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A movement criterion for running

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Abstract

The adjustment of the leg during running was addressed using a spring-mass model with a fixed landing angle of attack. The objective was to obtain periodic movement patterns. Spring-like running was monitored by a one-dimensional stride-to-stride mapping of the apex height to identify mechanically stable fixed points.

We found that for certain angles of attack, the system becomes self-stabilized if the leg stiffness was properly adjusted and a minimum running speed was exceeded. At a given speed, running techniques fulfilling a stable movement pattern are characterized by an almost constant maximum leg force. With increasing speed, the leg adjustment becomes less critical. The techniques predicted for stable running are in agreement with experimental studies.

Mechanically self-stabilized running requires a spring-like leg operation, a minimum running speed and a proper adjustment of leg stiffness and angle of attack. These conditions can be considered as a movement criterion for running.

Keywords: Biomechanics; Locomotion; Spring-mass model; Dynamic similarity; Leg stiffness; Stability

1. Introduction

An almost sinusoidal pattern of the ground reaction force is observed in many types of fast animal and human locomotion (Cavagna et al., 1964, 1977; Alexander et al., 1986; Full et al., 1991; Farley et al., 1993). Although this includes both energy production (muscle fibers) and absorption (soft tissue, ligaments, muscles) the leg stiffness is surprisingly constant during the stance time.

Blickhan (1989) and McMahon and Cheng (1990) introduced a simple spring-mass model to approximate this generally observed force pattern. This representation of the leg by a linear spring was successfully applied by biologists (Blickhan and Full, 1993; Farley et al., 1993; Farley and Gonzalez, 1996), sport scientists (Arampatzis et al., 1999; Seyfarth et al., 1999), and bioengineers (Herr, 1998) to describe and predict animal and human locomotion. However, there is only little known about the advantages of this type of leg operation.

The spring-like loading of a segmented leg can be achieved by elastic operation of the leg joints. To guarantee a homogeneous loading of the leg joints, nonlinear torque-angular displacement characteristics ($M \sim \Delta\varphi^{\nu}$) with exponents $\nu > 1.5$ are necessary (Seyfarth et al., 2000). For forcibly loaded legs, this characteristic may be supported by passive properties of the tendons connecting the muscles to the skeleton. Experimentally observed exponents in tendon stress–strain relationships (Ker, 1981) are well suited to result in almost linear spring-like behavior of the leg (Seyfarth et al., 2001). Therefore, the linear leg spring is a concept to solve the kinematic redundancy problem of a segmented leg.

If a movement objective (e.g. performance criteria) is given, the spring-like leg behavior may guide to understand technical aspects of locomotion as shown for the long jump (Seyfarth et al., 1999). Here, the maximum jumping distance specifies the required adjustment of leg stiffness and angle of attack. Unfortunately, such an objective is not known for running yet.

An approach to predict the leg spring adjustment in running was made by Blickhan (1989) and McMahon

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Nomenclature

α_0	angle of attack
$\Delta\ell$	amount of leg shortening
$\Delta\ell_{MAX}$	maximum leg shortening
F_{MAX}	maximum leg force
k_{LEG}	leg stiffness
ℓ_{LEG}	leg length
ℓ_0	leg length at touch-down (and take-off in the model)
m	body mass
ω	eigenfrequency
v_X, v_Y	components of the center of mass velocity
x, y	coordinates of the center of mass
y_i	apex height at stride i
y_0	initial apex height
y_{TD}	touch-down height

and Cheng (1990), which showed that for given parameters (running speed, leg stiffness, angle of attack) the spring-mass model might produce symmetric trajectories of the center of mass. Nevertheless, they did not prove whether the predicted solutions are stable with respect to deviations in landing conditions or leg stiffness. More recently, Schwind (1998) showed that for a running spring-mass system only symmetric stance phases with respect to the vertical axis might result in cyclic movement trajectories. As there is no analytical solution of the planar spring-mass system known, he investigated the system by using nonlinear spring characteristics and adapted controllers. The stability of the system with a simple linear spring was not investigated.

