STIFFNESS ESTIMATION IN HUMAN RUNNING

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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).

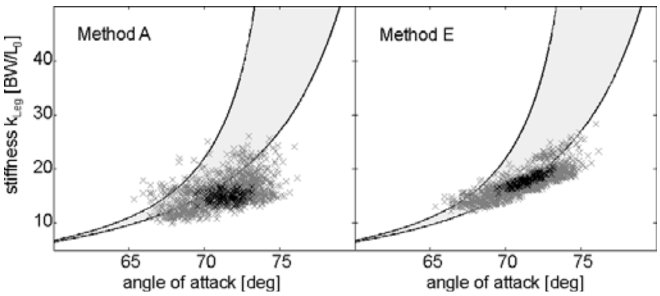

Figure 1: k-α distributions of 21 subjects running at v_x = 2.7 m/s (gray crosses) and one individual subject (black crosses), estimated based on method A and E. Predictions of reachable steps using steps to fall method (steps > 3) for the spring mass model in running (gray area).

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.

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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