2013 IEEE/RSJ International Conference on
Intelligent Robots and Systems (IROS)
November 3-7, 2013. Tokyo, Japan

Compliant hip function simplifies control for hopping and running

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Abstract— **Bouncing, balancing and swinging the leg forward can be considered as three basic control tasks for bipedal locomotion. Defining the trunk by an unstable inverted pendulum, balancing as being translated to trunk stabilization is the main focus of this paper. The control strategy is to generate a hip torque to have upright trunk to achieve robust hopping and running. It relies on the Virtual Pendulum (VP) concept which is recently proposed for trunk stabilization, based on human/animal locomotion analysis. Based on this concept, a control approach, named Virtual Pendulum Posture control (VPPC) is presented, in which the trunk is stabilized by redirecting the ground reaction force to a virtual support point. The required torques patterns generated by the controller, could partially be exerted by elastic structures like hip springs. Hybrid Zero Dynamics (HZD) control approach is also applied as an exact method of keeping the trunk upright. Stability of the motion which is investigated by Poincaré map analysis could be achieved by hip springs, VPPC and HZD. The results show that hip springs, revealing muscle properties, could facilitate trunk stabilization. Compliance in hip produces acceptable performance and robustness compared with VPPC and HZD, while it is a passive structure.**

Nomenclature	
CoM	Centre of Mass
GRF	Ground Reaction Force
VBLA	Velocity Based Leg Adjustment
TD	Touch Down
TO	Take Off
VPP	Virtual Pivot Point
VP	Virtual Pendulum
VPPC	VP Posture Control
LQR	Linear Quadratic Regulator
VPPC-FP	VPPC with Fixed Point
VPPC-LQR	VPPC with LQR
HZD	Hybrid Zero Dynamics
SLIP	Spring Loaded Inverted Pendulum
TSLIP	SLIP extended by Trunk

I. INTRODUCTION

Rebounding on compliant legs is one of the basic mechanical consideration in human locomotion, especially running [1]. Efficiency and robustness are two significant goals in designing the bipedal robots' structure and controlling the gaits. In that respect, several bipedal robots were developed based on human morphology and locomotion. On the other hand, simple conceptual models, coined "templates" [2] have proved to be very helpful for describing and analysis of animal locomotion. Despite their high level of abstraction, they inspired over the years the development of successful legged robots [3][4] or were used as explicit targets for control [5]. One of these templates is the spring-loaded inverted pendulum (SLIP) [6][7] consisting a point mass atop a massless spring and describes the human gaits (walking [1], hopping and running [6]) very well. However, as the upper body is represented by a point mass, stabilization of the trunk (*posture control*) which is required in an efficient bipedal gait [8] cannot be addressed with this template. For that purpose, the SLIP must be extended to include the upper body.

For trunk stabilization, many approaches have been employed like bisecting mechanism [9] and the common PD controller [3] which are different from human trunk control strategies. Another group of methods mostly rely on the same principle, i.e. the feedback control of the trunk orientation with respect to an absolute referential frame [5][10]. Recently, based on observations in different animals and humans motion, Virtual Pivot point (VPP) [8] (or Divergent Point (DP) [11]) is proposed as an innovative concept for posture stabilization which converts the trunk from being an inverted pendulum to a normal hanging pendulum pivoted at a virtual point (VPP) above its center of mass. With hip torque control without knowing the trunk absolute orientation, VPP is generated by redirecting the ground reaction force (GRF) vector towards it. The Virtual Pendulum Posture Control (VPPC) is represented based on this strategy which might be also the solution of nature for trunk stabilization. VPPC was validated in simulations to perform stable walking, running, [12] and perturbed hopping in place [13].