The aim of this study is to investigate the stability of spring-like leg operation during running at a constant speed. Therefore, a stride-to-stride analysis of a conservative spring-mass model is used. At given initial conditions we identify appropriate leg adjustments (stiffness, angle of attack) resulting in a periodic running pattern. The number of successful strides serves as a measure for periodicity. The variation of the stride number for different leg adjustments provides a measure of running robustness. The predicted leg operation for periodic running movements is compared to an experimental study on human running.

2. Methods

2.1. Experimental data acquisition and analysis

In order to prove the predictions of the running model, the dynamic and kinematic parameters during bare-foot running were recorded in an experimental study with 12 students (body weight $m = 69.5 \pm 9.8$ kg, height 1.77 ± 0.08 m). The subjects were instructed to run across a force plate (initial leg length $\ell_0 = 0.94 \pm 0.06$ m) at moderate speed ($v_X = 4.6 \pm 0.5$ m/s). In total 67 contact phases were analyzed in terms of ground reaction forces and kinematic landmarks of the stance leg (hip, knee, ankle and ball of the foot) with a sampling rate of 500 Hz.

During the contact phase, the leg length ℓ_{LEG} was defined as the distance between the hip and the ball of the foot. The leg stiffness k_{LEG} was defined by

$$k_{LEG} = F_{MAX}/\Delta\ell_{MAX}, \quad (1)$$

where F_{MAX} denotes the maximum amount of the ground reaction force and $\Delta\ell_{MAX}$ the amount of maximum leg shortening $\Delta\ell = \ell_0 - \ell_{LEG}(t)$ (Seyfarth et al., 1999).

2.2. The spring-mass model

Running can be described as a subsequent series of stance and flight phases (Fig. 1). The trajectory of the center of mass m is determined by the gravitational force (during flight and stance phase) and by the force generated by the stance leg during the contact phase. During the flight phase, the horizontal velocity remains constant whereas the vertical velocity crosses zero at the apex. This particular condition is used to define one stride within a periodic running pattern as the movement from one apex to the other includes one stance phase.

The operation of the stance leg, landing at a certain angle of attack α_0, is represented by a linear spring with the stiffness k_{LEG} and the nominal position ℓ_0. The length ℓ_0 is equal to the initial leg length to fulfill zero leg force at touch-down. The leg behavior for different body masses m remains kinematically unchanged as long as the leg stiffness k_{LEG} is properly adjusted to the body mass, i.e. the eigenfrequency $\omega = \sqrt{k/m}$ is kept constant.

2.3. Landing and take-off conditions

To describe periodic ground contacts of a spring-mass model the instant of touch-down after a flight phase must be characterized uniquely. In our approach, touch-down occurs if the center of mass reaches the critical height y_{TD}, which is a consequence of the fixed angle of

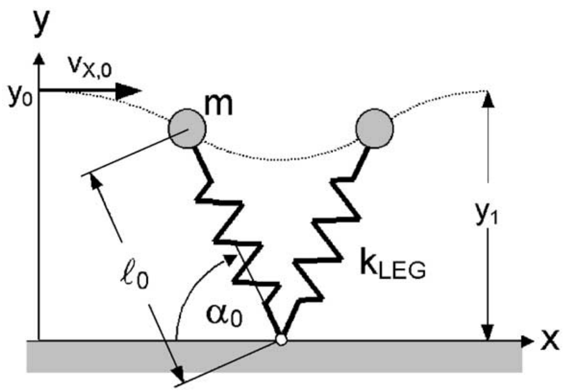

Fig. 1. The spring-mass model for running. The leg spring is characterized by the stiffness k_{LEG} and the nominal length ℓ_0 which is the leg length at touch-down and take-off. In our approach, the leg orientation at touch-down is characterized by a given angle of attack α_0. During the flight phase the horizontal velocity is constant. One stride can be defined as the movement from one apex (height y_i) to the next (height y_{i+1}). As the vertical velocity vanishes at these conditions the state of the system is uniquely characterized by the apex height and the horizontal velocity, e.g., as an initial condition ($y_0, v_{X,0}$).

attack α_0 and the initial leg length ℓ_0 at touch-down

$$y_{TD} = \ell_0 \sin \alpha_0. \qquad (2)$$

Take-off occurs if the initial leg length is reached again $\ell_{LEG}(t_{TO}) = \ell_0$. During the flight phase, the center of mass trajectory is simply determined by the gravitational acceleration. The model does not describe the leg movement during this period.

