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Faster and Smoother Walking of Humanoid HRP-2 with Passive Toe Joints*

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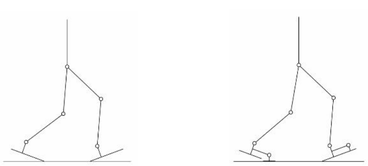
Abstract - **This paper addresses the role of toe joints in increasing the walking speed of biped robots. It is worthy that adding a toe joint will increase the step length thanks to the additional degree of freedom. But, the originality of this work is that longer steps are obtained thanks to an under-actuated phase and an appropriate ZMP trajectory. The simulations showed that adding passive toe joints allows smoother and 1.5 faster walking.**

Index Terms – Passive toe joint, Under-actuated phase, Pattern generation, ZMP trajectory, Walking speed.

I. Introduction

Research on humanoid type robots is an active field in robotics. Over the past decade, several anthropomorphic robots have been constructed. Some of them became well known even for non specialists. Especially, we have in mind Honda Robot Asimo [1], Sony's biped SDR-4X [2], Kawada's humanoid HRP-2 [3] and Jogging Johnnie at the Institute of Applied Mechanics of Munich [4]. Each of these robots has flat feet and is able to walk at different speeds. The major limitations to the walking speed are the length of the stance leg at heel strike and the joints angular velocities. This is due to the absence of heel rise during the single support phase which is an important property of the human walking gait [5].

This problem can be solved in two different ways. The first one is to introduce a rotation about the front edge of the stance foot before heel strike (Fig. 1.a.). The second one is to allow this rotation through the use of toe joint (Fig. 1.b.). Given the difficulty of controlling the robot stability when the support is limited to the front edge of its foot, the second solution will be easier to implement thanks to a larger surface kept on the ground and the possibility of encoding the foot rotation angle.



a. Flat foot b. Toed foot

Fig. 1 Foot rotation at the end of single support phase.

Several researchers focused on the advantages of toe joints for bipedal locomotion. Foot lifting stabilization, higher steps climbing and less energy consumption during walking are some of the stressed points. Since the year 2000, biped robots with toed feet were constructed and different kinds of design were presented.

Konno et al. proposed passive toe joints with torsion spring in order to achieve human like gaits [6]. Based on biomechanical studies, Scarfogliero et al. equipped the passive toe joints with spring-damper buffers for smoother foot rotation [7]. Nishiwaki et al. achieved faster walking on the humanoid H6 using an active toe joint [8]. Koganezawa et al. proposed a hybrid active/passive design for less energy consumption during walking [9].

In [8], the authors used toe joint rotation, during the double support phase, in order to decrease the knee joint angular velocity. They succeeded 1.8 times faster walking thanks to the active toe joints. Nevertheless, using the toe joint only in the double support phase, limits strongly the advantages introduced by this feature. In fact, during the double support phase, it is also possible to introduce a foot rotation about the front edge and it leads almost to the same results. This technique is already used for flat feet humanoid robots [10].

In this paper, we are focusing on the walking speed augmentation through the use of foot compliance during the single support phase. Simulations of flat and toed feet walking gaits are conducted using a new model of the humanoid robot HRP-2 with passive toe joints. The maximum step length, possibly fulfilled for both gaits, is the main comparison parameter.

II. Walking gait

Two different walking gaits were designed for this study. A fully actuated gait for the flat feet walking and a hybrid actuated / under actuated for the toed feet one. The different phases of these gaits are described in the following paragraphs.

A. *Flat feet gait*

The walking gait illustrated on Fig. 2 is common to the majority of humanoid robots with flat feet. It is composed of two fully actuated phases: the single support and the double support. During the single support, the swing leg is moving forward and the support foot is flat on the ground. The double support phase starts when the swing foot touches the ground.

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During this phase, the support is transferred to the former swing leg which becomes the support one.

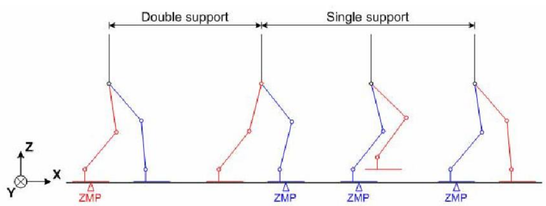


Fig. 2 Walking gait with flat feet.

