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Human-Oriented Biped Robot Design: Insights into the Development of a truly Anthropomorphic Leg

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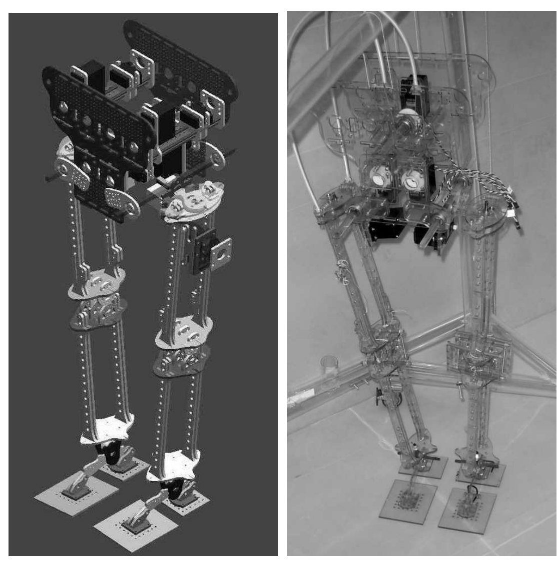
Abstract— **In this paper we present a human-oriented approach to the study of the biped gait for a humanoid robot. Starting from the analysis of the human lower-limbs, we figured out which features of the human legs are fundamental for a correct walking motion and can be adopted in the mechanical design of a humanoid robot. In particular we focus here on the knee, designed as a compliant human-like knee instead of a classical pin-joint. For the foot we tried to reproduce in a simple mechanical device the mobility and lightness of the human foot, which is very different from a flat surface and has a big impact on walking. We complete the presentation with considerations about the energy consumption of our humanoid design. In our approach the robot gains in adaptability and energetic efficiency, which are the most challenging issues for a biped robot.**

I. Introduction

During the last decade many advancements in the field of robotics have produced robots that are well integrated in the industry. Nevertheless the kinematic structure of these systems is limited in the mobility and in the number of tasks that they can perform. This is more evident if we intend to apply those robots in an unstructured environment like home, where movements are based on the human kinematic abilities, and should be performed with some compliance. The common solution for mobility is a wheeled traction system. This usually is a simple manner to move on flat floors, and is efficient from the energetic point of view (during the movement the center of mass acts on a straight line). However it presents important limitations, for example it is not possible for such a robot to overcome obstacles bigger than the wheels dimensions.

Those limitations can be overcome if the robot is equipped with legs, that normally act by increasing the robot's DOF(Degrees of Freedom). Many studies were conducted on legged robot in order to improve their efficiency and stability. A pioneering contribution was done by Professors Kato and Takanishi [1] at the Waseda University (Tokyo). Several modern robots are designed to walk and behave like humans [2] [3] but until now the efficiency of the human gait is still far from being reached. In this sense, the work of McGeer [4] can be considered exemplar. His passive dynamic walker made a stable gait without close position control, considering the walking motion as a natural oscillation of a double pendulum; and this is actually how humans seem to walk [5] [6]. His results inspired many other works, such as the stability analysis [7] and the physical implementation [8] [9] [10] of several prototypes.

In this paper we present LARP (Light Adaptive-Reactive biPed), our humanoid legged system, with the aim to explain how the mechanical design makes the robot able to adapt to the real operating environment. Our aim was to create a system that could represent a good model of human lower limbs, in order to understand how the natural walking motion is achieved and how it can be implemented in a humanoid robot. For this reason, we adopted anthropomorphic feet, knees and a mass-distribution similar to the human limbs. LARP (figure 1) has twelve active degrees of freedom; the range of motion of each joint is similar to that of humans during walking. It is 90 cm tall and weights less than five kg, being entirely made by pieces cut out from a polycarbonate sheet with laser cutting technology. Each leg has 6 actuated degrees of freedom, each foot has two passive degrees of freedom.



a. b.

