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Arm swing effects on walking bipedal gaits composed of impact, single and double support phases

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HIGHLIGHTS

- A walking gait for a planar biped is defined with single and double support phases.
- Three modes are compared: bound arm mode, active arm swing and passive arm swing.
- The effects of springs in shoulders on the oscillation of arms are explored.
- Passive arm movement due to the dynamics of the locomotor system are explored.
- The lowest values of sthenic criterion are obtained with actuated shoulders.

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ABSTRACT

In human walking, it is often assumed that the arms have a passive movement which reduces the energy consumption of walking. The issue addressed in this work is the influence of the arms on the walking of a humanoid robot. The study has two objectives: to verify the effect of arms on a sthenic criterion during walking, and to determine whether the optimal movement of the arms is passive or not.

Firstly, we defined optimal cyclic gaits for a biped robot moving in 2D. These gaits are composed of single support phases with a supporting flat foot, double support phases with rotation of the feet and an impact. Different evolutions of arms are studied: bound arms, arms having an active motion and passive arms.

The comparison of our results for different walking speeds shows the importance of an active movement of the arms. The part of the sthenic criterion supplied in the joints of arms allows reducing the global sthenic criterion especially for high walking speeds.

A passive movement of the arms will have large amplitude when the natural frequency of the arms coincides with the frequency of the walking gait. Adding springs at the shoulders allows to adjust the natural frequency of the arms to that of walking gait. However, the sthenic criterion with the active arms with or without spring remains less than with the passive arms.

1. Introduction

Several approaches of upper body motion generation are used to improve the walking of the robot [1–3]. Xing and Su generated the movements of the arms during walking by compensating the yaw moment of the robot during the motion [1]. This upper body motion can stabilize the foot spin for the walking robot. Approaches of generation of the motion of upper limbs from a given reference angular momentum around the center of mass (CoM) have been proposed by Kajita et al. [2]. Shafii et al. [3] generated optimal trajectories of a biped robot by using series of Fourier. They found that their model of control is more efficient and produces faster and more stable walk if they consider the influence of the arms of the robot. The study of S. Collins et al. [4] allowed to reveal the dynamics of the arms during the walking of a 3D passive biped robot without torso in simulation, but also their utility in the movement. From numerical tests, periodic movements were found through a gradient method. Several modes of arm swing were developed.

- Normal: where each arm oscillates in phase with the leg on the opposite side.
- Bound: the arms are mechanically constrained against rotation. They always remain aligned with the torso.

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- Anti-normal: each arm oscillates in phase with the leg on the same side.
- Parallel: during one step both arms swing together. The period of the arm swinging is the stride period.

Thus it has been shown with the numerical tests of S. Collins et al. that passive gaits with arm phasing anti-normal induced a much greater reaction moment from the ground. However these interesting results are obtained with a 3D biped robot the geometrical structure is little far from that of an anthropomorphic bipedal robot with knees and a torso.

Few studies and results are available to describe the effects of arms on bipedal walking gaits. The effect of the arms on the energy consumption during a ballistic walk was explored by Aoustin and Formalskii [5], who considered cyclic ballistic walking gaits with instantaneous double support phases and impulsive torques in 3D. Torques needed for walking are only applied at the moment of impact. The numerical results show that for a given period of the walking gait step and a length of the step, there is an optimum amplitude of arm swing for which a cost functional is minimum. They also proved that, for any amplitude of arm motion, the energy consumed is less for arms in normal mode than in anti-normal mode. At the instant of the instantaneous double support phase, they numerically proved that the jump of the angular momentum with respect to the vertical axe crossing the stance foot is less for the normal gait than for the anti-normal gait.

In this paper a sthenic criterion is considered. For a robot this criterion represents the energy dissipated by Joule effects in the electrical motors [6]. This criterion leads to the minimization of the maximal torque required and thus allows to choose less powerful actuators. We studied in a previous work, the effect of arm swing on the sthenic criterion during walking of the bipedal planar robot with a flat foot [7] and the effect of passive motion of the arms [8]. However, according to our knowledge, it has not been yet shown whether the effect of active or passive movements of the arms can reduce the energy consumption for bipedal walking gaits including double support phases. In this work, we will study the effects of the arms on the sthenic criterion of a planar biped during a walking gait, which is composed of single support phases with flat contact of the stance foot and double support phases with rotation of both feet.