We developed adaptive version of VPPC using optimal controller LQR (Linear Quadratic Regulator) to adjust the VPP at each step in order to make a robust hopping against perturbations [13]. It is performed by a feedback law using the states at the apex event in order to adjust the VPP position during the next stance phase. This increased the convergence speed which could remove considerably high perturbations in few steps. Since the main consequence of VPPC (and its extension to VPPC-LQR) is observed in producing upright trunk during locomotion [8], another control approach for balancing the trunk is investigated for comparison. Hybrid Zero Dynamics which employs feedback linearization to satisfy some virtual holonomic constraints is selected which is developed in [14] and [15]. The main reason of applying HZD to design the controller is its outstanding stability analysis background and successful applications to different

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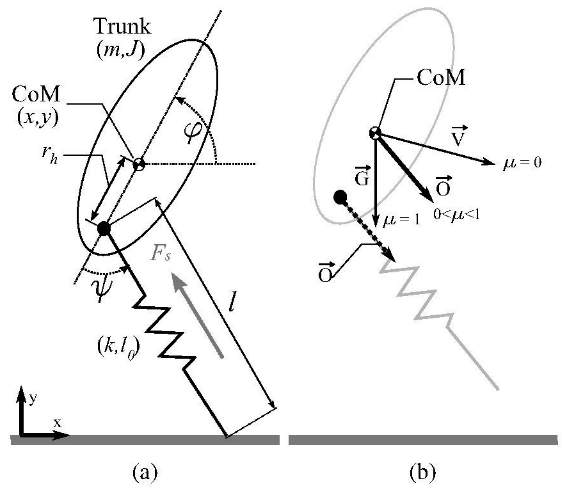

Fig. 1: (a) TSLIP model with a rigid trunk and a leg modeled as a massless prismatic spring. (b) Velocity-based leg adjustment (VBLA) during flight phase.

robots (see [5], [16], [17], [18] and [19]).

Two aforementioned control methods are from different viewpoints of bipedal locomotion. The goal of this paper is investigating whether stabilizing control torque for running and hopping could be produced passively. The robustness of this kind of passive posture control and its correspondence to produce VPP and balancing the trunk are the next questions to be responded. Hip springs were utilized between the legs, resulting in taking faster steps and having positive effect in swing leg motion [20][21]. The latter effect is also resulted from implementing elastic tendons between upper body and legs [22]. Reducing the energy consumption and increasing the walking robustness with upright trunk using a hip torsional spring were studied before [23][24].

In this paper, we apply VPPC+LQR and HZD hip torque controllers to achieve robust running and hopping. Velocity Based Leg Adjustment (VBLA) introduced in [13] is used during flight phase. Finally, the controllers are replaced by two unidirectional hip springs mimicking the muscles between upper body and hip. Optimizing the springs' characteristics to produce the required torques to resemble the VPP, results in comparable performance in running and hopping.

II. METHODS

A. Simulation model

The same mechanical model presented in [13] (TSLIP [1] for Trunk-SLIP) is an extension of the traditional SLIP, where the point mass is replaced by a trunk (a rigid upper body with mass m and moment of inertia J), as represented in Fig. 1a. The model parameters are set to match the characteristics of a human with 80 kg weight and 1.89 m height (see Table I). With this model, running and hopping could be explained by two motion phases: *flight* and *stance*. In flight phase, the leg does not touch the ground and the Center of Mass (CoM) moves in a ballistic motion. Since the leg is massless, the leg orientation can be arbitrarily adjusted.

Stance phase starts by touchdown (TD), the moment that the distal end of the leg hits the ground and ends with takeoff (TO) when the $GRF = [GRF_x \ GRF_y]$ has no vertical component ($GRF_y = 0$). In this phase, $F_s = k\ (l_0 - l)$ gives the spring force along the leg axis, where l, l_0 and k are respectively the current leg length, leg rest length and the spring stiffness. Defining the states x, y and φ as the CoM horizontal and vertical positions and the trunk orientation, respectively; the hip point ($X_h = [x_h, \ y_h]$) which is positioned below CoM with distance r_h is obtained as follows

$$\begin{aligned} x_h &= x - r_h \cos\varphi \\ y_h &= y - r_h \sin\varphi \end{aligned} \tag{1}$$

The hip torque τ produced by VPPC, HZD or hip springs, are applied at the hip to stabilize the posture of the trunk. Then, the ground reaction force components are computed as

$$\begin{aligned} GRF_x &= F_s \tfrac{x_h}{l} + \tfrac{\tau y_h}{l^2} \\ GRF_y &= F_s \tfrac{y_h}{l} - \tfrac{\tau x_h}{l^2} \end{aligned} \tag{2}$$

Finally, the stance phase equations of motion are given by

$$\begin{cases} m\ddot{x} &= GRF_x \\ m\ddot{y} &= GRF_y - g \\ J\ddot{\varphi} &= \tau + r_h(GRF_x \sin\varphi - GRF_y \cos\varphi) \end{cases} \tag{3}$$

where g is the gravity acceleration.