Fig. 1. (a) The 3D cad assembly of the robot. (b) The prototype, here with only one leg actuated.

Joint torques are provided by servo motors located in the upper part of the robot. According to McGeer [4] we designed an actuation system that can take advantage of the natural dynamics of the link, using servo motors equipped with a spring and a damper to control joint stiffness. Studying the results of our controller we found several similarities with the assumptions of the Equilibrium Point Theory. This is a widely debated theory, formulated in 1965 by A. Feldman [11] and still in evolution. This theory proposes that the segmental reflexes, together with the muscle-skeletal system, behave like a spring. Movement is achieved just by moving the equilibrium position of that spring [12] [13], and this is actually how our actuator [14] performs the movement.

In the following sections we concentrate on the design of the knee and the foot, which present several similarities to the human articulations (for more details on the robot prototype see [14]). Then we illustrate preliminary results on simulating the movement and the energy consumption of LARP.

II. The design of an anthropomorphic knee

A. The importance of the knee joint in biped walking

Using stiff legs could actually simplify the motion and the robot structure, as in the simple Fallis's toy [15]. In practice, however, the knee has several important functions in the walking dynamics that suggests the introduction of knee articulation.

In 1990 McGeer published "Passive Dynamic Walking" (PDW), where he demonstrated how it is possible to exploit the mass distribution of the robot to make it walk on a shallow slope without actuation [4]. The prototype was exploiting the gravity force to swing the leg forward, exactly as a double pendulum would do. The only power needed was the one necessary to shorten the leg in order to create foot clearance during the swinging motion. Today, several passive dynamic walkers have been developed, but in order to have a fully-passive walker, it became necessary to add knee joints [16], [10], [17]. As a matter of facts, this joint empowers the swinging motion due to gravity, and with the right mass distribution, it is possible to perform a fully-passive pace.

Apart from PDW, the knee is fundamental to ensure energetic efficiency. Let's consider a robot with straight legs; in this case the foot clearance would have to be created by an additional pelvic tilt. This means a reduced step length and a bigger energy consumption, as the pelvis is the heaviest part of the body while knee stretching just lifts the foot. Another effect of straight legs would be that the double support time is decreased during the step on behalf of the single support time. As the former is the most stable position, the straight leg walking is more critical from the stability point of view. So knee-walking needs less energy to ensure gait stability.

The knee is important also during the stance phase, while the supporting leg remains straight. In this case, while the swinging leg moves forward, the knee of the stance leg has to counteract the inertial load generated by gait motion. In this case, using a force control to actuate the knee (we used our spring-damper actuator [14], [18]) it is possible to store energy, exploiting the natural dynamics of the walking motion. The same happens in humans; during stance the knee bends a bit, storing energy as a spring would do. This energy is then released to empower the hip forward motion, with a relevant increase in the step length and foot clearance. The result is a more stable walk with the same energy consumption. This behavior was also underlined by simulations on a PDW, the robot Mike of the Delft University of Technology [17].

B. The design of the knee joint

Regarding the knee structure the most obvious and more adopted solution in robotics is a simple pin joint. Usually the motor is applied directly to the joint, but there are also some examples where, for mass-distribution reasons, the motor is placed in the upper part of the robot [19].

Looking at the prosthesis field, we find a completely different approach. Here the knee reveals its crucial importance, not only related to the prosthetic issues, but also for the walking motion. Passive prosthesis have to perform the knee bending using inertial torque generated by the forward acceleration of the thigh, in a similar manner as in passive dynamic walking. In addition, for safety reasons, during the stance phase the knee has to be locked. Today, prosthetic knees are build using multi-axial mechanisms. In these mechanisms, during the motion, the center of rotation *cr* is not fixed, as in a pin joint, but moves along a trajectory that depends on the mechanism structure. As the stability of the knee during the stance phase strongly depends on the *cr* position, variations in the mechanism proportions result in different *cr* trajectories with different stability properties.

