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Hopping Gait Generation for a Biped Robot with Hill-Type Muscles

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***Abstract*—This work presents a novel gait generation method for biped hopping with point feet. The investigated biped model consists of a kneed massless leg and a trunk with two Hill-type muscles at the hip and knee joints. The dynamic equations of the system are derived using Lagrange method. Since the most important phase to stabilize bipedal running and hopping motion is stance phase, this paper deals only with the stance phase and develops a control law for the actuators to generate an arbitrary trajectory for hip of the underactuated biped robot. Without loss of generality, a forth order curve with properly chosen parameters has been used as the desired robot trajectory in stance phase. This curve has similarities to the Spring Loaded Inverted Pendulum gait, and can generate the desired initial and final position and velocity of the stance phase. Hill-type muscles are used as the actuators of our model, because being simple it includes fundamental elements that are necessary for biped running efficiency. The proposed control law calculates the needed actuators inputs and gets the robot to undergo the desired trajectory. The designed control law is verified in simulation.**

Keywords*—*biped hopping; gait generation; Hill-type muscle

I. INTRODUCTION

Similarity to humans and having high performance and maneuverability has fascinated researchers to investigate bipedal locomotion more deeply in recent years. Energy efficiency makes it necessary to switch from walking to running as the progression speed increases [1]. To use compliant elements in legs reduces touch-down impact transferred to robot links, increases energy efficiency of bipedal running, and generates more natural looking gaits. However, compliant structure of the robot makes controller design more difficult. Biped running motion consists of stance phase, take-off, flight phase, and touch-down. In stance phase one leg is pivoted to the ground and another leg is swinging. For our biped model with point feet, the robot has one degree of underactuation in stance phase. In flight phase the robot has no contact point with the ground and undergoes a ballistic motion, so it has three degrees of underactuation. Most of the control effort to reject disturbances and stabilize biped running is done in the stance phase and so in this paper we concentrate to control this phase only. Touch-down is an instantaneous phase in which a leg contacts to the surface and the robot switches from flight phase to stance phase. Touch-down impact causes an instantaneous change in robot links velocities and can damage motors if no springy elements are used in legs of the robot.

Spring Loaded Inverted Pendulum (SLIP) is a simple and useful compliant model that was proposed by Blickhan [2] in 1989 to describe biped walking and running dynamics. This theoretical model consists of a point mass at the hip and two massless springs as robot legs. This model generates human's center of mass (CoM) trajectory and ground reaction force (GRF) profiles for walking and running [3]. The dynamic model of SLIP has no closed form solution but it has been solved approximately with small angles hypothesis [4]. In the general case it should be solved numerically. Although SLIP running gaits cannot be implemented directly on multibody robots, we use it to plan the desired trajectory for the biped robot investigated in this paper.

Animals and human running takes advantages of viscoelastic properties of their muscles. Hill [5] in 1949 proposed a mechanical model for muscle consisting of: (1) a main contraction part, (2) a passive elastic part series to 1, and (3) a passive elastic part parallel to 1 or parallel to 1 and 2. The part 3 prevents the actuator reaction to small initial loads. The passive elastic part series to the main active contraction part plays an important role in mechanical behavior of muscles. This part as an spring accumulates energy when a high tension is exerted to the muscle during its sudden change from rest to active state [6]. Ahmadi et al. [7] in 1997 presented a control method for a one legged hopper robot with compliant elements series to hip motor. They found unstable passive hopping gaits for their model and designed a controller to stabilize the hopping motion around its passive gait. Hyon et al. [8] in 2004 proposed an energy preserving controller for planar biped hopping with torso. Their controller aimed to preserve energy during touch-down. Sato et al. [9] in 2004 modeled a robot with one springy leg and a motor at hip to study SLIP model. They generated running motion in simulation and experiment with the velocity of 0.8 m/s. Meghdari et al. [10] in 2008 proposed a feedback linearization controller to follow SLIP trajectory by a three link rigid hopper. Their controller could generate stable hopping motion in simulation starting from Poincare map fixed point initial condition. Iida et al. [11] in 2008 designed a biped robot with only one motor at the hip and passive springs as muscles at the knees and ankles. Their robot could generate walking and running like motions in experiments. Eilenberg et al. [12] in 2009 proposed an adaptive muscle-reflex controller using Hill-type muscle model for flexor-plantar muscles of ankle joint. Oyama et al. [13] in 2009 designed and fabricated KenkenII robot which had springs similar to tendons of organisms. This robot was designed to run with 0.7 to 0.9 m/s using a robust controller to ground disturbances. Andrews et al. [14] in 2011 made successful experiments based on this controller for a one legged planar hopper. Their controller could stabilize hopping on unknown ground ups and downs less than %25 of the free leg length. Dadashzadeh et al. [15] in 2014 generated biped running gaits with constant motor torques for a biped model having springs parallel to motors. Then they stabilized it using a state feedback controller on the Poincare map.