B. System analysis

The model is investigated using Poincaré return map analysis. Then, the event used for the Poincaré section is the apex moment where the CoM reaches its highest height, characterized by $\dot{y} = 0$ with $\ddot{y} < 0$. Using this definition, the system states at apex are described with the reduced[2] state vector: $\mathbf{S} = [y, \varphi, \dot{x}, \dot{\varphi}]$. The Poincaré return map $\mathbf{F}$ between two consecutive apexes is thus defined by $\mathbf{S}_{k+1} = \mathbf{F}(\mathbf{S}_k)$. Periodic running motions correspond to the fixed points of $\mathbf{F}$ (i.e. $\mathbf{S}^*$ such that $\mathbf{S}^* = \mathbf{F}(\mathbf{S}^*)$) with general form: $\mathbf{S}^* = [y^*, 90°, v_x^*, 0]$ ($v_x^* = 0$ for hopping).

The local stability of a periodic motion is investigated by finding the eigenvalues λ_j of the Jacobian matrix at the fixed point $A = \frac{\partial \mathbf{F}}{\partial \mathbf{S}}(\mathbf{S}^*)$, computed numerically. As the leg is a perfect spring, the periodic motion is always neutrally stable with respect to the hopping/running height (y^*) changes, characterized by an eigenvalue at 1. Thus, a stable periodic motion is detected when all other eigenvalues are inside the unit circle. The robot is dropped from the nominal height and the system transient behavior is evaluated by applying perturbations to the model; the initial horizontal speed $\dot{x}_0 \neq v_x^*$ and/or trunk angle $\varphi_0 \neq 90°$.

[1]In [25] a similar model was introduced namely ASLIP, for "Asymmetric SLIP". However, as this term can also designate a SLIP model with asymmetric leg properties, we prefer to use the appellation TSLIP.

[2]The absolute horizontal position x is omitted because it does not influence the evolution of the system from one apex event to the next.

C. Leg adjustment during the swing phase

For the conservative locomotion models, leg adjustment which controls the motion velocity and upper body stabilization are two main tasks in hopping, running and walking. Since the main focus of this paper is on trunk stability, we present a short summary of our leg adjustment approach.

Unlike running [26] and walking [1], stable hopping cannot be achieved using a fixed angle of attack with respect to the ground. Also, the region of attraction for stable running is quite small. This drawback and sensitivity to running velocity and control parameters exist in other common leg adjustment methods. Most of the leg adjustment strategies rely on sensory information about the CoM velocity, following the approach pioneered by Raibert [3] in which the foot landing position is adjusted based on the horizontal velocity [5] [27]. In this paper, VBLA (Velocity Based Leg Adjustment) presented in [13] is used as a robust method. The similarity of this approach to human leg adjustment strategy for perturbed hopping [28] and a large achievable running velocities range by a fixed VBLA [29] are the advantages of this approach.

In this method, the leg direction is given by vector $\vec{O}$ as a weighted average of the CoM velocity vector $\vec{V}$ and the gravity vector $\vec{G} = [0, -g]^T$ (Fig. 1b).

$$\vec{O} \quad = \quad (1-\mu)\vec{V} + \mu\vec{G} \tag{4}$$

The portion of each vector is determined by gain $0 < \mu < 1$. Changing μ from 0 to 1 results in desired leg direction from vertical orientation to parallel to the CoM velocity vector.

D. Hip torque Generation

1) VPPC with Event-based Control: In [8], ground reaction force vectors were found at each moment and plotted from center of pressure for walking and running animals and it was shown that there exists one point above CoM which all the vectors intersect about that point. Therefore, creating a point of virtual support (VPP) located above the CoM is the key idea of the virtual pendulum concept. During the stance phase, it is done by redirecting the GRF vector towards this point, via joint torques. Hence, the trunk behavior is transformed, from an inverted pendulum mounted at the hip to a regular virtual pendulum suspended at the VPP.