Fig. 3 shows the ZMP trajectory, in the walking direction (X), for this kind of gait. During the single support phase (from $T_{Supp.}$ to T_{Double}), the ZMP keeps a constant position in the middle of the support foot (M). Then, during the double support phase (from T_{Double} to $T_{Supp.}$), it is transferred to the same position under the following support one.

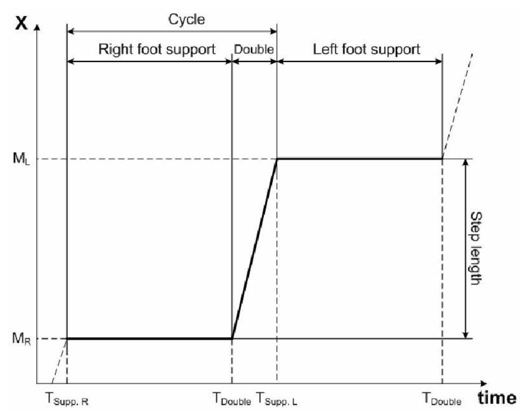


Fig. 3 ZMP trajectory (flat feet gait).

B. *Toed feet gait*

With toed feet, the walking gait described previously can be fulfilled. Nevertheless, in order to exploit plainly the advantages of the passive toe joint, an under actuated phase should be integrated at the end of the single support (Fig. 4). During this phase, the heel of the support foot starts to rise thanks to whole body dynamics. The maximal toe angular position is reached at the end of the single support.

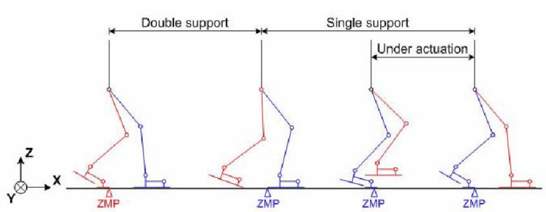


Fig. 4 Walking gait with toed feet.

Biomechanical studies showed that during the single support phase, the centre of pressure moves from the heel to the toes of the support foot [5]. Besides, during the acceleration phase, corresponding to the end of the single support, the centre of pressure is kept under the toes.

The ZMP trajectory, proposed for the toed feet gait, takes into account these biomechanical features (Fig. 5). During the single support phase, the ZMP moves linearly from the heel (H) to the toes (T). At the end of this phase (from T_{Stage} to T_{Double}), the ZMP is kept in a constant position between the toe joint (Tj) and the tip of the toe (T), which makes the whole body rotate around this joint. During the double support phase, starting with the swing foot touch down (T_{Double}), the ZMP is transferred from the toes of the support foot to the heel of the swing one.

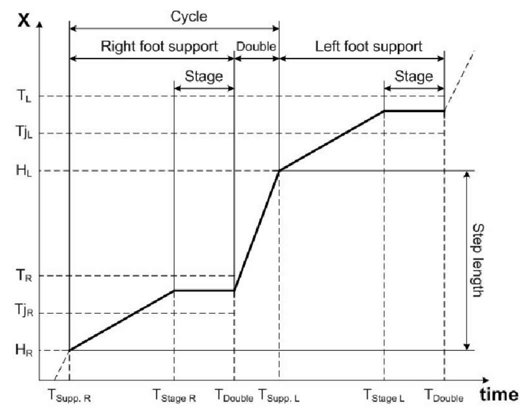


Fig. 5 ZMP trajectory (toed feet gait).

III. PATTERN GENERATION

Since the aim of this work is to compare two walking gaits, the same pattern generator must be used. In literature, we can find a large variety of walking pattern generators. Two representative methods were investigated: the inverted pendulum method [11] and the ZMP based method [12]. In this application, we will focus on the feet, so the inverted pendulum technique, with point foot, was avoided. Then, the method introduced by Kajita [12], was chosen for this work.