2.4. Simulation parameter setup

To investigate the periodic behavior of the bouncing spring-mass model, we start the simulation at the apex of the flight phase with following initial conditions of the point mass: $x_0 = 0$, $y_0 = \ell_0 = 1\,\mathrm{m}$, a horizontal velocity $v_{X,0}$ and zero vertical velocity $v_{Y,0} = 0$. The model parameters are the body mass m, the leg stiffness k_{LEG}, the initial leg length ℓ_0, the angle of attack α_0 and the gravitational acceleration $g = 9.81\,\mathrm{m/s^2}$.

2.5. Stability analysis

For given initial conditions and a set of model parameters, the system may (1) slow down and fall consequently, (2) overrun a step and fall, or (3) remain in a periodic movement pattern. The number of steps to fall n is counted. In condition (3), this number is infinite ($n = \infty$). In the numerical simulation, the calculation was stopped at $n = 24$.

The stability of the periodically operating spring-mass system can be analyzed using a return map in a one-parameter representation of the state vector: As the system is conservative, the sum of kinetic and potential energy is constant. During the flight phase, the system energy is merely characterized by the velocity and vertical position of the center of mass. Furthermore, at the apex of the flight phase ($v_Y = 0$) only the apex height and the horizontal velocity are influencing the center of mass trajectory. Due to the landing condition (fixed leg angle with respect to the ground), the horizontal position during flight has no influence on the system behavior. Therefore, we can set the x coordinate at apex to zero. For a given system energy, we can use the apex height to characterize the complete state vector.

The projection of the apex height from one stride (y_i) to the next (y_{i+1}) defines a return map (stride-to-stride analysis). Here, periodic movements require solutions with $y_{i+1} = y_i$ (fixed points). A stable periodic trajectory additionally requires a slope within $[-1,1]$ of the return map $y_{i+1}(y_i)$ in the neighborhood of the fixed point. Bistable solutions do not exist as only symmetric contact phases may result in a periodic movement pattern (Schwind, 1998).

2.6. Simulation tools

For the numerical integration of the spring-mass model, we used Matlab 5.3® (The MathWorks Inc.) and the built-in Simulink® tool with the ode113 Integrator (absolute and relative error tolerance 1e-5). The simulation results were checked by a 10 times higher accuracy.

3. Results

The analysis of the spring-mass system revealed that there exist leg adjustments (leg stiffness, angle of attack), which lead into periodic limit cycles in the movement pattern. These solutions proved to be robust with respect to adjustment errors and variations in kinematic parameters (speed, initial apex height). After giving some representative examples we will analyze the mechanisms of self-stabilizing running by using a stride-to-stride analysis of the spring-mass model.

3.1. Variability in leg adjustment for a given system energy (speed, apex height)

In Fig. 2A the stability of the spring-mass running was investigated for a given initial apex height ($y_0 = 1\,\mathrm{m}$) and speed ($v_{X,0} = 5\,\mathrm{m/s}$), different leg stiffness k_{LEG} and angles of attack α_0. Periodic running patterns were present within a ‘J’-shaped region in the (α_0, k_{LEG})-plane. Thereby, different leg stiffness empirically adapted to the angle of attack with

$$k_{LEG}(\alpha) = \frac{1}{1 - \sin\alpha}\mathrm{const} \qquad (3)$$

resulted in periodic solutions. According to the depicted function (solid line in Fig. 2A) the constant amounts to