In Fig. 2b, VPPC in the TSLIP model is shown which implements the VP concept by applying the hip torque (τ) to adjust GRF vector. The required torque to generate necessary force perpendicular to the leg axis (F_N) is computed by

$$\tau = F_s\ l\ \frac{r_h\ sin\ \psi + r_{\text{VPP}}\ sin(\psi-\gamma)}{l + r_h\ cos\ \psi + r_{\text{VPP}}\ cos(\psi-\gamma)} \tag{5}$$

As shown in (5), it does not require information about the absolute trunk orientation φ (only the force F_s and the leg orientation w.r.t. the body ψ are needed). Since the VPP is placed in the body coordinate system, the same approach of GRF direction adjustment can be easily extended for more complex models using measurements inside the robot model.

The performance and robustness of the hopping motion was improved using event-based control, introduced in [13].

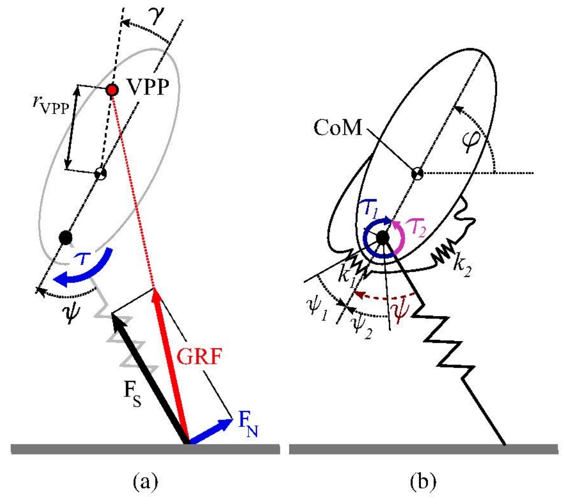

Fig. 2: (a) Virtual pendulum-based posture control (VPPC) during stance phase. (b) Hip spring configurations.

In this method, at each apex, the VPP position is adapted for the next stance phase using the current system state. To design the controller, the Poincaré return map is linearized around a nominal fixed point S^*, considering γ as input. The suggested controller was LQR to minimize the wighted cost function $J = \sum_{n=1}^{\infty} \mathbf{X}_n^T W^T W \mathbf{X}_n$ (with diagonal weight matrix W), using state feedback $\gamma_n = -KX_n$ in which $\mathbf{X}_n = [\Delta\varphi_n, \Delta\dot{x}_n, \Delta\dot{\varphi}_n]$; with the following optimal gain.

$$K = (B^T PB)^{-1} B^T PA \tag{6}$$

in which P is a symmetric positive definite matrix, the solution of the following discrete Riccati Algebraic Equation.

$$P = Q + A^T(P - PB(B^T PB)^{-1} B^T P)A \tag{7}$$

where $Q = W^T W$ and the weight matrix W can be used to give more importance to some of the state variables. This method is called VPPC-LQR whereas the original VPP based controller with fixed point is called VPPC-FP. With VPPC-LQR, a more stable motion with smoother and faster convergence to the steady state values is achieved.

2) HZD Controller: Since the model has just one actuator, in order to design the Hybrid Zero Dynamics controller, the output should be scalar. Regarding to the goal of this control layer, difference of the trunk angle to the desired value φ^d (90° for upright trunk) is considered as the output; $q = \varphi - \varphi^d$. This output results in second order input-output dynamics

$$\begin{aligned} J\ddot{q} \quad = \quad & F_s r_h (\tfrac{x_h}{l}\sin\varphi - \tfrac{y_h}{l}\cos\varphi) + \\ & \tau(1 + r_h(\tfrac{y_h}{l^2}\sin\varphi + \tfrac{x_h}{l^2}\cos\varphi)) \end{aligned} \tag{8}$$

Putting $\frac{x_h}{l} = \cos(\varphi+\psi)$ and $\frac{y_h}{l} = \sin(\varphi+\psi)$ in Eq. 8, it is straight forward to find τ^* such that zero $\ddot{q}$.