In this paper we consider a one legged hopper with three links and two Hill-type muscles as actuators. The trunk angle is assumed to be constrained as vertical any time. The dynamic equations are derived using Lagrange equation. A symmetric trajectory is planned for the stance phase consistent with initial condition of the robot. Then the necessary angles, velocities and accelerations of the robot links are calculated using inverse kinematics and inverse dynamics to make the robot undergo the desired trajectory. Using the calculated parameters, the control inputs of the robot can be found at any time. The designed control law is verified in simulation. The main contribution of this paper is developing a control law for underactuated biped hopper to make the robot to undergo any arbitrary trajectory. The other contribution is generating efficient hopping gaits using Hill-type muscle model.

II. Trajectory Planning

The first step in our controller design procedure for stance phase is to plan a desired trajectory. Inspired by SLIP trajectory in stance phase, without loss of generality, we choose a 4th order curve

$$y = -\frac{a^2 x^4}{12} + \frac{b^2 x^2}{2} + c\,, \tag{1}$$

which is symmetric around y axis and has two points of inflection during stance phase as shown in Fig. 1. The velocity and acceleration equations are derived using derivatives of (1) as

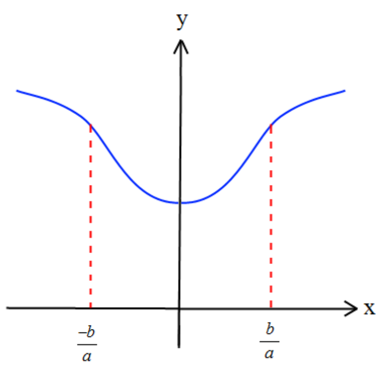

Fig. 1. Schematic view of 4th order curve chosen as the desired trajectory for the stance phase

$$\dot{y} = \frac{-a^2 \dot{x} x^3}{3} + b^2 \dot{x} x\,, \tag{2}$$

$$\ddot{y} = \frac{-a^2 \ddot{x} x^3}{3} - a^2 \dot{x}^2 x^2 + b^2 x \ddot{x} + b^2 \dot{x}^2\,. \tag{3}$$

Parameters a, b, and c are calculated using stance phase initial condition of the robot CoM. Assuming massless feet and constrained torso angle, the GRF passes through the robot's hip and using Newton method the dynamic equations can be written as:

$$\sum F_x = m\ddot{x} \rightarrow -F_r \sin\theta = m\ddot{x}\,, \tag{4}$$

$$\sum F_y = m\ddot{y} \rightarrow F_r \cos\theta - mg = m\ddot{y}\,. \tag{5}$$

Using trigonometric equations sin and cos can be written in terms of x and y:

$$\sin\theta = \frac{-x}{\sqrt{x^2 + y^2}}\,, \tag{6}$$

$$\cos\theta = \frac{y}{\sqrt{x^2 + y^2}}\,. \tag{7}$$

Equations (1-7) are combined to obtain acceleration equation as

$$\ddot{x} = \frac{-a^2 \dot{x}^2 x^3 + b^2 x \dot{x}^2 + xg}{\frac{a^2 x^4}{4} - b^2 x^2 + \frac{b^2 x^2}{2} + d}\,. \tag{8}$$

By solving (8) numerically, the velocity and acceleration on the robot CoM for the chosen trajectory are found over time.

III. Dynamic Model of the System

The one legged robot model in this paper consists of a kneed massless leg and a constrained vertical trunk with mass. According to Fig. 3 the robot has 2 degrees of freedom (DOF) in stance phase with variables θ_1 and θ_2.