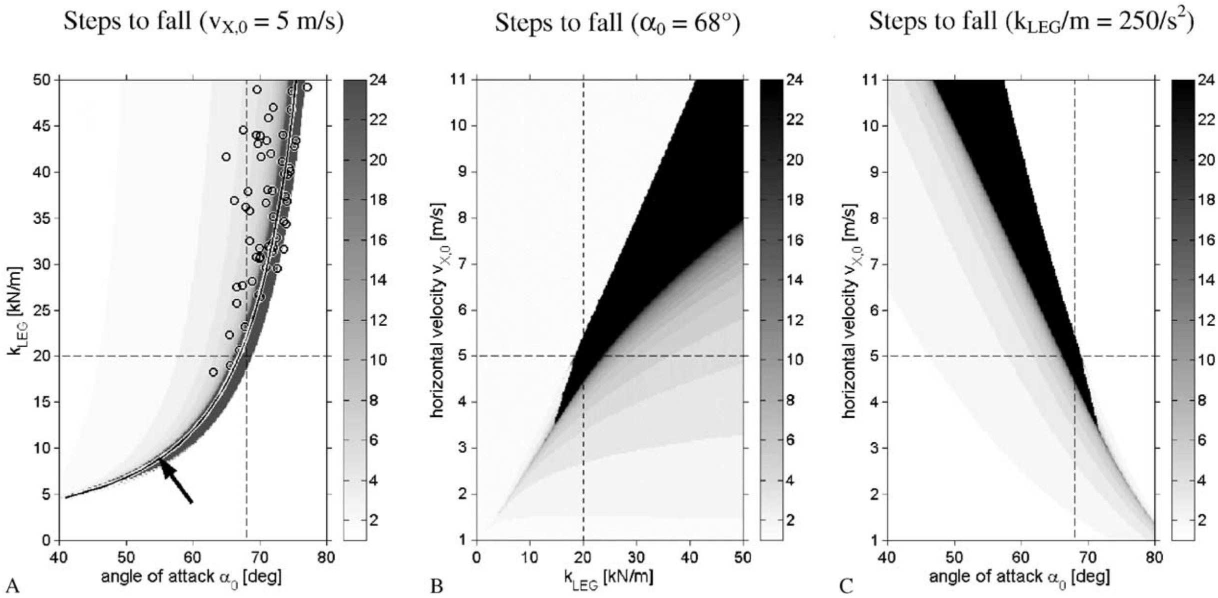

Fig. 2. Stable running requires a proper adjustment of leg stiffness k_{LEG}, angle of attack α_0 and running speed $v_{X,0}$. The integration stopped if the point mass fell onto the ground ($y = 0$) or the step number exceeded 24 (right grayscale). In each diagram (A–C) one parameter was kept constant: (A) running speed, (B) angle of attack, and (C) leg stiffness k_{LEG}. In (A) experimental data for running at 4.6 ± 0.5 m/s are denoted by small circles ○. To fit with the simulation parameters, the individual leg stiffness was scaled to a body mass of 80 kg. The arrow points to a solid line described by a function with $k \cdot (1 - \sin \alpha)$ = const. Initial conditions: $y_0 = 1$ m, $v_{X,0} = 5$ m/s, $v_{Y,0} = 0$ m/s. Model parameters: $k_{LEG} = 20$ kN/m, $m = 80$ kg, $l_0 = 1$ m, $\alpha_0 = 68$.

1600 N/m and equals approximately the maximum leg force F_{MAX} divided by the leg length at touch-down ℓ_0. For a leg stiffness k_{LEG} between 16 and 24 kN/m angles of attack within 64° and 71° were predicted.

Small variations in the leg stiffness (± 2.4 kN/m) and angle of attack ($\pm 1°$) were tolerated by the system without leaving the periodic running pattern (see below: return maps of the apex height, Fig. 3A).

The experimental data showed a fairly good coincidence with the predicted leg adjustments. The subjects used different strategies: either stiff legs with steep angles of attack or more compliant legs with flatter angles.