$$\tau^* = F_s l \frac{r_h \sin\psi}{l + r_h\cos\psi} \tag{9}$$

Let complete state vector $X = [x, \dot{x}, y, \dot{y}, \varphi, \dot{\varphi}]$. If $\varphi^d = 90°$, the zero dynamics manifold $\mathcal{Z} = \{X \in \mathbb{R}^6 | q = \dot{q} = 0\}$ is hybrid invariant and the stance phase equation is reduced to

$$\dot{z} = f_z(z) = \begin{cases} m\ddot{x}_h = \frac{F_s}{l} x_h \bar{l} \\ m\ddot{y}_h = \frac{F_s}{l}(y_h + r_h)\bar{l} \end{cases} \tag{10}$$

in which $\bar{l} = \frac{l^2}{l^2 + r_h y_h}$. The hybrid zero dynamics are stable if the eigenvalues of the linearization of the Poincaré map of the following hybrid model are placed inside the unit circle. This could be satisfied using VBLA and checked numerically.

$$\begin{cases} \dot{z} = f_z(z) & z \notin \mathcal{S} \\ z^+ = \Delta z^- & z \in \mathcal{S} \end{cases} \tag{11}$$

where $\mathcal{S}$ is the touch down surface and Δ is computed by integrating the flight phase (from TO to TD). Finally to converge to manifold $\mathcal{Z}$, a high gain PD controller is used after the feedback lineariztion and the hip torque will be

$$\tau = l\frac{v + F_s r_h \sin\psi}{l + r_h \cos\psi}, \quad v = -\frac{K_p}{\epsilon^2}(\varphi - \varphi^d) - \frac{K_d}{\epsilon}\dot{\varphi} \tag{12}$$

Hence, with small enough ϵ, sufficiently fast convergence to $\mathcal{Z}$ is guaranteed and the system (3) is stable if the eigenvalues of the hybrid zero dynamics system (11) are in the unit circle.

3) Passive hip control: The last method of posture control is producing hip torque τ by hip compliance. This includes two springs working in opposite directions and a damper parallel to them. The springs are unidirectional with a certain rest angles ψ_1 and ψ_2 and stiffnesses k_1 and k_2 as shown in Fig. 2b.

$$\tau = k_1 max(0, \psi - \psi_1) + k_2 min(0, \psi - \psi_2) - d\dot{\psi} \tag{13}$$

Therefore, the hip torque depends on ψ, $\dot{\psi}$, springs' rest angles and coefficients and damping ratio d. The mechanism is like human muscles, hamstring and rectus femoris[3]. Since the leg motion in flight phase is neglected, one of the springs (regarding to angle of attack) may be preloaded at touch down which means increasing the energy of the system in hopping and damping helps to stabilize the level of energy. Another option could be addition of the leg dynamics during flight and removing the damper, but it needs another controller for this phase which affects the whole motion and disturbs a fair comparison condition with other posture control approaches. On the other hand, damping is the phenomenon observed in human locomotion [30].

4) VPP location estimation: As mentioned before, VPP is a concept which is observed in human/animal upper body balancing. It is also possible to check it in other control methods. Through [8] the VPP is defined as "the single point at which the total transferred angular momentum remains constant and the sum-of-squares difference to the original angular momentum over time is minimal, if the GRF is applied at exactly this point". In the next section, this point is found for different approaches. If it is above the center of mass, it can be concluded that the VPP concept is used implicitly in that method.

[3]In human body, these muscles are biarticular which need two-segment leg. Hip springs can be interpreted as a mechanical representation of these muscles and can be extended in future to models with segmented legs.

III. RESULTS

In this section, the stability and robustness of different aforementioned controllers are compared. As a standard model, TSLIP for hopping with parameters of Table I is simulated in MATLAB/SIMULINK 2012b using ode45 solver. First, hip spring, HZD and original VPPC (with fixed VPP position) are applied to make stable hopping and running against small perturbations, and the position of VPP are compared together. Next, the time responses for three methods after addition of damping to the passive model for hopping and adapting the VPP point with LQR are compared.