A. *Preview control of Zero Moment Point*

The main idea of this method is to consider the pattern generation as a ZMP tracking servo controller using the preview control theory. The walking pattern is then calculated by solving an inverse kinematics problem such that the ZMP of the robot follows the output of the preview controller. Fig. 7 shows the global scheme of the walking pattern generation.

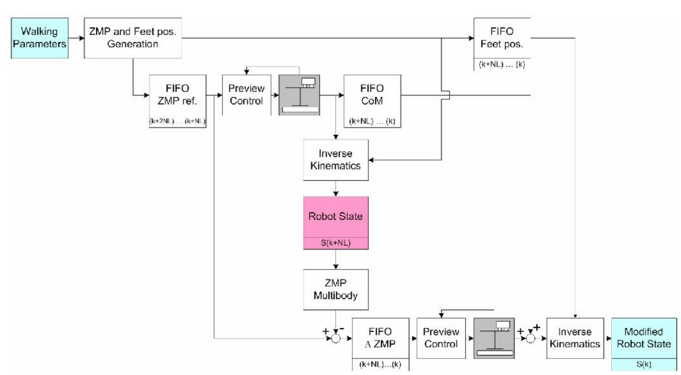


Fig. 6 Pattern generator scheme.

Given the walking parameters (step length, step height, cycle time etc.), the ZMP and feet trajectories are generated. Then, the CoM trajectory is derived by preview control using a simple model of the robot (such as the CoM has a constant position in the waist frame and a constant height in the world frame). Given the waist and the feet trajectories, a robot state is computed by inverse kinematics. The tracking errors of ZMP caused by the difference between the simple model and the multi-body one, defined by the robot parameters, are computed. A second preview control is then implemented in order to correct these errors and obtain a modified robot state.

B. *Flat feet gait generation*

For the flat feet gait, the reference ZMP trajectory presented in paragraph (II.A.) was implemented. Fig. 7 shows the ZMP and CoM trajectories obtained with the pattern generation shown in Fig. 6. The pattern is generated for 6 walking steps with the following parameters:

- Step length = 0.2 m,
- Step height = 0.07 m,
- CoM height = 0.814 m,
- Cycle time = 0.8 s,
- Single support time = 0.75 s,
- Double support time = 0.05 s.

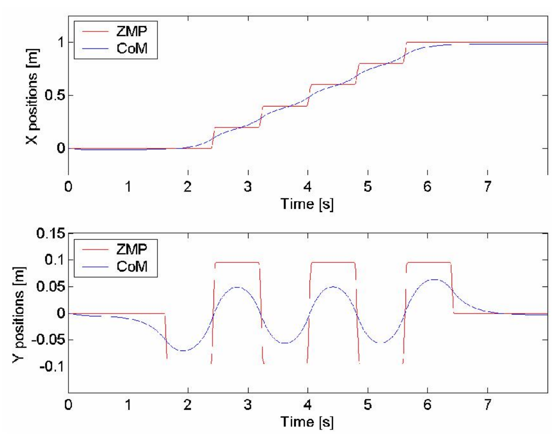


Fig. 7 ZMP and CoM trajectories (flat feet gait).

A projection on the horizontal plane is given on Fig. 8.

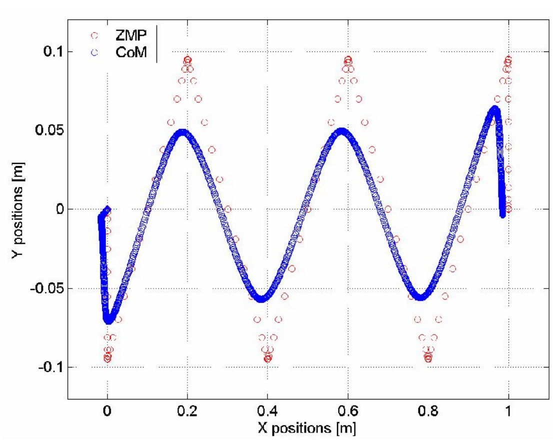


Fig. 8 Horizontal projection of ZMP and CoM trajectories (flat feet gait).

