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Human like trajectory generation for a biped robot with a four-bar linkage for the knees

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HIGHLIGHTS

- Simulation the locomotion of a planar biped robot equipped with four-bar knees.
- Walking trajectories with phases of double support, single support and impacts.
- In single support the biped can be fully actuated and under actuated respectively.
- A sthenic criterion to compare a four-bar knee with revolute knees.
- Numerical results show that the four-bar linkage could be a good technological way.

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ABSTRACT

The design of a knee joint is a key issue in robotics to improve the locomotion and the performances of the bipedal robots. We study a design for the knee joints of a planar bipedal robot, based on a four-bar linkage. We design walking reference trajectories composed of double support phases, single support phases and impacts. The single support phases are divided in two sub-phases. During the first sub-phase the stance foot has a flat contact with the ground. During the second sub-phase the stance foot rotates on its toes. In the double support phase, both stance feet rotate. This phase is ended by an impact on the ground of the toe of the forward foot, the rear foot taking off. The single support phase is ended by an impact of the heel of the swing foot, the other foot keeping contact with the ground through its toes. A parametric optimization problem is presented for the determination of the parameters corresponding to the optimal cyclic walking gaits. In the optimization process this novel bipedal robot is successively, overactuated (double support with rotation of both stance feet), fully actuated (single support sub-phase with a flat foot contact), and underactuated (single support sub-phase with a rotation of the stance foot). A comparison of the performances with respect to a sthenic criterion is proposed between a biped equipped with four-bar knees and another with revolute joints. Our numerical results show that the performances with a four-bar linkage are bad for the smaller velocities and better for the higher velocities. These numerical results allows us to think that the four-bar linkage could be a good technological way to increase the speed of the future bipedal robots.

1. Introduction

Since several years researchers in robotics have done many efforts to develop walking robots, especially bipedal robots. Experimental bipedal robots are composed of links, which can be connected through actuated revolute joints, see for example Rabbit [1] and Mabel [2], or through actuated prismatic joints, such as the biped with telescopic legs developed by Grishin et al. [3]. T. Yang et al. [4] use a compliant parallel knee to improve the walking motion. Several authors also deal with the walking and running gaits using the toe rotation [5–7]. However from biomechanics studies a lot the understanding of the human lower limb is improved, and especially the knee joint [8] and the ankle joint [9]. Indeed, these two joints have a complex architecture formed by non symmetric surfaces. Their motion is more complex than a revolute joint motion. The motions of the femur with respect to the tibia are limited due to the patella and many ligaments. In addition to the flexion in the sagittal plane, there is an internal rotation with a displacement of the Instantaneous Center of Rotation (*ICR*) of the knee joint and a posterior translation of the femur on the tibia. These motions are

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guided by the cruciate ligaments and the articular contact [10,8]. These motions cannot be represented by one or two revolute joints. Different studies have confirmed these results by an observation of the motions of the human knee in the 3D space [11]. Consequently, for bipedal robots complex knee joints appear with a displacement of their Instantaneous Center of Rotation (*ICR*), see G. Gini et al. [12]. They use knee joints based on the human knee surfaces. F. Wang et al. [13] have developed a bipedal robot with two different joints, a revolute joint and a four-bar linkage. However, the singularities of the common four-bar linkage, i.e., non crossed four-bar linkage, usually limit the flexion of the knee. On the contrary, the flexion of the knee joint based on a crossed four-bar linkage is usually less limited with the kinematic singularities. One possible advantage of a four-bar linkage for the knee joints would be to reduce the consumption of energy. In [14] it is shown from optimal walking gaits that a knee based on a four-bar linkage is better than a knee designed with a revolute joint in terms of energy consumption. However these walking gaits are very simple and not realistic because each step is composed of a single support phase ending with an instantaneous double support phase to define the impact the swing foot on the ground.

This paper aims to study the performance of a planar bipedal robot equipped with knees based on crossed four-bar linkages for a more realistic walking gait composed of double support phases, single support sub-phases with a flat foot contact, and single support sub-phases with a rotation of the foot around its toe. The works of [15–18], show that the presence of toe joints allows to perform longer strides, climb higher steps, reduce the energy consumption and walk at a higher speed. This biped robot is fully actuated in single support sub-phase with a flat foot contact. It is underactuated in single support sub-phase with a rotation of the stance foot around its toes. And it is overactuated in double support phase with a feet rotation on the front heel and the rear toe. We developed a parametric optimization method, which takes into account these previous characteristics, to define a set of optimal cyclic reference trajectories. We studied a sthenic criterion, which relates to the driving torques of the biped robot, for different speeds. The main contribution of this paper is to obtain a set of dynamical stable walking gaits with double support phases, impacts, and single support phases for this bipedal biped. A comparison with a bipedal robot, which is equipped with revolute knee joints show that the four-bar linkage could preserve the torques of the actuators for the higher speeds. The paper is organized as follows. Section 2 presents the novel planar bipedal robot whose knees are based on four-bar linkages. Section 3 is devoted to the biped modeling with specific difficulties due to the four-bar linkage of each knee. Section 4 deals with the trajectory planning. Section 5 presents numerical results on the walking reference trajectories. Finally, Section 6 offers our conclusion and several perspectives.