TABLE I: Model parameters

Parameter	symbol	value [units]
trunk mass	m	80 [kg]
trunk moment of inertia	J	4.58 [kg m^2]
distance hip-CoM	r_{CoM}	0.1 [m]
leg stiffness	k	16000 [N/m]
leg rest length	l_0	1 [m]
Nominal hopping/running height	y^*	2.5 [cm]

A. Existence of VPP in different methods

Stable hopping against lateral trunk perturbations is the first task. For leg adjustment, $\mu = 0.3$ is selected in VBLA. The only remaining parameter in trunk stabilization with VPPC-FP is the position of the VPP. As we aim at an upright trunk position, we set the VPP angle γ to zero. Exploring different values for r_{VPP} results in 10 cm as the value with the smallest eigenvalue. Hip springs with stiffnesses 250 $\frac{Nm}{rad}$ and rest angles $\psi_1 = \psi_2 = 0°$ are utilized as a passive controller instead of VPPC-FP. Time responses of φ, $\dot{\varphi}$ and $\dot{x}$ are shown in Fig. 3, for perturbation $\dot{x}_0 = 1\frac{m}{s}$. Responses are quite comparable to each other which demonstrate the similarity between the action of the passive hip springs and the VPP concept. To investigate this claim, the VPP location is found for passive hip control approach. There exists a VPP point above CoM with $r_{VPP} = 13.25\ cm$ as shown in Fig. 4a. Here, CoM is the origin and the ground reaction forces, originating at the center of pressure are displayed at different time instances. The estimated location of the VPP measured over hopping steps, is depicted by red point above the CoM. $r_{VPP} = 3.8\ cm$ is found in the similar experiment with HZD controller. Since, the trunk is vertical and the perturbation just happens in horizontal speed, with HZD the convergence to vertical hopping is achieved in fewer steps.

Next, a stable running with speed $3\frac{m}{s}$ is produced by VPPC-FP with $\mu = 0.43$ and $r_{VPP} = 6\ cm$. To evaluate the robustness, 20° trunk deviation from vertical orientation is considered as the perturbation. With the same μ, hip springs with stiffnesses 300 $\frac{Nm}{rad}$ and rest angles $\psi_1 = -\psi_2 = 2°$ result in stable running with states' trajectory patterns similar to VPPC-FP. Estimated r_{VPP} for this passive running is 7.6 cm (see Fig. 4b) which is close to 6 cm, used for VPPC-FP. Applying HZD controller for such a running, results in variable VPP for removing the perturbation, shown in Fig. 5.

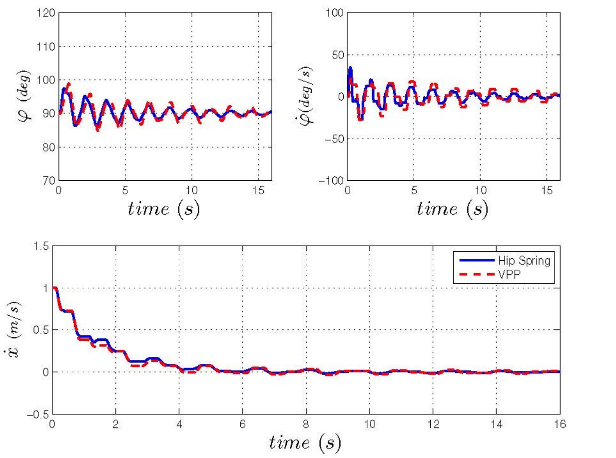

Fig. 3: Hopping response to 1 m/s perturbation with hip spring and VPPC-FP.

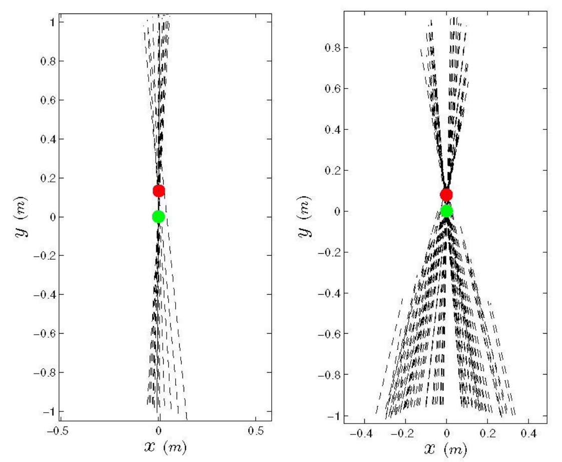

Fig. 4: VPP in passive motion of (a) hopping and (b) running.