For LARP we designed a special joint based on the human articulation. The human knee, from an engineering point of view, is an hybrid juncture, similar to a compliant joint but with rolling surfaces. This structure is very close to the compliant rolling-contact joint, designed by J. Herder [20], composed by two circular surfaces rolling on each other. Flexible bands constrain the joint and avoid the knee luxation, leaving only one degree of freedom. During the motion, the tendons wrap on a surface or on the other, letting the joint rotate without scratch. This significantly reduces friction.

Critical in this kind of joint are the torsional stiffness and the rigidity respect to external forces. This issue is fundamental for the robot, where the knee is subject to high torsional and flexional disturbances. To solve this aspect, we strengthened the joint, designing the articulation shown in fig.2. Instead of flexible bands, we used three Coramide strings that can all be independently fastened. This makes the articulation more firm as well as allows a fine joint calibration. In addition, we added two springs, which increase the contact force between the circular surfaces. Connecting the spring ends to the center of curvature of the two profiles results in a constant spring-length - equal to two times the radius of the profile. In this case no torque interferes with the joint rotation. Anyhow, it is possible to arrange the springs in a way that they force the joint to rotate to a particular equilibrium position.

In the knee we arranged the springs as shown in fig. 3 so that during rotation, the spring length has a maximum

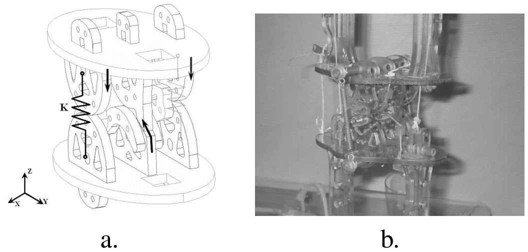


Fig. 2. (a) The knee joint designed for our robot. The arrows show the way the tendons are wrapped. (b) The knee prototype

for $\theta = \bar{\theta}$, where θ is the angle that the shank forms with the vertical. In the figure, γ represents the angle between the shank axis and the force direction. When this angle is zero, the springs torque is zero too and θ equals $\bar{\theta}$. This permits to find one equilibrium position, in particular, an instable equilibrium position, as the spring is at its maximum extension. Attaching the spring forward, with $\psi < 0$ (see figure), we can both help knee bending during leg swinging and knee stretching at the end of the step.

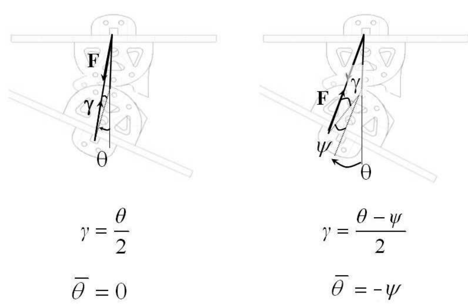


Fig. 3. We can exploit the action of the springs to impose a suited torque on the joint. In particular, it is possible to generate a position of instable equilibrium ($\theta = \bar{\theta}$) to favor knee bending and stretching.

This kind of joint for the knee articulation has several advantages respect to a pin joint. The first consideration is about energy efficiency. A reduced friction at the knee not only reduces knee actuation, but can influence the whole gait. As pointed out in the previous paragraph, using elastic actuators or even a passive knee, the leg can be bent exploiting inertial forces due to hip actuation. In this sense, an efficient knee joint is fundamental to reduce the demand of high hip torque.

Another aspect that strongly characterizes this compliant joint is that the center of rotation (*cr*) is not fixed, as in a pin joint, but moves upward and backward during rotation (fig. 4). This motion increases the foot clearance necessary to swing the leg, and the shank active rotation can thus be reduced. The effect is both on energy consumption - i.e. the knee could be passive in some robots - and on the gait stability. As a matter of facts, the inertial load of knee-bending and knee-stretching is one of the most important in the dynamics of walking. This is also the reason why the foot must be designed as light as possible, as described in the next section.