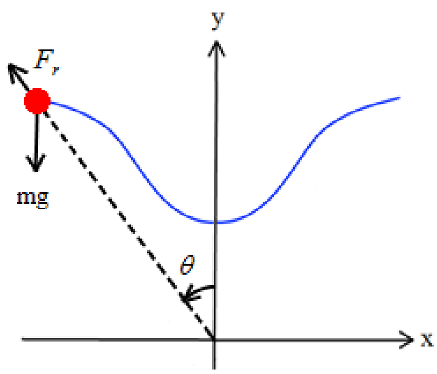

Fig. 2. The free diagram of the system

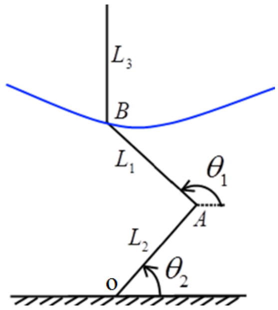

Fig. 3. Robot parameters and stance phase generalized coordinates

Using hip velocity $\vec{V}_B$ and acceleration $\vec{a}_B$ calculated from desired trajectory and relative velocity and acceleration equations, the angular velocity and acceleration of the links can be calculated as

$$\begin{cases} \vec{V}_A = \vec{V}_B + \vec{V}_{A/B} \\ \vec{V}_A = \vec{\omega}_{OA} \times \vec{r}_A \\ \vec{V}_{A/B} = \vec{\omega}_{AB} \times \vec{r}_{A/B} \end{cases}, \tag{9}$$

$$\begin{cases} \vec{a}_A = \vec{a}_B + (\vec{a}_{A/B})_n + (\vec{a}_{A/B})_t \\ \vec{a}_A = \vec{\alpha}_{OA} \times \vec{r}_A + \vec{\omega}_{OA} \times (\vec{\omega}_{OA} \times \vec{r}_A) \\ (\vec{a}_{A/B})_n = \vec{\omega}_{AB} \times (\vec{\omega}_{AB} \times \vec{r}_{A/B}) \\ (\vec{a}_{A/B})_t = \vec{\alpha}_{AB} \times \vec{r}_{A/B} \end{cases}. \tag{10}$$

The Lagrange equations corresponding to θ_1 and θ_2 are written as

$$\frac{d}{dt}\left(\frac{dT}{d\dot{\theta}_1}\right) - \frac{dT}{d\theta_1} + \frac{dV}{d\theta_1} = Q_1, \tag{11}$$

$$\frac{d}{dt}\left(\frac{dT}{d\dot{\theta}_2}\right) - \frac{dT}{d\theta_2} + \frac{dV}{d\theta_2} = Q_2, \tag{12}$$

in which kinetic energy consists of trunk translational energy

$$T = \frac{1}{2} m(\dot{\theta}_2^2 L_2^2 + \dot{\theta}_1^2 L_1^2 + 2\dot{\theta}_1\dot{\theta}_2 L_1 L_2 \cos(\theta_1 - \theta_2)), \tag{13}$$

and the potential energy consists of gravitational energy

$$V = mg(L_1 \sin(\theta_1) + L_2 \sin(\theta_2) + \frac{L_3}{2}). \tag{14}$$

Similar to organisms and to generate torque, the muscles of our robot are attached to the leg segments using two little arms L_4 and L_5 which are fixed to L_3 and L_1 respectively, as shown in Fig. 4. Therefore θ_3 and θ_4 are fixed angles. To find the generalized forces Q_1 and Q_2, we use virtual work of muscle forces F_1 and F_2 as:

$$\begin{aligned} \delta W &= F_1\left(\frac{\partial AD}{\partial q_1}\delta q_1 + \frac{\partial AD}{\partial q_2}\delta q_2\right) \\ &+ F_2\left(\frac{\partial OC}{\partial q_1}\delta q_1 + \frac{\partial OC}{\partial q_2}\delta q_2\right). \\ &= \sum Q_i \delta q_i \end{aligned} \tag{15}$$

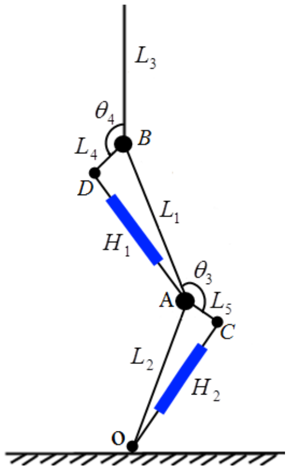

Fig. 4. Muscles configurations on the leg

The parameters values of the robot model are shown in table 1. By solving Lagrange equations for the velocities and accelerations of the desired trajectory, the needed muscle forces are found as a function of time.

