

Human leg adjustment in perturbed hopping

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1 Motivation

Robots can help to demonstrate and prove concepts on human locomotion such as concepts based on springlike leg behavior. Hopping is a fundamental requirement for running in two basic functions: bouncing and balancing. In addition, for robust hopping against perturbations, swinging the leg in flight/swing phase is observed. These three elements need to be integrated for stable/robust locomotion in bipeds. Unlike running [1] and walking [2], stable hopping cannot be achieved with a fixed angle of attack with respect to the ground. So, finding an appropriate leg direction during the flight phase is needed for stable hopping in place. In this study, different methods of leg adjustment during swing phase are compared both in simulation with SLIP (Spring Loaded Inverted Pendulum) model and in human experiment. Because of the lack of space and since we reported the simulation results previously [3], in this paper, it is just reported with a few sentences. Our presented method called VBLA (Velocity Based Leg Adjustment) shows better performance in modeling and is also closer to what humans do.

2 Methods

Most leg adjustment strategies rely on sensory information about the CoM velocity, following the Raibert approach [4] in which the foot landing position is adjusted based on the horizontal velocity (for example [5])

$$x_f = \frac{v_x T_s}{2} + k(v_x - v_x^d) \quad (1)$$

in which x , v_x and v_x^d are the horizontal position, speed and desired horizontal speed of the Center of Mass (CoM), re-

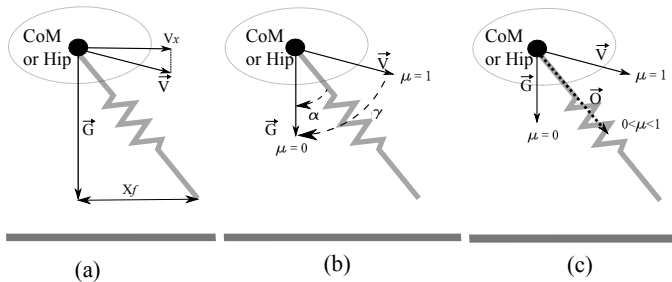


Figure 1: Different leg Adjustment approaches. a) Raibert method, b) Peuker approach c) VBLA.

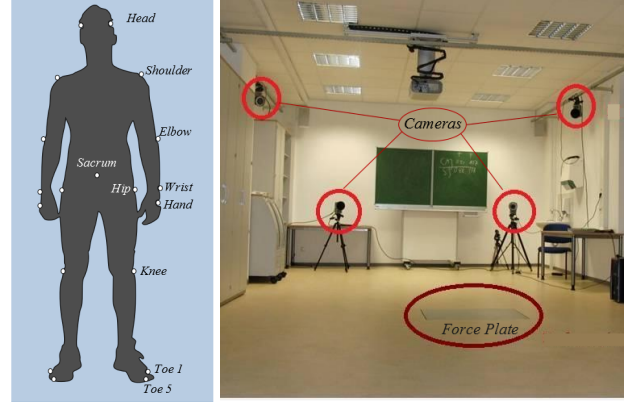


Figure 2: Experimental setting. Left: marker positions, right: lab setup

spectively. Also, k is a control constant and T_s is the stance time. The output of this controller is the horizontal distance between the desired foot point at Touch Down (TD) and hip point named x_f (see Fig. 1(a)). For hopping, where $v_x^d = 0$, Eq. (2) converts to $x_h = \mu v_x$ (for hopping the stance time is fixed and we can have a constant μ).

Recently, various strategies were investigated by Peuker et al. [6] who concluded that leg placement with respect to both the CoM velocity and the gravity vectors yielded the most robust and stable hopping and running motions with the SLIP model. Defining the angles of the gravity vector with the velocity vector and leg orientation by γ and α as shown in Fig. 1, this method gives the leg orientation by $\alpha = \mu \gamma$, where μ is a constant between 0 and 1. A modified version of this strategy, called VBLA, is presented [3]: the leg direction is given by vector \vec{O} , a weighted average of the CoM velocity vector \vec{V} and the gravity vector \vec{G} . The weight of each vector is determined by coefficient $0 < \mu < 1$ (see Fig. 1(c)). Unlike Peuker's approach which just consider the angle of velocity vector, in VBLA, both direction and angle of the velocity vector affects the desired leg direction

$$\begin{aligned} \vec{V} &= [v_x, v_y]^T; \vec{G} = [0, -g]^T \\ \vec{O} &= \mu \vec{V} + (1 - \mu) \vec{G} \end{aligned} \quad (2)$$

In all methods, when $\mu = 0$, the leg is exactly vertical and in the two recent ones, the leg is parallel to the CoM velocity vector for $\mu = 1$.