3.2. Influence of speed

The influence of the horizontal apex velocity on the leg adjustment was investigated in Figs. 2B and C. Following statements can be made:

(1) Running with constant techniques (leg stiffness and angle of attack) requires a minimum speed (here about 3.5 m/s).
(2) With increasing speed the leg adjustment for stable running becomes less sensitive, i.e. larger variations in leg stiffness and angle of attack are tolerated by the system.
(3) Higher running velocities require either a higher leg stiffness assuming a constant angle of attack (Fig. 2B) or flatter angles of attack for a constant leg stiffness (Fig. 2C). Both strategies are competitive, e.g. deficits in leg stiffness may be compensated to a certain degree by flatter leg angles (compare Fig. 2A). The 'J'-shaped region of stable running in Fig. 2A is shifted to higher stiffness values and flatter angles of attack for increased running speeds. The general shape of the region remains similar although the region is enlarged (compare Fig. 2B and C).

3.3. Return map of the apex height

To prove the stability in running for an infinite number of steps we are now focusing on only one stride cycle between two apexes. Taking the conservative nature of the spring-mass system into account we can reduce the apex state vector to one free parameter (see methods): the apex height y_i. The relationship between the apex height of two proceeding flight phases $y_{i+1}(y_i)$ is shown in Fig. 3 for a horizontal velocity of 5 m/s, a leg stiffness $k_{LEG} = 20$ kN/m and different angles of attack α_0. The configurations with a maximum number of steps ($n = 24$ for $\alpha_0 = 67°$, 68°; Fig. 2A) proved to result in periodic running movements with stable fixed points in the return map $y_{i+1}(y_i)$. Lower angles of attack ($\alpha_0 = 66°$) may still result in a certain number of steps but with decreasing running velocity and increasing vertical excursions (Fig. 2A). This is a consequence of the adjacent alignment of the $y_{i+1}(y_i)$-curve with the diagonal $y_{i+1} = y_i$.