At this stage the waist trajectory during the walking gait is generated. In order to compute the joints angles, the feet positions are also needed. The support feet positions can be easily derived from the walking parameters. The swing feet trajectories are computed using polynomials respecting the continuity of position, velocity and acceleration. In X and Y directions, where only the starting and finishing positions are fixed, 5th order polynomials were used. Along the Z axis, a medial position, where the foot is at its highest position, is also given. Then, 6th order polynomials were used in this direction. Fig. 9 shows the feet trajectories for the simulated walking gait.

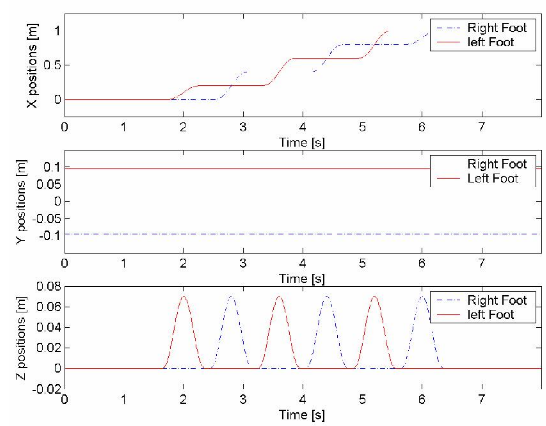


Fig. 9 Feet trajectories.

C. *Toed feet gait generation*

For the toed feet gait, the reference ZMP trajectory presented in paragraph (II.B.) was implemented. Fig. 10 shows the obtained ZMP and CoM trajectories. The walking parameters are similar to the previous walking gait with a stage time set to 0.3 s.

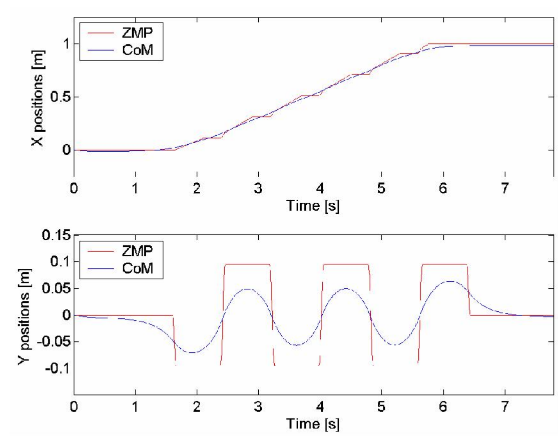


Fig. 10 ZMP and CoM trajectories (toed feet gait).

The projection on the horizontal plane is also given on Fig. 11.

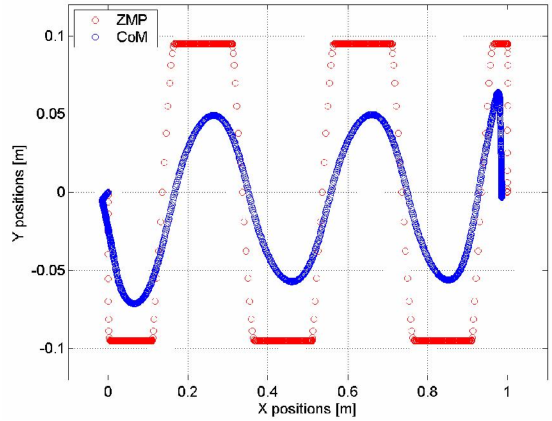


Fig. 11 Horizontal projection of ZMP and CoM trajectories (toed feet gait).

During the flat feet walking gait, the feet are kept parallel to the ground. Then specifying the waist and feet trajectories was enough for the joints angles computation. On the other hand, during the toed feet walking gait, the feet orientations are also needed for the inverse kinematics. The estimation of the toe joints angles can be obtained through the following procedure.

