffness changing rate, matching the mean swing leg characteristics (circle), and translates parallel with increasing and decreasing changing rates.

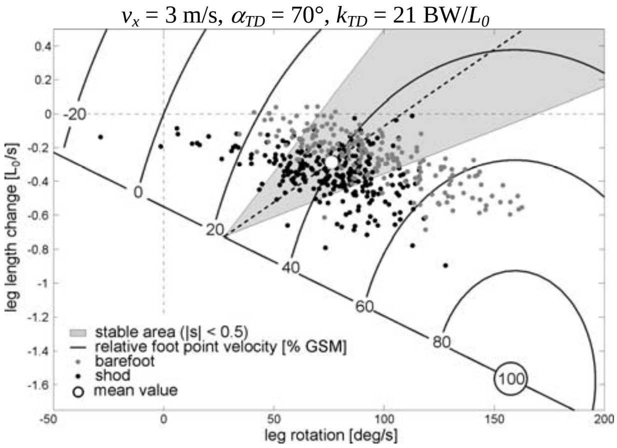

Figure 1: Swing leg control in spring mass running with adaptation of leg length, leg angle and (one selected) leg stiffness. The stable region $|s| < 0.5$ (gray area) is matching the mean swing leg characteristics (circle) assuming superstable behavior ($s = 0$) of barefoot (gray dots) and shod (black dots) running.

Every realizable running solution can be stabilized, but control strategies enforce a compromise between stability and suffered impacts.

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REFERENCES

1. Alexander, R.M., *IJRR*, **9**: 53-61, 1990
2. Blickhan, R., *J Biomech*, **22**: 1217-1227, 1989
3. Seyfarth, A., et al., *J Biomech*, **35**: 649-655, 2002
4. De Wit, B., et al., *J Biomech*, **33**: 269-278, 2000
5. Seyfarth, A., et al., *J Exp Biol*, **206**: 2547-2555, 2003

Appendix: Stiffness Estimation in Human Running

INTRODUCTION

Leg stiffness is a common parameter used to characterize leg function during bouncing gaits, like running and hopping. In the scientific literature, different methods to approximate leg stiffness based on kinetic and kinematic parameters are described. In this work one simple (as the required parameters are easy accessible) method of estimating leg stiffness is presented and, with regard to the predictions of the spring mass model [1], compared with other established methods [2, 3, 4].

METHODS

Many approaches assume that leg stiffness k_{Leg} is given by the ratio of maximum vertical GRF (ground reaction force) F_{max} and leg compression ΔL. But the approximation of the leg compression is not unique and several methods are used.

Method A: ΔL can be expressed as a function of the vertical displacement of the CoM (center of mass), the resting leg length and the angle of attack α_{TD}. Assuming symmetric contact phases, α_{TD} can be substituted by horizontal velocity v_x and contact time [2].

Method B: Another way of calculating ΔL is the measurement of the CoM-CoP (center of pressure) displacement [3]. TD-TO-asymmetry (touch down, take off) is taken into account by the linear adjustment of the resting leg length during contact.

Method C: To estimate leg stiffness during hopping a completely different approach was proposed by Dalleau et al. [4]. The GRF was approximated by a sine shaped force curve of amplitude F_{max} and the corresponding ΔL was calculated. This method is adopted for running.

Method D: By assuming a simple sinusoidal force pattern the area underneath the theoretical sine-curve is slightly larger than the area underneath the experimentally observed force curve. In order to equalize the impulses generated by the experimentally observed and the sine-shaped force curves, a correction factor Γ is introduced that decreases the amplitude of the sine to $\Gamma \cdot F_{max}$.

Method E: In this work, a last method only relying on contact time, flight time, body mass, resting leg length and touch down angle is presented.

RESULTS AND DISCUSSION

The five different methods A - E lead to different k-α distributions. Mean stiffness and standard deviations are listed in table 1 for 21 subjects, running at three different speeds (v_x = 1.6, 2.2 and 2.7 m/s). In figure 1 the k-α pairs of each step are shown for two methods (A and E) at one speed (v_x = 2.7 m/s).

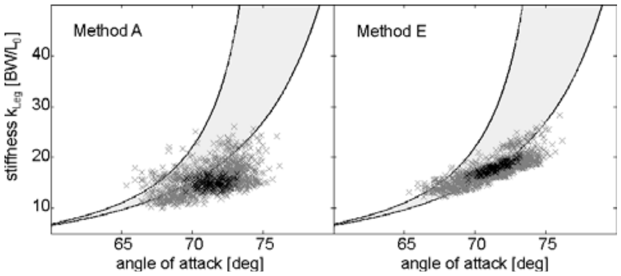

Figure 1: k-α distributions of 21 subjects running at v_x = 2.7 m/s (gray crosses) and one individual subject (black crosses), estimated based on method A and E. Predictions of reachable steps using steps to fall method (steps > 3) for the spring mass model in running (gray area).

Whereas stiffness estimation based on method A and B leads to very distributed k-α pairs, which underestimate (method A) or overestimated (method B) model predictions, stiffness approximation based on sine-shaped GRF is an appropriate approach for hopping and running. For higher speeds (v_x > 2.5 m/s) only F_{max} needs to be determined and the influence of Γ is negligible. In this case, method C is sufficient. For lower speeds, both, F_{max} and Γ are required to estimate appropriate leg stiffness (method D). However, for stiffness estimation, the need of calculating the correction factor Γ can be avoided by deriving the corresponding maximum GRF F'_{max} from the duty factor (method E). By estimating maximum GRF based on DF, the correction factor Γ becomes obsolete, as the vertical impulses generated i) by the sine of amplitude F'_{max} and ii) by the experimental force pattern are equal.

In conclusion, independent from the running speed, the method which was presented here (method E) is the best and simplest approach to derive an effective leg stiffness corresponding to the spring mass model.

REFERENCES

1. Blickhan, R., *J Biomech*, **22**: 1217-1227, 1989
2. McMahon, T.A., Cheng, G.C., *J Biomech*, **23**: 65-78, 1990
3. Arampatzis, A., et al., *J Biomech*, **32**: 1349-1353, 1999
4. Dalleau., et al., *Int J Sports Med*, **25**: 170-176, 2004

Table 1: Mean value and standard deviation of leg stiffness estimated by methods A - E for 21 subjects (11 females, 10 males, age 25 ± 3 yrs, body mass m = 77 ± 9 kg, resting leg length L_0 = 0.96 ± 0.08 m) at 3 speeds.

	leg stiffness k [BW/L$_0$]				
v_x [m/s]	A	B	C	D	E
1.6	18.6 ± 3.4	22.4 ± 3.6	16.9 ± 3.0	19.2 ± 3.3	19.2 ± 3.1
2.2	17.1 ± 3.2	23.6 ± 3.7	16.6 ± 2.7	18.0 ± 2.8	18.0 ± 2.7
2.7	16.1 ± 2.9	24.1 ± 3.7	16.7 ± 2.4	17.4 ± 2.6	17.4 ± 2.6