Regarding the radius of curvature of the two surfaces, an optimal design could maximize the foot clearance during the rotation. We can consider that if one contact surface (for example the upper one) has radius infinite or zero, the upward translation is null during the rotation. This means that there must be a finite rate value of the two radius that maximizes the upward motion. Considering that the two surfaces are in contact without slipping, the upward motion Δy can be expressed as (fig. 4):

$$\alpha R_1 = \theta R_2 \quad (1)$$

$$\Delta y = R_1(1 - \cos(\alpha)) = R_1(1 - cos(\frac{R_2}{R_1}\theta)) \quad (2)$$

If we consider R_1 fixed and we vary R_2, the maximum can be found quite straightforward for a fixed $\overline{\theta}$

$$R_2 = (\pi/\overline{\theta})R_1 \quad (3)$$

$\overline{\theta}$ can be considered as the angle of the bent knee in the instant the foot is closer to the ground.

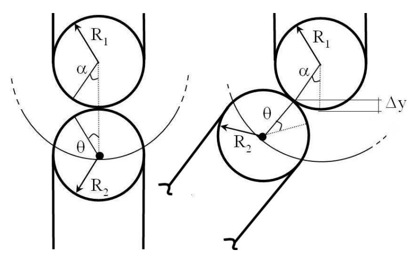


Fig. 4. The upward movement can be expressed as a function of R_1, R_2 and the rotation θ, due to the constrain of rolling without slipping.

According to this analysis, the radius R_2 should be longer than R_1, and the bigger the ratio between the two radius, the smaller will be the shank rotation, till having a flat surface rolling on the upper one.

III. The design of the foot

A. The importance of foot in stability and efficiency of walking

The foot is probably the most challenging part for a biped robot to be anthropomorphic. Not only from the sensory point of view, but for the unique combination of mobility and lightness.

First of all, the foot inertia must be negligible with respect to the leg inertia. There are several evidences for this. One reason is the energy efficiency. To understand that, try to run or kick wearing heavy boots. During the swing-phase, the torque needed to move the leg forward is mainly due to inertial loads, that highly depend on the foot weight. In addition, these loads would act on the hip and the stance leg; their impact on the stability is more critical when the ratio body weight/foot weight is low. But it is not only a matter of the foot motion on the dynamic balance. It is fundamental for stability to keep the center of mass as high as possible.

At the beginning of the stance phase, the biped robot can be considered as an inverted pendulum, both in the fore-aft plane and in the frontal plane. Placing the center of mass higher increases the inertia of the pendulum respect to the hinge. It is well known that this imply slower changes respect to the initial position and thus a wider stability respect to external disturbances [21]. As pointed out above about the knee, stability and energy efficiency are strictly related. A more stable gait requires less motor action to counteract disturbances [22].

Another aspect that characterizes the human foot is its mobility and elasticity. Ker et al. found that the foot behaves like an elastic body, returning about 78% of the energy in its elastic recoil. During running, the arc of the foot stores and returns 17% of the energy the body loses and regains at each footfall, while till the 35% of this energy is stored and returned by Achilles tendon [23].

The foot mobility of course has a big influence on the whole kinematics and dynamics of the motion, especially on the ankle. In particular, during the stance phase, the contact point moves from the heel to the toe, and the foot is rotated before the toe-off. The position of the contact force plays a very important role in determining the joint torques, thus the energy consumption. As in normal walking the ground reaction is much higher than inertial forces, in first approximation, we can consider only this force acting on the stance leg [24]. From this point of view, the bigger the arm between the joint and the contact force, the bigger would be the torque needed. In order to minimize energy consumption, while walking we naturally pose the leg joints close to the line of action of the contact force [25]. For this reason it is important to have a foot that let adapt the position of the ankle, and thus the other joints, without losing grip.