Studies of human walking can provide useful information to improve the humanoid robots. The swinging of the arms is not a purely incidental accompaniment of a forward movement but is an integral part of the dynamics of progression, as shown in [9]. It has been shown that the oscillation of the arm reduces the energy costs during human walking [10,11,4]. It is suggested that the high metabolic costs of walking without swinging the arms are either due to the greater momentum around vertical axis that needs to be counteracted [4,12], either because the oscillations of the arms limit the vertical oscillations of the center of mass [13,11]. Furthermore, several authors argued that the arm swing during human locomotion enhances gait stability [13,10,14]. Collins et al. [4] have shown that to swing the arms in anti-normal mode requires the greatest metabolic energy.

The nature of movement of arms is not yet fully understood. Besides, biomechanics do not agree on the passivity of this movement [4,15–17]. For example, Pontzer and al. [15], from the analysis of human walking and running, hypothesize of a passive oscillation of arms. F. Ballesteros et al. [16], using electrodes to measure muscular activity, show that the motion of the arms is accompanied by the activity of the deltoid muscle, particularly during retraction. Jackson et al. [17] make the assumption that the movement of arms is not completely passive. Several experimental measurements on humans show that normal arm swinging requires a minimal shoulder torque, while to hold the arms requires more torque in the shoulder [4]. In this work, optimal trajectories are defined for the biped, when the arms are bound to the torso, with a passive motion of arms, and with actuated arms. The sthenic criteria respectively obtained while walking for these three modes are compared.

Cyclic walking gaits are defined with double support phases. Our study has two main goals: the first is to check the effect of the arms on the sthenic criterion during walking. The second is to check the nature of the activation of arms for the optimal gaits and whether the optimal walking requires active or passive movement of the arms.

In order to reach our objective three modes of arm motion are studied:

1. *Bound arm mode* where the arms are attached to the trunk. Since they are attached the torque useful to keep the desired constant relative position with the torso is not taken into account in the criterion. It is assumed that an external mechanical system is used to maintain the arm held as in the experiments done by S. Collins et al. [4]. A simplified model consists to consider only a torso such that its mass and inertia include mass and inertia of the arms. Thus they are an additional charge on the torso.
2. *Active arm swing* where the arms are actuated and swing freely in amplitude about the torso.
3. *Passive arm swing* where the arms are unactuated and swing freely in amplitude about the torso.

The paper is structured as follows:

The studied robot is presented in Section 2. The study takes place in the sagittal plane. We use a kinematic structure of biped robot with arms. Starting from this structure, we define a dynamic model of biped for different phases of the walking gait.

In Section 3, trajectories of cyclic motion for fully actuated biped are defined. We also define the method to generate passive motion of the arms. Then, the optimization strategy is explained. The results of trajectory optimization for one step in the different cases of the arm motions are shown and arm swing effects are discussed in Section 4. Section 5 presents our conclusion and perspectives.

2. The biped modeling in 2D

This section is devoted to the development of the model of the biped robot, its generalized coordinates, the different geometrical structures with active or bound arms, and its model. This model will be used for the generation of optimal movements presented in Section 3.

2.1. Presentation of the biped

As most of the movements are in the sagittal plan during walking, our study is based on a 2D biped, see Figs. 1 and 2. Its physical parameters are derived from the humanoid robot HYDROÏD (HYDraulic andROÏD). It is a 3D biped, which was built through the cooperation of several French laboratories and an industrial partner, supported by the French national agency of research, *ANR*, see [18]. It is equipped with hydraulic actuators. The size of HYDROÏD is 1.40 m, its mass is 45 kg. It has 30 degrees of freedom. Its locomotor system has 16 degrees of freedom (three for each hip, one for each knee, three for each ankle and one for the toe of each foot). It is designed to have geometrical and dynamical parameters close to those of the model of Hanavan established to characterize the human body. To determine the behavior of the biped during different phases, we are going to define the dynamic model of the biped robot for each phase of the studied walking gait. From HYDROÏD we keep only the joints that produce movements in the sagittal plane. The mechanical system is a nine-link bipedal robot composed of two identical legs, two identical one-link arms and a torso. Each leg consists of a femur, a tibia, and a rigid foot. Each arm is composed of one link only. The trunk and the head form a single body too. Table 1 gathers the physical parameters of the biped. From [19], we can observe that the geometrical parameters are close to the dimensions of an occidental subject, who is 15 years old.

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