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## Compliance for a cross four-bar knee joint.

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We propose a mechanical design for the knee joints of a planar bipedal robot. Each knee joint is composed of cross four-bar with springs. The dynamic model of a planar bipedal robot with cross four-bar knees and a parametric optimization problem are presented to produce a set of optimal reference trajectories. We use these trajectories to compare the performance of the bipedal robot with respect to different physical characteristics of the knee joints.

*Keywords:* Humanoids; Knee joints with springs; Cross four-bar mechanism; Parametric optimization

### 1. Introduction

The biomechanics researchers have done important progress in the comprehension of the human lower limb and especially on the knee joint<sup>1</sup> and the ankle joint.<sup>2</sup> Indeed, these two joints have a complex structure formed by non symmetric surfaces. They can produce more complex movements than a simple revolute joint. In addition to the flexion in the sagittal plane, there are an internal rotation with displacement of the Instantaneous Center of rotation(ICR) of the knee joint and a posterior translation of the femur on the tibia. These motions cannot be represented by one or two revolute joints. Different studies have confirmed these results by an observation of the movements of the human knee in the 3D space.<sup>3</sup>

From these studies, a new kind of prosthetic knee is appeared, called polycentric knee. A classical polycentric knee is the four-bar linkage,<sup>4</sup> which used in most prosthetic knees. This structure forms a closed mechanism, which allows a combined rotation and translation of the knee joint in the sagittal plain without using of artificial ligaments to keep the rigidity of the mechanism. The dimensions of the four-bar structure can be chosen by measurement, on a real subject, of the length of the anterior and posterior

ligaments, and the position of the cross ligament attachments on the tibia and the femur, projected in the sagittal plain in the maximum extension position.<sup>5</sup> This choice of the dimensions produces similar motions in the sagittal plain of the knee than those obtained with the human knee.<sup>6</sup>

Our objective is to improve the bipedal robot performance by a new conception of the knee joint. Several papers are devoted to bipedal robots equipped with complex knees, like G. Gini et al.<sup>7</sup> which used knee joints based on the human knee surfaces. F. Wang et al.<sup>8</sup> developed a bipedal robot with two different joints, a rotoide joint and a four-bar joint. However, a four-bar structure presents a configuration of singularity which limits the flexion of the knee contrary to a cross four-bar solution for which the singular position is out of the range of use of the knee joint. In,<sup>9</sup> we have proved a cross four-bar joint is a better solution for the knee than a rotoide joint in term of energy consumption. In this paper, we improved the study by adding a compliance in the knee with different solutions of springs.

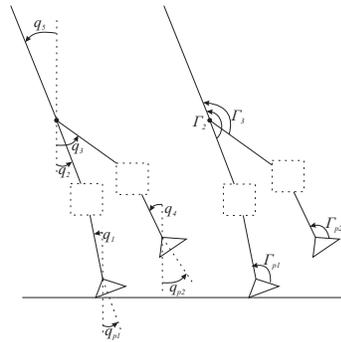


Fig. 1. Diagram of a planar bipedal robot. Absolute angular variables and torques.

## 2. Effect of the springs on the knee joints on the energy consumption.

In this paper, we compare the effect of a cross four-bar knees with spring units on the energy consumption of the biped during a cyclic walking gait. We use different springs : a torsion spring in parallel of the actuator of the knee or two extension springs on the two side of the cross four-bar knee. Indeed, several papers pay interest to the effect of springs equipping the bipedal robot joints.<sup>10</sup> We produce a set of optimal trajectories for the bipedal robot where the stiffness coefficient is an optimization parameter.

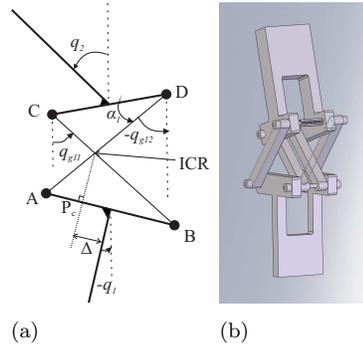


Fig. 2. Details of the cross four-bar joint and position of the Instantaneous Center of Rotation (ICR)

The stiffness coefficient of the springs depends on the walking velocity and can be different for the support leg and for the swing leg. This choice implies the spring units used, have a variable stiffness. We can note, the work of S. Wolf,<sup>11</sup> which designs a rotoide joint with a control of the stiffness coefficient. Different types of springs can be used for the knee joint. We can see on Fig.3, the energy consumption according to the walking velocity of the bipedal robot equipped of cross four-bar knees without springs and with the two solutions of springs. We observed the biped equipped of cross four-bar knees with extension springs is more efficient than the biped equipped of simple cross four-bar knees for the walking velocity lower than  $2.5 \text{ Km}/H$ . Moreover, the biped equipped of cross four-bar knee with torsion spring have a similar energy consumption than the biped with cross four-bar knees with extension springs for the walking rates lower than  $2 \text{ Km}/H$ . For the higher walking velocities the cross four-bar knees with torsion springs is the better solution of knee.

### 3. Conclusions

We have proposed a mechanical structure for the knee of a planar bipedal robot called cross four-bar knee and different solutions of actuation with spring units. We have produced with a parametric optimization method a set of optimal reference walking trajectories for a bipedal robot for different solutions of knee structures. We have compared the energy consumption of the bipedal robot for the different structure of the knees. This study proved that the cross four-bar knee with spring units can reduce the energy consumption of the biped. The perspective of this study is to extend this

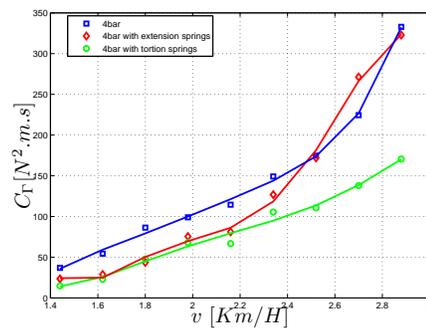


Fig. 3. Evolution of the energy consumption according to the walking rate for the cross four bar knee without springs and with extension springs and torsion springs.

work for a 3D bipedal robots. Moreover a measure of the evolution of center of rotation of the human knee during a walking gait will be used to choose more precisely the dimension of the cross four-bar mechanism.

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