3 Results

It is analytically proved for SLIP model that with proper selection of μ in VBLA the dead beat response is achievable. Thus, with this approach it is possible to remove all perturbations at most in two steps. The perfect results of applying this method beside VPPC (Virtual Pendulum Posture Controller) to SLIP model with upper-body (called TSLIP for Trunk+SLIP) are reported in our previous work [3].

We did an experiment to investigate which method approximates to human leg adjustment best. In this experiment, the subject hops in place with arms akimbo and suddenly a perturbation occurs at apex by pushing him/her from behind. The pushing point is near sacrum which is an approximation of CoM. The kinematic behavior of the body is derived using markers shown in Fig. 2. We use a force-plate to measure GRF during stance phase. CoM motion was obtained by integrating the GRFs twice. Initial values for velocity and position of CoM were obtained from the sacrum position [7]. The markers positions, cameras and the force-plate are shown in Fig. 2.

To evaluate the aforementioned methods, the velocity at touch down and the leg orientation (the vector from the CoM to the foot contact point with the ground) are detected. In order to approximate μ in different approaches, two parameters (assume a and b) are computed and then a least square approximation is used to find μ such that $a = \mu b$. In Raibert approach, $a = x_f$ and b is the horizontal velocity. For the second approach, $a = \alpha$ and $b = \gamma$. Finally, from (3) for VBLA $a = n$ and $b = m$ are obtained by

$$\begin{aligned} \frac{O_y}{O_x} &= \frac{\mu V_y - (1-\mu)g}{\mu V_x} \Rightarrow \\ \underbrace{gO_x}_n &= \underbrace{\mu(O_x V_y + gO_x - O_y V_x)}_m \end{aligned} \quad (3)$$

All these parameters and their linear estimations are plotted in Fig. 3. VBLA has the best fitting to the data which describes the human leg adjustment by a fixed value of μ . In addition, Table. 1 shows the statistical information about these data. The maximum R^2 index (for correlation) and the minimum variance correspond to VBLA. The closer R^2 correlation index to one, the better fitting of data points to a line. This value is about 0.95 for VBLA, showing an appropriate matching of the data to this method. At each TD moment, related μ is also obtained by a/b and then the variance of these values are computed.

4 Discussion

The VBLA shows the best performance of leg adjustment for perturbed hopping in simulation of SLIP model. The ability of this method to converge from any point in the

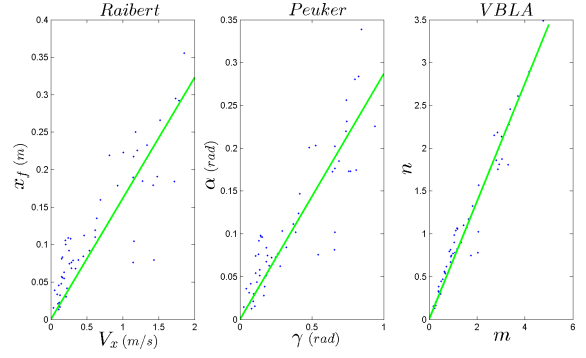


Figure 3: Fitting data to a line. From left to right Raibert, Peuker and VBLA approaches.

region of attraction to the limit cycle of the periodic vertical hopping is provable. In this paper, its validity for human hopping is investigated. The proposed method fits perfectly to the human experiment data which is shown by correlation and variance computation. This method can also be evaluated for running. Application of this approach in addition to a stance phase control schemes can be evaluated for more complex models.

5 Format

We prefer to present this paper as an oral presentation.

References

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Table 1: Different approaches statistical characteristics

Method	μ	R^2 index	Variance
Raibert	0.1614	0.6753	0.0182
Peuker	0.2865	0.763	0.0248
VBLA	0.6881	0.9486	0.0162