This aspect is particularly relevant at toe-off, when only a small region of the foot is in contact. Also here the mobility and elasticity of the foot plays a very important role [26], [27]. Fig.5 shows a simple biped model at heel-strike: the rear leg is in the stance phase, and the fore leg is about at foot-fall. The energy loss at the impact depends on the vertical velocity of the center of mass (*cm*). The ideal situation is when the *cm* velocity is parallel to the ground, and the legs simulate the wheel [4]. In normal walking, without toe-off the motion of the center of mass is rotational along the contact point of the stance leg. This means that at foot fall there is a component of *cm* vertical velocity that causes impact loss. Using toe-off, this component can be significantly reduced, resulting in a more efficient and smooth gait. Kuo figured out that providing all the energy necessary for walking by the toe-off muscle instead of the hip reduces the energy cost by a factor of 4 [27].

B. The anthropomorphic foot

Nowadays, almost all the biped robots adopt a flat foot, with relatively heavy dampers to smooth the heel-strike. In the previous paragraph, we underlined that the key issues for the foot design are:

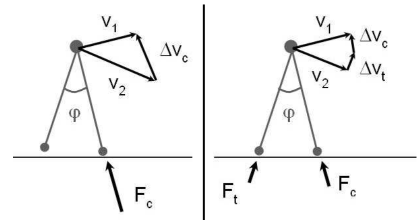


Fig. 5. In the figure, v_1 and v_2 are the *cm* velocities respectively before and after heel-strike, while F_c and Ft are the ground reaction forces. With toe off (on the right) the *cm* vertical velocity is reduced, and the gait is smoother and more efficient.

- The possibility to change ankle position without losing grip (a key issue for energy efficiency [25])
- A good elasticity to store and release part of the energy lost at footfall. Also a good damping is required to smooth the impact occurring at every step
- The capacity to adapt to different ground situation without losing grip in different step phases, as at toe-off

Using a flat foot implies that the ankle position is fixed during the whole stance phase and, at toe-off, the contact is reduced to the foot edge (fig.6). On the other hand, a flat foot is probably the simplest design that can be conceived, and ensure a big base on which lean during the stance phase. Another type of simple foot profile, adopted mainly on passive dynamic walkers, is the round foot. The advantage of this kind of foot is that the ankle joint is moved forward during the rotation, minimizing the torque needed at toe-off. The drawback of the round profile is that the contact surface is reduced to a thin area. That is why this kind of foot is mainly adopted on 2-D bipeds.

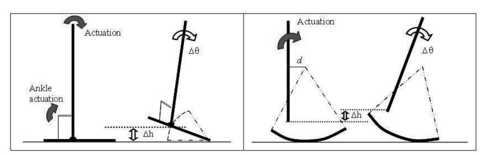


Fig. 6. The flat foot compared to a circular foot

Thus, our goal was to develop a foot with the right trade-off between mobility and stability, keeping at the same time the structure as light as possible, adopting performing materials, as polycarbonate covered by rubber in order to avoid sliding. We designed the foot with a two-dof device, shown in fig.7. The foot has one passive degree of freedom that represents the heel, an arc, and another passive dof for the toe. In addition, we inserted an artificial tendon between the heel and the arc.

The articulations in the foot play an important role in determining the gait kinematics and dynamics. As shown in fig.7, at heel-strike and at toe-off the ankle position is not constrained in one fixed position. This gives the ankle an addition degree of freedom, which makes it possible to minimize energy consumption. Generally speaking, during the stance phase the contact position moves from the heel

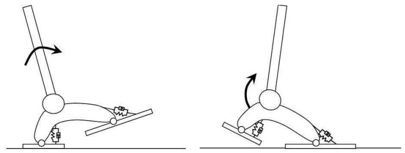


Fig. 7. The foot developed to mimic the human one. It has two passive degrees of freedom, and a spring-damper system to smooth the heel-strike

to the toe. With our foot the center of rotation follows the same motion. This means that the lever arm of the ground reaction force is already reduced respect to a flat foot, where the ankle and the center of rotation are constrained in the same fixed point. Moreover, the foot keeps a firm base to lean even at toe-off, when the ankle is moved forward and upward for knee-bending. In this way the double support time - the time when both feet lean on the ground - can be increased, resulting in a more stable walk.