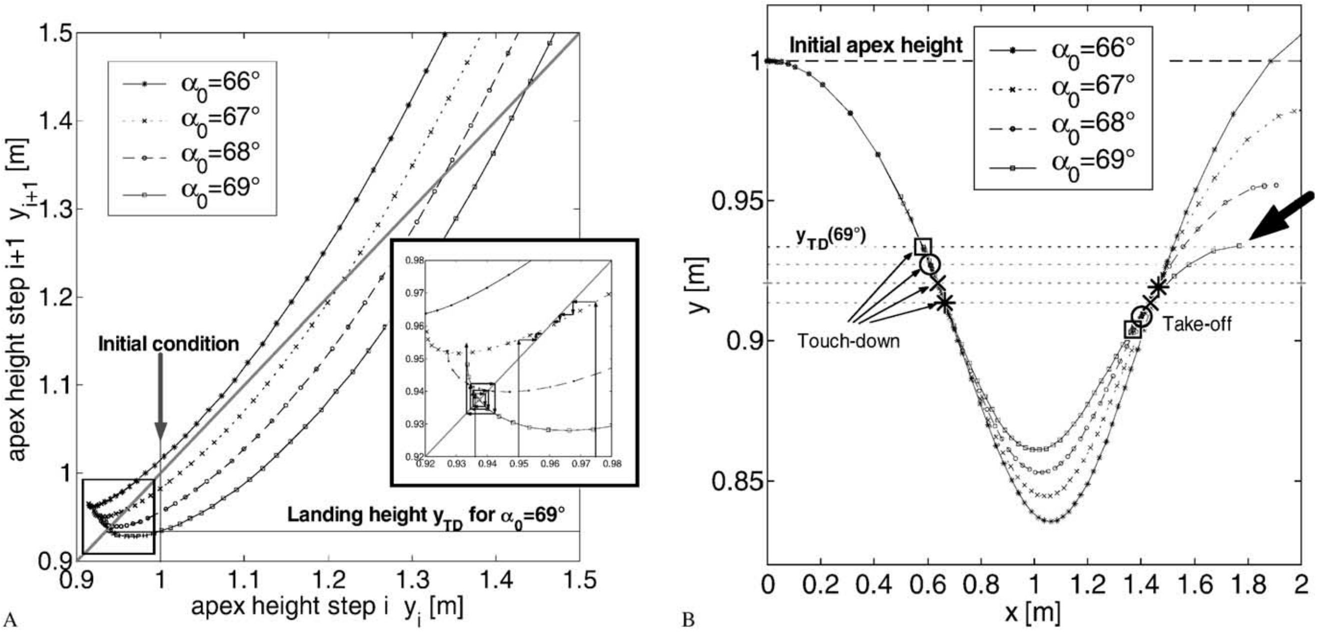

Fig. 3. (A) Return map of the apex height $y_{i+1}(y_i)$ of two subsequent flight phases and (B) trajectories of center of mass during one stride for different angles of attack α_0 including regions of periodic and aperiodic movements (initial apex condition and model parameters corresponding to Fig. 2). Periodic running movements require fixed points $y_i = y_{i+1}$ (holds for $\alpha_0 = 67^\circ, 68^\circ, 69^\circ$). A stable fixed point requires additionally a slope of the $y_{i+1}(y_i)$-function between $[-1, 1]$ in the neighborhood (holds for $\alpha_0 = 67^\circ, 68^\circ$ at the lower fixed point). Two examples of the local behavior next to the fixed points are illustrated for $\alpha_0 = 67^\circ$ and 69° in the magnified region in (A). For a given angle of attack α_0 variations in the apex height can be tolerated by the system without loosing the periodicity until the upper intersection is reached. Furthermore, periodicity is also lost if either the landing height y_{TD} is missed in the following step ($\alpha_0 = 69^\circ$) or if the system increases the vertical excursions ($\alpha_0 = 66^\circ$) (B).

In contrast, increasing the angle of attack ($\alpha_0 = 69^\circ$) leads to a sudden fall. Although a limited number of steps is possible within a small neighborhood of the intersection with the diagonal $y_{i+1} = y_i$ (Fig. 3A), a fall occurs if the landing height y_{TD} cannot be reached by the apex of the following flight phase y_{i+1}.

4. Discussion

Our investigation was based on the spring-mass model with a fixed adjustment of the landing leg. Due to the simplicity of this approach, it was possible to explore the configuration space of the system. It allowed us to identify periodic limit cycles using a stride number analysis and a stride-to-stride analysis in terms of a one-dimensional return map of the apex height.

Spring-like leg operation within the proper conditions facilitates control during periodic running exercises. The system showed mechanically stable solutions for a variety of chosen leg adjustments as long as a minimum running speed was exceeded. Different angles of attack may result in a stable running pattern if the leg stiffness is properly adapted. The simulation showed that there is a 'J'-shaped dependency in the adjustment of angle of attack to leg stiffness for a stable running pattern with given speed. This resulted in an almost constant maximum leg force independent of the chosen leg compliance.

In the long jump, a similar leg adjustment was identified (Seyfarth et al., 1999) for maximum jumping distance assuming a spring-like leg. For a given speed, different angles of attack and leg stiffness may result in the same jumping distance. In contrast to running, here an asymmetric contact phase is used.

4.1. Comparison with experimental studies

Adaptations in the chosen angle of attack similar to our findings has been observed during running for largely different animals (Farley et al. 1993) and humans (Farley and Gonzalez, 1996).

In our experimental data angles of attack between 65° and 75° were used within a speed range of 4–5 m/s. The estimated leg stiffness values are higher as compared to other studies as we used the hip position of the stance leg to approximate the center of mass. This resulted in smaller leg lengths and a smaller magnitude of leg shortening during ground contact. However, the distribution within the (k, α_0)-space largely agrees with the prediction of the model.

With increasing speed experimental observations showed mostly either constant or increasing leg stiffness (Farley et al., 1993; Arampatzis et al., 1999). However, in some cases even smaller leg stiffness may be used (e.g. kangaroos). Farley et al. (1993) found that the angle swept by the leg during the stance phase always increased with speed (i.e. a decrease in the angle of attack α_0). The experimentally observed adjustments in leg angle correspond to the changes predicted by the spring-mass model for a constant leg stiffness (Fig. 2C).