2. Presentation of the bipedal robot with knees composed of a four-bar linkage

Let us introduce the bipedal robot, which is depicted in Fig. 1. Table 1 gathers the physical data of the biped, which are taken from *Hydroid*, an experimental humanoid robot [18].

The dimensions of the four-bar linkage are chosen with respect to the human characteristics measured by J. Bradley et al. through radiography in [19].

Figs. 1, 2(a) and (b) depict the bipedal robot under study and its four-bar knee linkage. Fig. 2(a) represents the four-bar knee linkage. The angular variable α_1 is the actuated variable of the four-bar linkage.

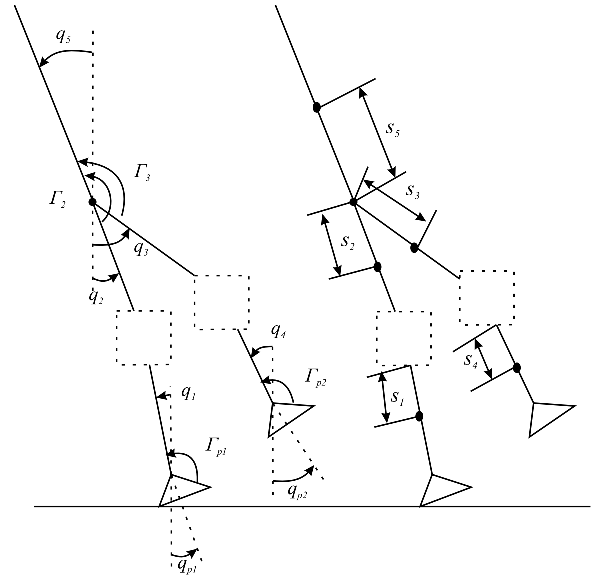

Fig. 1. Schematic of the planar bipedal robot. Absolute angular variables and torques.

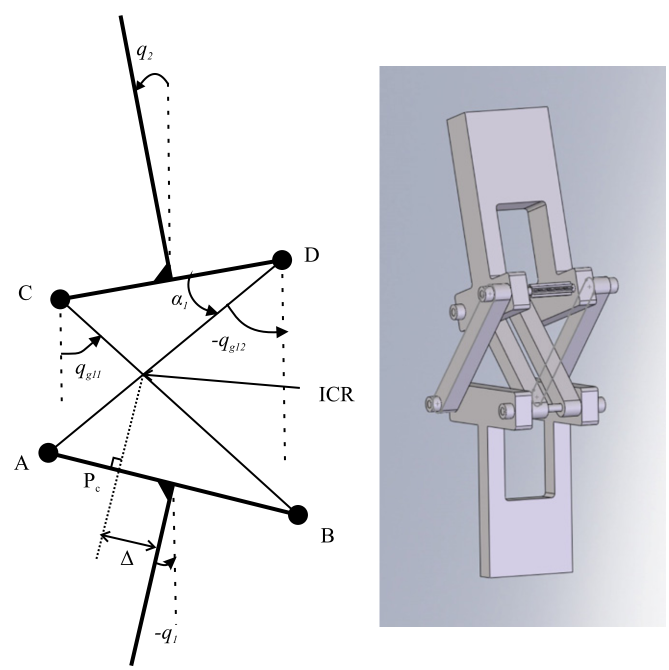

Fig. 2. Details of the four-bar joint and position of the Instantaneous Center of Rotation (*ICR*).

3. The biped modeling

3.1. General dynamic model in double support phase

The bipedal robot is equipped with two closed-loop knees. Let us introduce the constraint equations solving the dynamic model [20]. Equations for the knee joints 1 and 2 are similar. For the sake of clarity we consider knee joint 1 only. The equations of the closed-loop geometric constraints are defined as follows:

$$l_a \cos q_1 - l_b \sin q_{g_{11}} + l_c \cos q_2 + l_d \sin q_{g_{12}} = 0$$
$$l_a \sin q_1 + l_b \cos q_{g_{11}} + l_c \sin q_2 - l_d \cos q_{g_{12}} = 0. \quad (1)$$