IV. Estimation of energy consumption

In this section we present some simulation results obtained using the direct/inverse kinematic model of our biped. We do not enter in details of this models, but we concentrate our attention on a first valuation for the energetic consumption during the execution of different gaits. The movement of the biped robot was performed using a controller based on the Equilibrium Point Hypothesis [18].

Using the inverse kinematic solution we can set a reference trajectory for the foot and calculate the relative joints positions. A gait is characterized by the step length and height, the minimum height that the pelvis is allowed to reach during motion, and the maximum lateral movement admissible (oscillations in frontal plane). During all the motion the robot assumes only stable configurations, so if we arrest the movement the robot maintains balance. A sufficient condition for the static stability is that the projection of the robot center of mass falls inside the convex area that cover the contact surface of the two feet. In our simulation the static stability is guaranteed by a software module that adjusts the pelvis position when the stability condition is not verified (see [14]).

To evaluate the energy required to complete a step we made the following assumptions and approximations:

- Each robot link is modelled by a mass located in its barycenter.
- The center of mass for the entire robot is calculated by a weighted average of each link's center of masses.
- The robot moves very slowly, therefore inertia forces are neglected.
- We do not consider friction forces present in the joints.
- We consider that kinetic energy during the falling phase (the foot lifted approaches the ground) is completely lost during the movement.

The energy to lift each single link was therefore calculated with equation 4, where m_i is the mass of the link-i, g the gravity constant and Δh_i the excursion along the z-axis for the center of mass of link-i.

$$W_i = m_i g \Delta h_i \tag{4}$$

Clearly we have introduced a big approximation of the real energy required for the movement, but our aim is to discriminate between efficient and non efficient gaits.

In the first simulation in figure 8 we set the step length at 0.5m, the minimum height for the pelvis at 0.68m and the maximum lateral excursion at 0.09m.

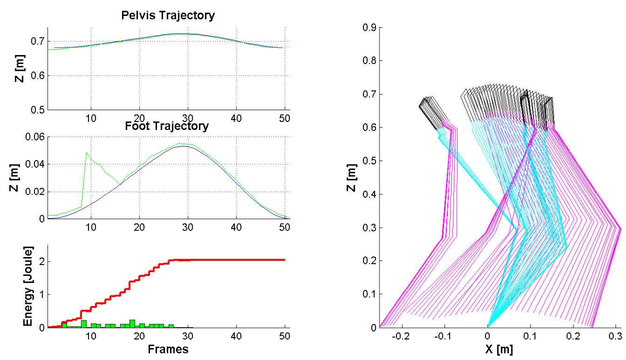


Fig. 8. Energy consumption with minimum height for pelvis at 0.68m

The first two graphs on the left in figure 8 represent the Z coordinates for the pelvis and the foot during the motion (in blue the reference trajectory, in green the real one). In the third graph on the left we see that the total energy consumed to perform the gait is about 2 joules. We note that at the eighth frame the real foot trajectory deviates significantly from the reference, as a result of the stability algorithm that tries to maintain the balance. Finally on the right side we see a stick model for the robot in the lateral plane for all the phases.

In the second simulation we changed the minimum height for the pelvis at 0.55m. As illustrated in figure 9 now the reference trajectory for the foot is well followed, but the energy spent increased up to 6 joules, since the links of the robot have a greater excursion along the z axis.