The toe joint is orthogonal to the sagittal plane (**X**, **Z**). Then its angular position depends on the dynamical effects in this plane. During the single support phase, the forces acting on the CoM are the gravitational and the forward accelerations. A simple model was used in order to compute the toe joint angle (Fig. 12). At the end of this phase, the ZMP is located under the toe, which can be considered as stable on the ground (Slipping phenomena are not considered at this stage). This leads to the following equations:

$$\mathbf{f} = -M(\mathbf{g} - \ddot{\mathbf{x}}) . \quad (1)$$

$$\boldsymbol{\tau}_{\mathbf{toe}} = -\mathbf{r}_{\mathbf{TZ}} \times \mathbf{f} . \quad (2)$$

$$\boldsymbol{\tau}_{\mathbf{toe}} = -(K_p \alpha + K_d \dot{\alpha}) \cdot \mathbf{Y} . \quad (3)$$

Where:

- $\mathbf{f}$: ground reaction force,
- M : mass of the robot,
- $\mathbf{g}$: gravitational acceleration,
- $\ddot{\mathbf{x}}$: CoM acceleration along the $\mathbf{X}$ axis,
- $\boldsymbol{\tau}_{\mathbf{toe}}$: torque acting at the toe joint,
- $\mathbf{r}_{\mathbf{TZ}}$: position vector of ZMP with respect to the toe joint,
- α : toe joint angle,
- K_p and K_d : toe joint spring and dumper constants,

Given the CoM acceleration along the X axis, the torque acting at the toe joint is computed using (1) and (2). If $\boldsymbol{\tau}_{\mathbf{toe}}$ is positive, the foot rotates around the toe joint which angular position α is derived from the spring dumper model (3). In the opposite case ($\boldsymbol{\tau}_{\mathbf{toe}} < 0$), the foot remains flat on the ground and the toe joint keeps its rest position.

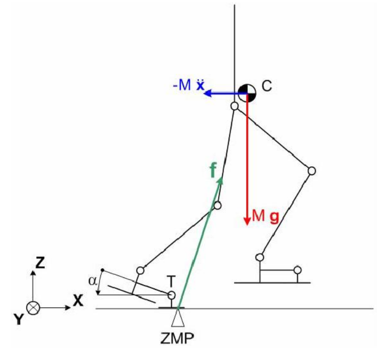


Fig. 12 Toe joint angle.

IV. Dynamic Simulations

The dynamic simulations of the designed walking gaits were performed using the software platform OpenHRP, which is composed of a dynamic simulator and a motion control library for humanoid robots [13]. A stabilizer was also necessary to realize these walking simulations. It consists of a body inclination control, ZMP dumping control and foot adjusting control [14]. The humanoid model used for simulation is presented in the next paragraph.

A. Humanoid robot HRP-2TJ

The simulation model HRP-2TJ is a 32 DOF humanoid robot with a total mass of 54 kg for 1.54 m height (TABLE I). It is a new version of the humanoid robot HRP-2 which has flat feet [15].

TABLE I
Model Specifications

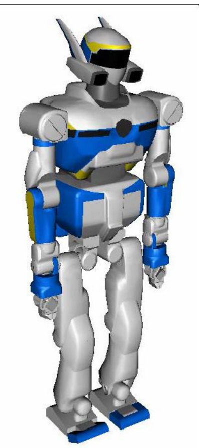
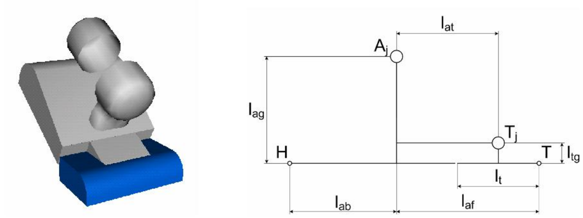
	Upper body	D.O.F.	Neck	2
			Torso	2
			Shoulder	3 × 2
			Elbow	2 × 2
			Wrist	1 × 2
			Hand	1 × 2
	Lower body	D.O.F.	Hip	3 × 2
			Knee	1 × 2
			Ankle	2 × 2
			Toe	1 × 2
		Dimensions	Thigh	300 mm
			Leg	300 mm

Fig. 13 shows the compliant foot of HRP-2TJ. It is equipped with a passive toe joint modelled as a spring dumper mechanism. The main dimensions in the sagittal plane are as follows: (l_{at}, l_{ag}, l_{ab}, l_{af}, l_{tg}, l_t) = (100, 105, 140, 20, 80) mm.



a. 3D model b. Foot parameters

Fig. 13 Compliant foot.

