Three-segmented hopping leg for the analysis of human running locomotion

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Summary. Legged locomotion is an interesting subject because it may contribute to our understanding of the biomechanics of human walking and running, as well as to the developement of legged mobile robots. Here, a planar model for a hopping three-segmented single leg with an associated control concept is introduced. The overall model is capable of passive hopping motion by means of torsional springs in the joints, and it can be used for the analysis of some aspects of running motion, such as ground-foot impact, energy efficiency or balancing. The control actions are realized by actuator torques in the ankle and knee joints and in the hip, which is coupled to a reaction wheel. We show that stable periodic motion exists, which imitates human locomotion.

Introduction

Although, there are many experimental and theoretical results in biomechanics, bipedal locomotion of humans still attracts the interest of many researchers. Yet unresolved issues are the effects of running kinematics and foot placement techniques on the ground-foot collision intensity. Depending on the form of running, high impacts and therefore high kinetic energy absorption may occur, which should actually be avoided in order to minimize the risk of injuries and also to increase energy efficiency when running. A mechanical model containing the foot and the shank was introduced in [1] for the investigation of the effect of the foot strike pattern. A further developed but still two-segmented and vertically dropped model was introduced in [2]. Both papers concluded that forefoot-strike induces lower impact intensity than heel-strike. The results in the paper [3] showed that not only the strike pattern matters, but that also the angle of the shank is important for the properties of the ground-foot impact. The model in [3] involves the thigh and the total mass of the human body and the horizontal velocity component of the body is considered as a free parameter; however, the segments perform a rigid-body-like motion in the pre-impact phase with no relative motion of the body segments, which is not realistic.

A realistic pre-impact velocity condition could be obtained from experiments or from a dynamic model that performs stable periodic running motion. This paper introduces such model in the form of a mechanical model with torque control, which is designed to aid the further biomechanical analysis of the human running performance. The advantage over an experiment is that the control parameters can be tuned to optimise different cost functions, such as running speed, energy efficiency and impact intensity.

We report here that our segmented leg model admits stable periodic, running-like motion. Many aspects of periodic motion of legged systems are detailed in [4], where several walking, running and hopping models are reviewed. Stable locomotion of a three segmented leg model is also presented in [5], but for a case where the masses of the segments are neglected.

Mechanical model and control concept

Our single-legged, planar mechanical model depicted in Fig. 1 is an extension of the model in [3]. The new aspect is that a controller is introduced to the model from [3], which was not actuated at all. The proposed control concept also involves a reaction wheel which is attached in the hip. The overall model consists of the equation of motion and the control.

Mechanical model

The three segments 1, 2 and 3 correspond to the foot, shank and thigh, respectively. Points A, B, C and D correspond to the tiptoe, the ankle, the knee and the hip, respectively. The reaction wheel plays the role of the upper body: the torque M_D that rotates the thigh has the reaction torque exerted on the wheel. The reaction wheel has mass m_r and moment of inertia J_r. The homogeneous, prismatic bars have masses m_i and lengths l_i, $i = 1 \dots 3$. The centre of gravity is located at point G. The segments are interconnected by torsional springs with stiffnesses k_B and k_C. Actuating torques M_B and M_C assist the motion according to the control, which will be introduced below.

The model has a total of 6 DoFs in the flight phase: $\mathbf{q}^\mathrm{f} = [x_\mathrm{A}, z_\mathrm{A}, \theta_1, \theta_{12}, \theta_{23}, \theta_\mathrm{r}]$ (where x_A and z_A are the Cartesian coordinates of the tiptoe); and it has 4 DoFs in grounded phase: $\mathbf{q}^\mathrm{g} = [\theta_1, \theta_{12}, \theta_{23}, \theta_\mathrm{r}]$. We assume that the ground-foot impact is completely inelastic, there is no rebound and the friction coefficient is high enough to prevent sliding of the foot. These assumptions allows us to constrain the tiptoe to the ground until the contact force is positive.

Impact-free touchdown

In general the tiptoe touches the ground with non-zero velocity. This causes an impact and a certain kinetic energy loss, called constrained motion space kinetic energy (CMSKE) [2, 3]. As a consequence, periodic hopping motion is not possible without some kind of energy input, which is provided by the muscles in humans and by motors in legged robots. An alternative possibility to avoid energy loss is to achieve zero-velocity collision, which means that the tiptoe velocity becomes zero at the instance of time when the foot touches down. However, impact-free motion does not guarantee periodicity, because the model can fall over, and using a controller is a more feasible approach.