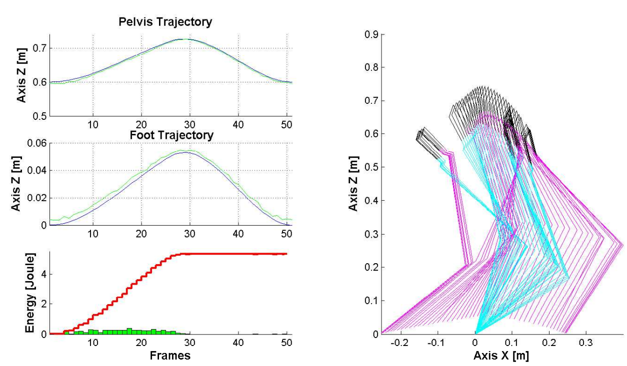


Fig. 9. Energy consumption with minimum height for pelvis at 0.55m

These preliminary results confirm that the position of the barycenter of the robot has a great impact on energy consumption. If the barycenter is maintained low the stability algorithm does not interfere with the trajectory following for the foot in statical condition. Nevertheless these kind of postures require more energy, while limiting the vertical movement of the pelvis can save energy during the gait. We can also assert that the knee joint covers a very important role during the gait, to move down the robot's barycenter and therefore to stabilize the posture.

The strategy to decrease the height of the barycenter is advantageous to control the robot stability in static conditions (at low acceleration and velocities the inertia forces can be neglected), nevertheless with this kind of posture the robot is not able to perform fast walking, and also the energy required for the movement is high. The human walking, on the contrary, can be assumed as dynamic; indeed in each instant the body is not in a stable position. Furthermore the pelvis is maintained high and as fixed as possible to reduce the energy required for the movement, as confirmed by our results.

To be energetically efficient our robot should be tested also in dynamical conditions, to take advantage of the knee and foot design that were thought to store the inertia and impact forces.

V. Conclusions

Today several humanoids robots are able to walk and perform human-like movements. Anyhow, the structure of such robots significantly differs from the human's one. This causes the robots to be energetically inefficient (as they are unable to exploit the natural dynamics of the links), and very poorly adaptable to unstructured terrains. Studying the human knee and foot we found several advantages in adopting human-oriented design for these parts. In particular, a compliant knee was developed, having two circular contact surfaces and five tendons. This articulation is highly efficient and permits to increase the foot clearance during the swing phase. Regarding the foot, two passive joints were introduced to mimic the high mobility of the human foot. To ensure stability both at heel-strike and toe-off we used two planar surfaces connected to the arc of the foot by two passive degrees of freedom.

Further work has to be done for the complete design of a human-like robot, starting from a new design of hip and ankle articulation. In this case we should investigate the role of the third dof in the human ankle (torsion of the foot along the leg axis), which is omitted in most of the modern humanoid robots. Also, it remains to test our model in dynamical conditions, in order to find the more efficient and efficacious gait. The similarity between the behavior of our robot and of human walking can be exploited to promote a further research comparing the biped behavior with human theories assumptions.

References

[1] H.-O. Lim, S. A. Setiawan, and A. Takanishi, "Position-based impedance control of a biped humanoid robot," *Advanced Robotics*, vol. 18, no. 4, pp. 415–435, 2004.

[2] S. Hashimoto and al., "Humanoid robots in waseda university. hadaly-2 and wabian," *Autonomous Robots*, vol. 12, no. 1, pp. 25–38, 2002.

[3] K. Hirai, M. Hirose, Y. Haikawa, and T. Takenaka, "The development of honda humanoid robot," *IEEE International Conference on Robotics and Automation*, pp. 1321–1326, 1998.

[4] T. McGeer, "Passive dynamic walking," *The International Journal of Robotics Research*, vol. 9, no. 2, pp. 62–82, 1990.

[5] P. Kiriazov, "Humanoid robots: How to achieve human-like motion," *Journal of Biomechanics*, no. 24, pp. 21–35, 1991.

[6] G. Gottlieb, Q. Song, D. Hong, G. Almeida, and D. Corcos, "Co-ordinating movement at two joints:a principle of linear covariance," *Neurophysiology*, vol. 75, no. 5, pp. 1760–1764, 1996.

[7] M. Garcia, A. Chatterje, A. Ruina, and M. Coleman, "The simplest walking model: Stability, complexity and scaling," *ASME Journal of Biomechanical Engineering Vol. 120 p.281-288*, vol. 120, pp. 281–288, 1998.