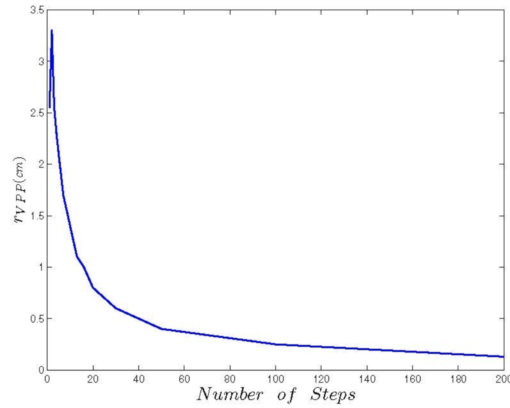

Fig. 5: Variations of VPP for HZD control approach in stable perturbed running.

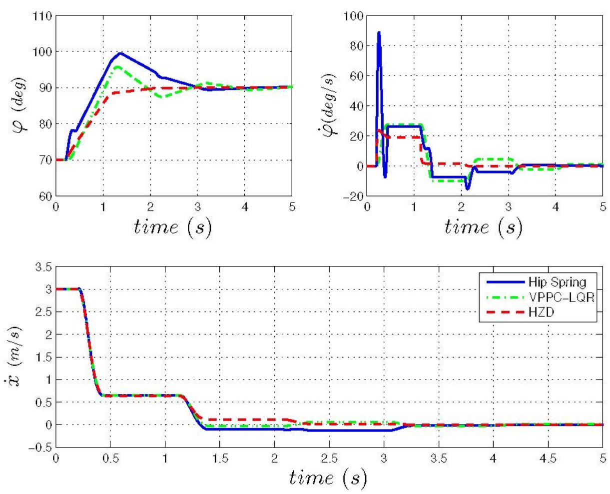

Fig. 6: Perturbed hopping performance with different control methods. Perturbations are 3 m/s horizontal speed and 20° trunk angle deviation from upright posture.

From (5) and (9), it is obvious that after converging to the stable limit cycle, HZD controller results in VPPC with VPP at CoM. Hence, HZD control strategy could be interpreted as changing VPP position with respect to the trunk orientation error and finally converging to CoM for upright trunk.

B. Performance comparison

In order to evaluate the abilities of passive control more, running and hopping behavior against larger perturbations are investigated in this section. HZD and VPPC-LQR (which has smaller eigenvalue and higher robustness than VPPC-FP) are used for comparison. In addition to improve the control quality of the passive control approach for hopping, damping is considered in parallel to the hip spring. The control parameters for hopping are $\mu = 0.2$, $k_1 = k_2 = 300\ \frac{Nm}{rad}$, $d = 15\ \frac{Nms}{rad}$ and $\psi_1 = \psi_2 = 0$. The perturbation includes $3\frac{m}{s}$ horizontal speed and 20° trunk angle deviation which are reduced to less than 5% of their initial values in less than 2.5 seconds as shown in Fig. 6. The performance of passive structure is comparable to HZD and VPPC-LQR with $r_{VPP} = 1\ cm$ and $W = diag(1, 1, 8)$.

For running, the leg direction at touch down should be closer to gravity vector and damping should be removed; otherwise, the energy of the system never converges to a constant value. The results for trunk angular perturbation 20° are shown in Fig. 7. The running transient behavior with passive structure is not as good as two other active methods performances, but it is acceptable. In this figure, the states at apexes are displayed to make the figure more readable. Although there exist some oscillations in trunk, final speed is close to its desired value and the running is robust against perturbations. In order to analyze the periodic motion after convergence to stable limit cycle, trunk angle and hip torques are compared in Fig. 8 for one gait cycle. HZD controller could keep the trunk exactly upright with small hip torques. VPPC-LQR needs more torque and results in very small oscillations in trunk orientation (less than 1 degree). Note that this method does not use the trunk angle, while HZD