In human, running at different stride frequencies for a given speed almost constant peak ground reaction forces were observed for largely different leg stiffness and angles of attack (Farley and Gonzalez, 1996). This supports our observation in Eq. (3) indicating a constant leg force within the region of stable running.

The minimum running speed predicted in this study is about twice the natural transition speed between human walking and running (Margaria, 1938; Thorstensson and Roberthson, 1987). Running at low speeds requires a careful adjustment (control) of the mechanical parameters. In consequence, step-by-step adjustments would be necessary. Sensory information must be taken into account. These feedback mechanisms are also present in faster running, but some studies indicate a reduced sensory sensitivity during fast movements (Collins et al., 1998; Simonsen and Dyhre-Poulsen, 1999). This corresponds to the increased robustness of the mechanical system with higher speed.

Recently Donelan and Kram (2000) investigated dynamic similarity in human running using simulated reduced gravity. Comparing the kinematic and dynamic parameters at different running speeds they found that no single parameter is sufficient to uniquely characterize dynamically similar movements.

The behavior of the spring-mass model can be scaled by substituting the leg stiffness, the body mass, the leg length and the gravitational constant with one dimensionless constant (introduced as relative leg stiffness by Blickhan and Full, 1993) using transformations in space and time (Blickhan, 1989). Although the flight phase was not considered previously it proves to hold even for a periodically running spring-mass system (due to the nature of the differential equations for the flight phase). According to our findings stable running requires a proper adjustment of (scaled) leg stiffness, angle of attack and (scaled) speed (similar to Fig. 2).

The experimental evidences of the model predictions lead to the conclusion that mechanically self-stabilized running requires a spring-like leg operation with a minimum running speed as well as a proper adjustment of the leg stiffness and the angle of attack. These conditions can be considered as a movement criterion for running.

4.2. *Variability in leg adjustment and possible muscular limitations*

With increasing speed different leg strategies become possible. The decision which strategy is appropriate for which animal requires to take properties of the musculoskeleton system into account.

To fulfill periodic running elastic operation on the musculo-skeletal level is of advantage. At high speeds flat angles of attack would lead to high lengthening rates of the muscle-tendon complex. With increasing stretching velocity, muscles may not any more be able to compensate the eccentric losses by concentric work. Here, compliant elastic tendons or long muscle fibers may reduce the effective muscle fiber velocity and consequently support high running speeds at flat angles of attack.

In contrast, steep angles of attack would require to build up leg forces rapidly. Therefore, stiff tendons and strong muscles would be necessary. Thus, depending on the muscle and tendon properties either the maximum muscle fiber velocity or the maximum fiber force capability would determine the strategy used with increasing running speed. In addition, stiff strategies would increase load to the skeleton and hamper exteroception. Furthermore, increased loads and loading rates of the musculature result in increased metabolic costs (Kram and Taylor, 1990).

Even though the animal's leg represents a nonconservative system special steps can be taken to provide stability, i.e. a return to the envisioned periodic condition without changing control (Wagner and Blickhan, 1999). The influence of this intrinsic stability at the muscle-skeleton level on stable movement strategies of the global system will be subject of further investigations.

4.3. *Outlook*

The spring-mass model is probably the simplest template of fast legged locomotion (Full and Koditschek, 1999). It was successfully applied to different movement patterns (bipedal, quadrupedal, hexapedal) in sagittal and horizontal plane (Blickhan and Full, 1993; Kubow and Full, 1999). Based on the mechanisms of running identified with the spring-mass model it is possible to derive the appropriate movement criteria for bi- and quadrupedal systems.

In humans, an alternate contact of both legs is characteristic but also synchronous leg operation can be realized with two legs (e.g. kangaroos, birds). Here, the arrangement of the legs and the mechanical properties of the supported body must be taken into account to identify the appropriate manner of leg operation with two legs. Multiple legged systems can take advantage of mechanically self-stabilized spring-like running if the integral stiffness of several legs contacting the ground simultaneously is properly adjusted. However, elastic operation is not necessary at every individual leg as long as the integral behavior remains the same (McMahon, 1985).

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