TABLE I. THE ROBOT NOMENCLATURE

Parameter	Value (in SI units)
m	58 (kg)
L_1	0.5 (m)
L_2	0.5 (m)
L_3	1 (m)
L_4	0.1 (m)
L_5	0.1 (m)
θ_3	0.75π (rad)
θ_4	0.75π (rad)

IV. CONTROL INPUT OF THE MUSCLES

In the previous section we calculated the needed overall muscle force. In this section, considering muscle elements, we aim to calculate the needed force for the main active part of the muscle. It is noticeable that to avoid unnecessary complications in simulation, we assume that the main active part of the muscle can generate both tensile and compressive forces. In muscles of organisms this part is contractive and just exerts tensile force, so each joint has biarticular muscles. With the mentioned assumption we can actuate each joint by a single muscle that is feasible in robotics. Components of the muscle are shown in Fig. 5. The dynamic equations of the muscle are written as:

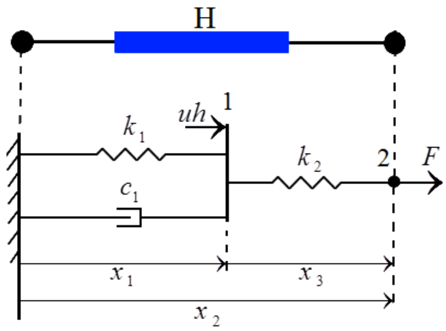

Fig. 5. Hill-type muscle model used as actuation system of our robot

$$-F_1 = k_2(x_3 - x_{3,0}) \rightarrow x_1 = x_2 - x_{3,0} + \frac{F}{k_2}, \qquad (16)$$

$$uh = k_1(x_2 - x_{1,0}) + c_1\dot{x}_1 + k_2(x_2 - x_1 - x_{3,0}), \qquad (17)$$

which its parameters are shown in Fig. 5, and subscript 0 indicates the free lengths of springs. The springs are assumed to be in their free length at touch-down. The used muscle parameters in simulations are shown in table 2. We have defined these parameters using trial and error to generate feasible motion for the robot.

TABLE II. THE MUSCLE MODEL PARAMETERS

Parameter		**Value (in SI units)**
Muscle 1	k_1	20
	k_2	30
	c_1	0.001
Muscle 2	k_1	30000
	k_2	40000
	c_1	0.001

V. SIMULATION RESULTS AND DISCUSSION

Starting from an appropriate initial condition and using control law (17), the robot follows the desired trajectory and generates a periodic running gait as shown in Fig. 6. In this figure, the hip trajectory is shown by solid line in stance phase and by dashed line in flight phase. This figure verifies the validity of our control law, because it shows that the dynamic response of the system with the designed controller is coincident with the desired trajectory.

Fig. 8 depicts the overall force (solid line) and active part force (dashed line) of muscle 1 in stance phase which shows an almost zero force for this muscle. This is because the trunk angle is constrained to be vertical and shows that for hopping motion of this configuration the muscle 1 in hip joint can be removed. The overall force (solid line) and active part force (dashed line) of muscle 2 in stance phase are depicted in Fig. 8. According to this figure, the active part of the muscle needs to generate smaller forces than the coverall muscle. This is a desirable matter and shows usefulness of hill-type muscle actuation system. Also the muscle force starts from zero and ends with zero in stance phase which is again desirable in biped robots.

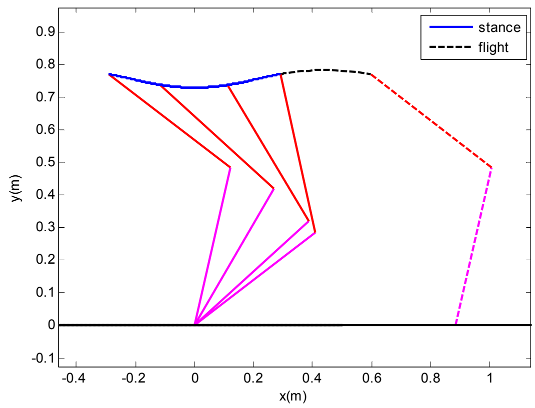

Fig. 6. One step of running using the proposed control law

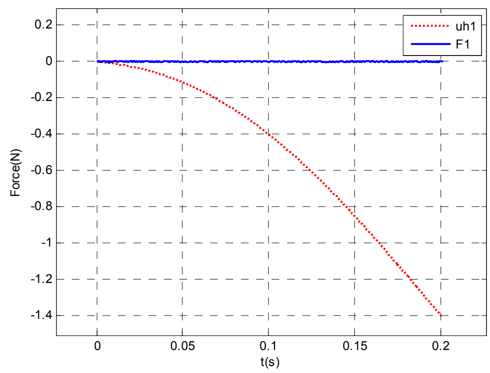

Fig. 7. The overall force (solid line) and active part force (dashed line) of muscle 1 in stance phase