B. Simulated gaits

In this paragraph, the simulations of the two walking gaits, previously introduced, are presented. Snapshots of the flat feet walking gait are given on Fig. 14. During the single support phase, the ZMP is kept behind the toe joint which keeps its rest angular position. This demonstrates that even with passive toed feet robot, flat feet gaits can be achieved.

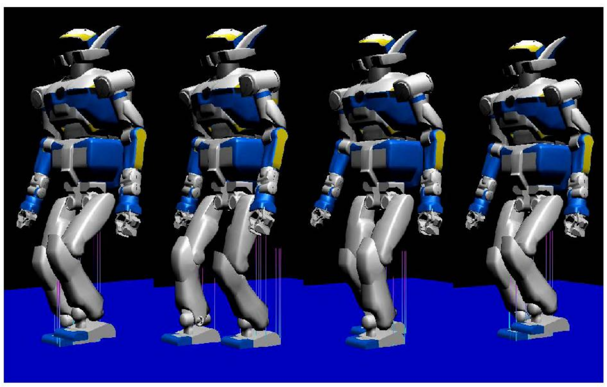


Fig. 14 Flat feet walking.

Then, changing the ZMP reference trajectory, toed feet gait with an under actuated phase was simulated (Fig. 15). The toe joint spring dumper constants were tuned in order to obtain smooth heel rising during the single support. The chosen values are K_p = 10 Nm/rad and K_d = 5 Nm.s/rad.

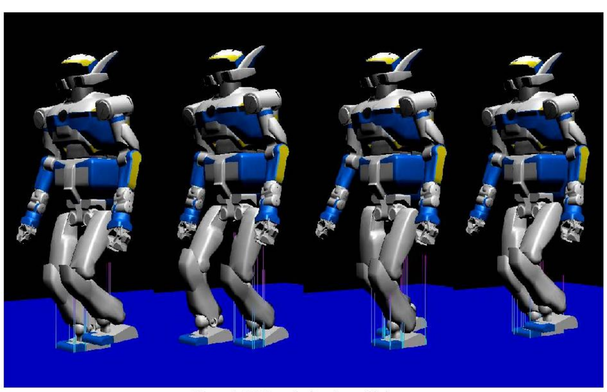


Fig. 15 Toed feet walking.

Fig. 16 shows the toe joints angles data and the feet orientation during this walking gait. We notice that during the single support phase the feet orientation is estimated using the simple model previously presented. Then during the double support and the swing phase it is decreased smoothly to reach the zero value before the touch down.

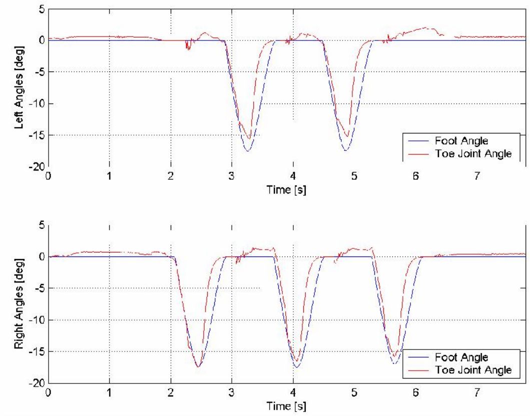


Fig. 16 Feet and Toe joints angles.

C. Walking speed

The walking speed is defined as the step length divided by the cycle time. Then two ways are possible to have faster walking. The first one consists on decreasing the cycle time and the main limitation, in this case, is the knee joints maximum velocities. The second way consists on increasing the step length, and the major limitation, for this case, will be the straight leg singularity at the end of the single support. In this paper the step length augmentation is investigated.

Let us consider the knee joints angles. The minimum possible value, which corresponds to the straight leg configuration, is zero. Fig. 17 shows the right leg knee joint angle obtained for both walking gaits. We can easily observe that for the flat feet gait knee joint angle approaches the minimum value at the end of the single support phases. On the contrary, for toed feet gait, the depicted values are comparatively far from this singularity. This proves that for toed feet gait, the straight leg singularity is reached for bigger steps than with flat feet one.