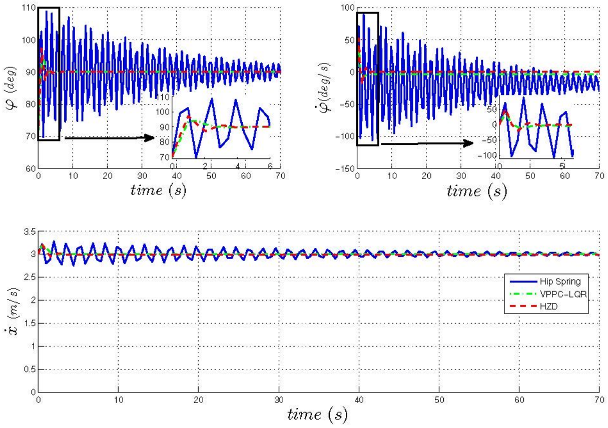

Fig. 7: States at apexes for perturbed running. Perturbation is 20° trunk angle deviation from upright posture.

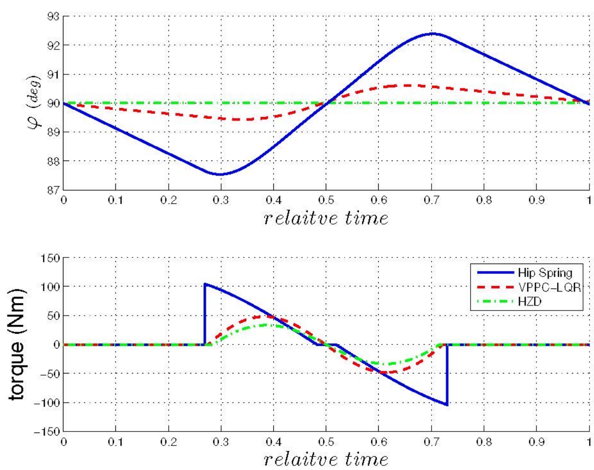

Fig. 8: Hip Torques an trunk angle for stable running. Time is relative to gait cycle duration.

employs it in the PD controller (see (12)). Applying hip springs, the range of oscillations becomes two degrees and maximum exerted torque doubles, but this method even does not use the force sensor in the leg.

IV. DISCUSSION

In this paper the relation between hybrid zero dynamics controller, virtual pendulum posture control and hip springs to produce stable hopping and running is investigated. In HZD, full sensory information including leg force, leg angle and trunk orientation are needed. In VPPC, trunk and leg angles are not required and just the angle between them should be known beside the leg force. Finally, using hip springs, no sensor and actuator are needed and only the angle between trunk and leg affects the torque generated by springs. For running, the results of employing hip springs show similar torque patterns and comparable robustness against perturbations with respect to two other approaches. Nonlinear springs may mimic more similar torque-angle behavior which could be explored in future.

Stable hopping is achievable against small perturbations using hip springs, but for larger perturbations, a rotational damper is added to the model. This increases the ability to recover from large perturbations, like 3 $\frac{m}{s}$ speed and 20° trunk angle deviation, happening simultaneously. Replacement of damping with variable stiffness mechanism could be another alternative to increase the robustness of hopping.

Another finding of this study is analyzing the VPP point produced by HZD and hip springs. It is demonstrated that with hip springs, VPP is observed whereas its distance to CoM is close to this value in VPPC. VPP point above CoM is also found in HZD for hopping. In running limit cycles, HZD behaves like VPPC with VPP at CoM, but it changes when perturbation occurs. HZD strategy to remove the trunk deviation from upright position could be interpreted as variable VPP control approach. This is the strategy for which VPPC-LQR presents a systematic method to adjust.

In order to combine a passive design as proposed by the hip springs and the hip control approaches such as HZD and VPPC, we could follow the design of a biological muscle-tendon-complex (MTC). Here the spring (tendon) is arranged in series to the actuator (muscle fibre). When the muscle is deactivated, no force is produced by the spring. With increasing activation, the coupling of the spring to the joint is established. In order to mimic the idea of the VPP in such an actuator, the leg force could be used as a signal to drive the muscle. This would ensure that the spring will only be active when high forces are applied by the leg. At the same time, the intrinsic properties of the muscle (e.g. force-velocity curve, [31]) will ensure, that hip stiffness will be complemented by additional damping, which would support faster convergence as observed in VPP-LQR or in HZD. The function of such a biologically motivated hip control could be simulated based on a series-elastic-actuator concept as proposed by [32].

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