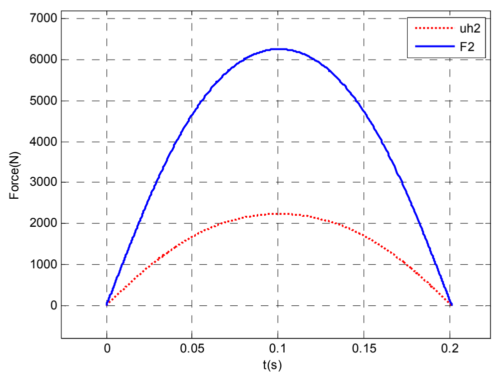

Fig. 8. The overall force (solid line) and active part force (dashed line) of muscle 2 in stance phase

To calculate ground reaction force components we use acceleration components of the robot CoM:

$$\sum F_x = m_G \bar{a}_x , \tag{18}$$

$$\sum F_y = m_G \bar{a}_y . \tag{19}$$

The horizontal (solid line) and vertical (dashed line) GRF profiles in stance phase are shown in Fig. 9. These profiles are qualitatively similar to SLIP running force profiles.

Cost of Transport (COT) is defined as the consumed energy per weight of the robot per traveled distance:

$$COT = \frac{\int_0^t |F.\dot{x}| dt}{m_G gL} , \tag{20}$$

in which t is stance time and L is range of one complete step. COTs of hopping with and without Hill-type muscles are shown in table 3. According to this table COT using muscles is greater than COT without muscle. This is undesirable and we aim to reach better COTs using muscles. COT is proportional to the product of the applied force by its velocity. Although the active part of the muscle had smaller values of forces than the overall muscle (Fig. 8), it has greater values of velocity than the overall muscle (Fig. 10) and their product causes bigger

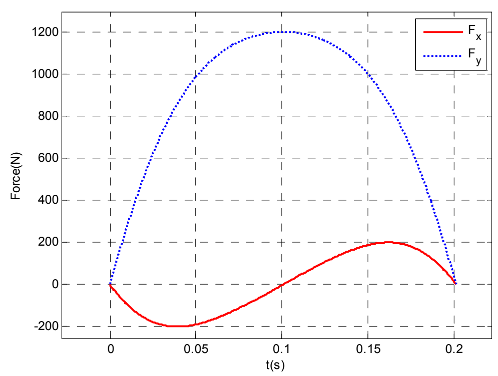

Fig. 9. Ground Reaction Force Components in stance phase

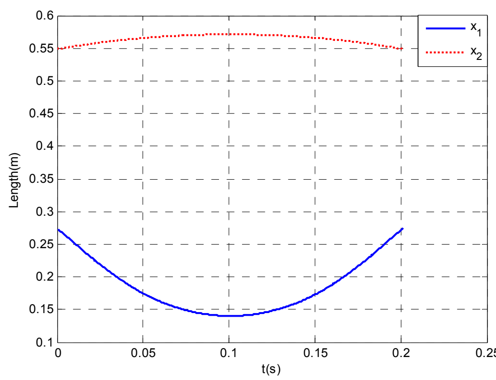

Fig. 10. The overall muscle length displacement (dashed line) and active part displacement (solid line) of muscle 2 in stance phase

TABLE III. HOPPING COT VALUES

Parameter	Value (in SI units)
COT of the overall muscle	0.3057
COT of the active part of the muscle	0.6064

COT for the active part. This is because the muscles parameters shown in table 2 are not optimized for minimum energy consumption and they were chosen just to generate a feasible hopping motion. By optimizing these parameters we would be able to reach more efficient biped hopping and running using muscles.

VI. CONCLUSIONS

A novel control strategy was proposed in this work to generate an arbitrary trajectory for underactuated biped robots running and hopping in stance phase. The desired trajectory should be consistent with stance phase initial conditions. A 4th order trajectory was chosen due to its similarity to SLIP trajectory. This strategy was applied to a kneed three link hopper. At first the necessary velocities and accelerations were found and then using dynamic equations its necessary actuators forces were found to undergo the desired trajectory. Then Hill-type muscles were considered as actuators of the robot and their necessary active parts forces were found. Simulation results showed that the proposed control law gets the robot to undergo the desired trajectory very well. The corresponding force of the active part of the muscle was smaller than the overall muscle force which shows a positive effect of using Hill-type muscle. But the COT of the active part was greater than the COT of the overall muscle which is not desirable.

As future works we are going to apply this method to more general biped running with unlocked torso. Also optimizing muscles parameters to reach lower active part forces and lower COTs seems to be very promising. This would guarantee the optimal use of muscles in robotic actuating systems.

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