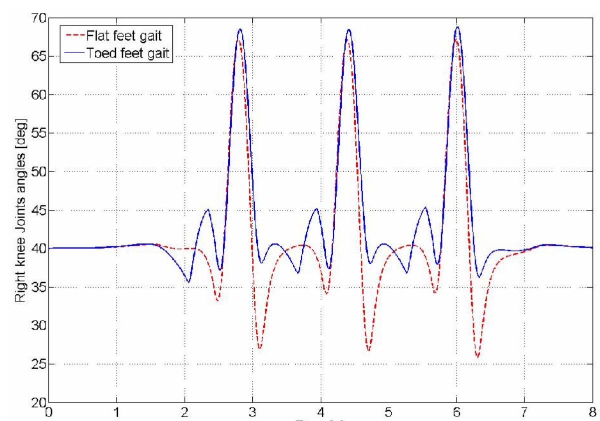


Fig. 17 Knee joints angles.

In order to increase the step length for the flat feet gait, we must decrease the waist height. But this solution makes the knees bending more important and increases the energy consumption. That shows the importance of the toed feet for the step length augmentation.

With flat feet walking gaits the humanoid robot HRP-2TJ was able to reach a maximum step length of 230 mm with a CoM height of 0.814 m. This corresponds to a walking speed of about 1.04 km/h. On the other hand, step lengths up to 360 mm were reached with toed feet walking gaits for the same CoM height and with the following spring dumper parameters: K_p = 5 Nm/rad and K_v = 3 Nm.s/rad. As a result, 1.5 times faster walking was fulfilled thanks to the passive toe joints (1.62 km/h).

Concerning the walking smoothness, let us consider the CoM velocity in the walking direction. During the walking gait, this value oscillates around the desired walking speed (Fig. 18). We can easily notice that for toed feet gaits these fluctuations are remarkably decreased. This result is mainly due to a better ZMP trajectory used for the toed feet gait.

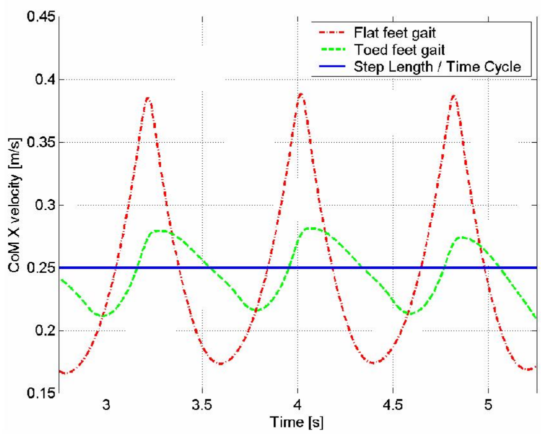


Fig. 18 CoM velocity in walking direction.

Another consideration, which must be taken in account, is the joints angular velocities. Simulations showed that for 360 mm step length, the maximum knee joints velocities were under the limit of 300 deg/s. Then we can conclude that the walking speed improvement, introduced by the toe joints, respects the maximum joints angular velocity.

V. Conclusion and Further Developments

The majority of humanoid robots are flat feet and this introduces many limitations in their performance. Some researchers proposed the toed feet as a basic way to enhance the humanoids capabilities.

In this paper we followed the same direction and we proved the advantage of compliant toe joints in terms of walking speed augmentation. Dynamic simulations were conduced using the humanoid HRP-2TJ model. This robot has compliant feet with passive toe joints. Both flat and toed feet walking gaits where generated using the preview control of ZMP method. It was proved that passive toe joints allow 1.5 faster walking.

This result is due to the integration of an under actuated phase at the end of the single support phase. During this phase the support foot rotates around the toe joint and allows the ankle joint to rise. Farther from the straight leg singularity, the robot was able to fulfil larger steps and increased, by the way, its walking speed. The walking smoothness was also improved thanks to the appropriate ZMP trajectories designed for this purpose.

The development of the HRP-2TJ humanoid robot, in order to validate this study through experiments, will be the next target.

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