Control during flight-phase

The vibrations of the leg segments are suppressed by M_B and M_C in the flight phase. A proportional-derivative controller tries to keep the tiptoe (A) below the centre of mass (G) of the model in order to avoid falling over. A further goal, which is achieved by M_D, is to reach the prescribed velocity v_0. The control torques at the ankle, knee and hip are calculated as:

$$M_\mathrm{B}^\mathrm{f} = D_\mathrm{B}\dot{\theta}_{12}\,, \qquad M_\mathrm{C}^\mathrm{f} = D_\mathrm{C}\dot{\theta}_{23}\,, \qquad M_\mathrm{D}^\mathrm{f} = P(x_\mathrm{G} - x_\mathrm{A}) + D(\dot{x}_\mathrm{G} - \dot{x}_\mathrm{A}) + K(\dot{x}_\mathrm{G} - v_0)\,. \tag{1}$$

Control during grounded-phase

The energy is supplied by the control torques in the ankle and the knee. The power of these torques is positive only if the joints are in extension, so that $\dot{\theta}_{12}$ is positive and $\dot{\theta}_{23}$ is negative. The desired energy level is E_0, and E is the total mechanical energy of the system. The angular velocity $\dot{\theta}_\mathrm{r}$ may grow continuously, which is prevented by the control torque M_D in the ground-phase. The control gains both for flight-phase and grounded-phase (D_B, D_C, P, D, K, P_E and D_r) are tuned by a trial-and error method at this first stage of the research.

$$M_\mathrm{B}^\mathrm{g} = P_E(E - E_0)\,\mathrm{sgn}(\dot{\theta}_{12})\,, \qquad M_\mathrm{C}^\mathrm{g} = P_E(E - E_0)\,\mathrm{sgn}(-\dot{\theta}_{23})\,, \qquad M_\mathrm{D}^\mathrm{g} = D_\mathrm{r}\dot{\theta}_\mathrm{r}\,. \tag{2}$$

Stable periodic motion

Fig. 2 shows the result of a simulation, where stable periodic motion is reached. Here the upper panel illustrates the hopping motion and the lower panel shows the associated horizontal velocity of the mass, which becomes effectively constant after a transient.

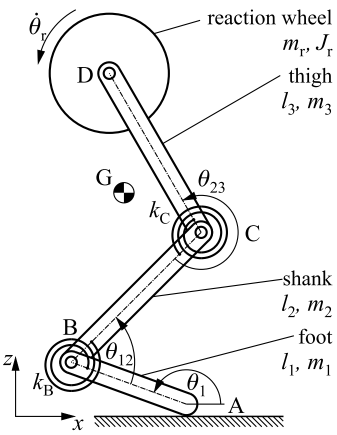

Figure 1: Mechanical model of the hopping three-segmented leg

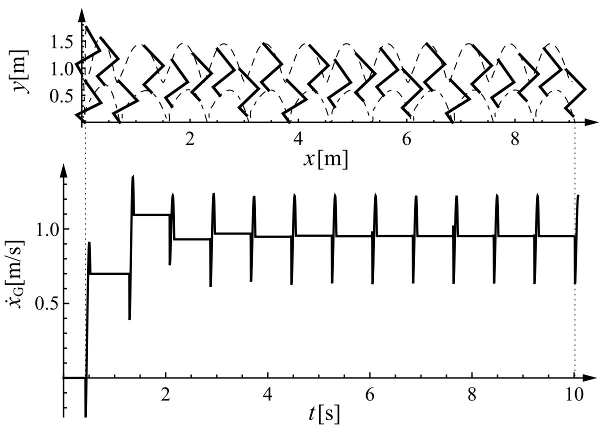

Figure 2: Stable hopping motion (upper panel) and associated horizontal velocity of the centre of mass (lower panel)

Conclusions

Stable periodic motion, i.e. running was achieved with the three-segmented leg model by means of control torques in the ankle and the knee joint and with a reaction wheel placed at the hip. In order to better understand the properties of this model, a further step is to investigate how the stability of periodic motion depends on the control gains. The model will be developed further in order to achieve more human-like motion; in particular, two legs and a more accurate model for the upper body can be considered. Before conclusion can be made from mathematically generated trajectories of such a model, its behaviour needs to be compared with that of humans in laboratory experiments.

After refinement of mechanical model and controller, the calculation of ground-foot impact intensity and other performance measures of human running may become feasible. A possible direction of our further research is to discover and compare the energy consumption needed for balancing when standing still and while running. Humans standing still stabilize themselves in an unstable equilibrium and a certain oscillation can be observed; naturally some energy is needed for this stabilization. Running, on the other hand, is a periodic motion for which the energy consumption can be divided into two parts: the propulsion needs a certain amount of energy and some effort is needed for the prevention of falling over. This stabilizing energy may actually be less than that for the case of standing still.

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