[8] M. Wisse, A. L. Schwab, and R. Q. vd. Linde, "A 3d passive dynamic biped with yaw and roll compensation," *Robotica*, no. 19, pp. 275–284, 2001.

[9] A. Kuo, "Stabilization of lateral motion in passive dynamic walking," *The International Journal of Robotics Research*, vol. 18, no. 9, pp. 917–930, 1999.

[10] S. Collins, M. Wisse, and A. Ruina, "A three dimensional passive-dynamic walking robot with two legs and knees," *The International Journal of Robotics Research*, vol. 20, no. 7, pp. 607–615, 2001.

[11] D. Asatryan and A. Feldman, "Functional tuning of the nervous system with control of movement or maintenance of a steady posture - i mechanographic analysis of the work of the joint or execution of a postural task," *Biofizika*, vol. 10, pp. 837–846, 1965.

[12] J. McIntyre and E. Bizzi, "Servo hypotheses for biological control of movement," *Journal of Motor Behavior*, vol. 25, no. 3, pp. 193–202, 1993.

[13] G. Gottlieb, D. Corcos, and G. Agarwal, "Strategies for the control of single mechanical degree of freedom voluntary movements," *Behavioral and Brain Sciences*, vol. 12, no. 2, pp. 189–210, 1989.

[14] U. Scarfogliero, M. Folgheraiter, and G. Gini, "Advanced steps in biped robotics: Innovative design and intuitive control through spring-damper actuator," *In Proc. IEEE Humanoids 2004, Los Angeles, USA*, 2004.

[15] G. Fallis, "Walking toy," *U.S. Patent No.376588*, 1888.

[16] T. McGeer, "Passive walking with knees," *IEEE International Conference on Robotics and Automation*, vol. 2, pp. 1640–1645, 1990.

[17] M. Wisse and J. Frankenhuyzen, "Design and construction of mike; a 2d autonomous biped based on passive dynamic walking." *Delft University of technology*, 2002.

[18] U. Scarfogliero, M. Folgheraiter, and G. Gini, "Larp: Biped robotics conceived as human modelling," *In Proc. Neurobotics KI 2004, Ulm, Germany*, 2004.

[19] J. Pratt, C. Chew, A. Torres, P. Dilworth, and G. Pratt, "Virtual model control: An intuitive approach for bipedal locomotion," *The International Journal of Robotics Research*, vol. 20, no. 2, pp. 129–143, 2001.

[20] A. Jeanneau, J. Herder, T. Lalibert, and C. Gosselin, "A compliant rolling contact joint and its application in a 3-dof planar parallel mechanism with kinematic analysis," *In Proc. DETC 2004 Salt Lake City, Utah*, 2004.

[21] P. Sardain, M. Rostami, E. Thomas, and G. Bessonnet, "Biped robots: Correlations between technological design and dynamic behaviour," *Control Engineering Practice*, vol. 7, pp. 401–411, 1999.

[22] G. Maloiy, N. Heglund, L. Prager, G. Cavagna, and C. Taylor, "Energetic costs of carrying loads: have african women discovered an economic way?" *Nature*, vol. 319, pp. 668–669, 1986.

[23] R. Ker, M. Bennett, S. Bibby, R. Kerster, and R. M. Alexander, "The spring in the arc of the human foot," *Nature*, vol. 325, pp. 147–149, 1987.

[24] C. Vaughan, "Are joint torques the holy grail of human gait analysis?" *Human Movement Science*, vol. 15, pp. 423–443, 1996.

[25] R. Alexander, *The Human Machine*. Columbia University Press. New York, 1992.

[26] J. Doneland, R. Kram, and D. A. Kuo, "Simultaneus positive and negative external mechanical work in human walking," *Journal of Biomechanics*, vol. 35, pp. 117–124, 2002.

[27] A. D. Kuo, "Energetics of actively powered locomotion using the simplest walking model," *ASME Journal of Biomechanical Engineering*, vol. 124, pp. 281–288, 1998.