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Humanoid Robot Motion in Unstructured Environment – Generation of Various Gait Patterns from a Single Nominal

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1. Introduction

Humanoid robotics has been in the focus of scientific community for decades. For a long time already, robots have not been present only in the industrial plants, at a time their traditional work space, but have been increasingly more engaged in the close living and working environment of humans. This fact inevitably leads to the need of “working coexistence” of man and robot and sharing their common working environment. The fact that no significant rearrangement of the environment of humans could be expected as a consequence of the presence of their mechatronic partners, robots will have to further “adapt” to the environment previously dedicated only to men. Besides, it is expected that the robots cooperating with humans will have an operation efficiency matching that of humans. The working and living environment, adapted to humans, imposes on robot's mechanical-control structure at least two types of tasks related to its motion: motion in a specific environment with the obstacles of the type of staircases, thresholds, multi-level floors, etc., and the motion within a very dynamic scene in which the trajectory of system's motion can be only globally planned and the actual trajectory determined on the basis of the instantaneous situation.

The first task is solved by using legged locomotion instead of wheels, and since the robots will be in a “close contact” with men and will act in the working and living environment adapted to humans, the most logical choice is the bipedal locomotion.

The other important aspect of the above problem is the planning of the robot's motion. While in industrial robotics, dealing with a very structured environment, it is possible to plan the entire robot's motion in the task execution and then this motion is repeated over and over again, in this sort of tasks such detailed planning is not possible because the human's environment in which robot is to move is very dynamic and unstructured. A basic characteristic of the locomotion activity in a dynamic and unstructured environment is the need to swiftly modify the motion trajectory, planned previously only in a global way. Thus, for example, there may appear the need to bypass an obstacle that suddenly appeared, accelerate or slow down the walk, and the like. Naturally, each of these modified gaits can be synthesized as a separate pattern, stored in the memory of the robot control system, and requested when needed. However, two questions arise then: a) How many trajectories are to be synthesized in order to “cover” all the situations that might be of interest, that is that might appear?, and b) Is it possible to accomplish in real time to search through all the set of synthesized trajectories and retrieve the most appropriate one

in the given situation? In order to cope with these issues and enable robot to react sufficiently fast to the disturbances and realize the previously “unplanned” trajectories in real time, we propose here an approach based on modification of the adopted in advance, nominal motion (straight motion on a level surface) that has been synthesized by semi-inverse method. The basis for preserving dynamic balance is the method of Zero-Moment Point (ZMP).

During the walk, all biped mechanism joints are powered and directly controllable except for the contact of the foot and the ground (it can be considered as an additional DOF), which is the only site in which the mechanism interacts with the environment. This contact is essential for the walk realization because the mechanism's position with respect to the environment depends on the relative position of the foot with respect to the ground. The foot cannot be controlled directly but in an indirect way – by ensuring appropriate dynamics of the mechanism above the foot. Thus, the overall indicator of the mechanism behavior is the point where the influence of all the forces acting on the mechanism can be replaced by one single force; hence, this point was termed Zero-Moment Point (Vukobratovic M. & Juricic D. 1968, Vukobratovic M. & Juricic D. 1969, Vukobratovic M. & Stepanenko Yu., 1972). Recognition of the significance and role of ZMP in biped artificial walk was a turning point in robotic gait planning and control.

In the gait synthesis by semi-inverse method (Vukobratovic M. & Juricic D. 1968, Vukobratovic M. & Juricic D. 1969, Vukobratovic M. & Stepanenko Yu., 1972) legs' trajectories are predefined while the trunk motion is determined so as to ensure dynamic balance of the system as a whole (the ZMP position is within the desired area under the supporting foot). Such motion is called nominal motion.

The problem addressed in this paper is how to achieve robot's coping with the situations in the dynamic scene and the motion realization if the change of the planned trajectory is to be carried out on-line. The idea we propose is to use a nominal motion selected in advance as a basic motion pattern (we used a nominal synthesized by semi-inverse method for the straight walk on a flat ground), whereas all other motions are to be obtained by its on-line modification (Vukobratovic et al. 2004), taking simultaneously care that the condition of dynamic balance is constantly satisfied. This approach is also convenient because it encompasses the cases when a situation arises when small modifications of the basic gait regime are needed to adapt to the momentary requirements imposed on the biped system. We believe that, at least in some basic cases, it is not necessary to perform a new nominal synthesis but is possible to do on-line modification of the existing nominal.

2. Mechanism Structure and its Nominal Motion

Our idea was tested on the example of a locomotion mechanism (Fig. 1) having 20 DOFs, with all joints being rotational (Vukobratovic et al. 1990). Between two joints is placed one link. A joint having more DOFs is modeled as a set of simple rotational joints, each having only one DOF. In the case of a multi-DOF joint, modeling the links between single-DOF joints are considered as being of zero length, mass and moments of inertia. In Fig. 1, these "fictitious" links are denoted by dashed line (for example link 3 at the ankle joint, links 6 and 7 at the hip joint of the right leg, etc.). Accordingly, the ankle joint having 2 DOFs is represented by joints 3 and 4 (the joint axes are defined by the unit vectors e_3 and e_4), hip joint of the right leg by joints 6, 7 and 8, trunk joint (waist) by joints 15 and 16. All other joints are modeled as simple rotational joints having one DOF.

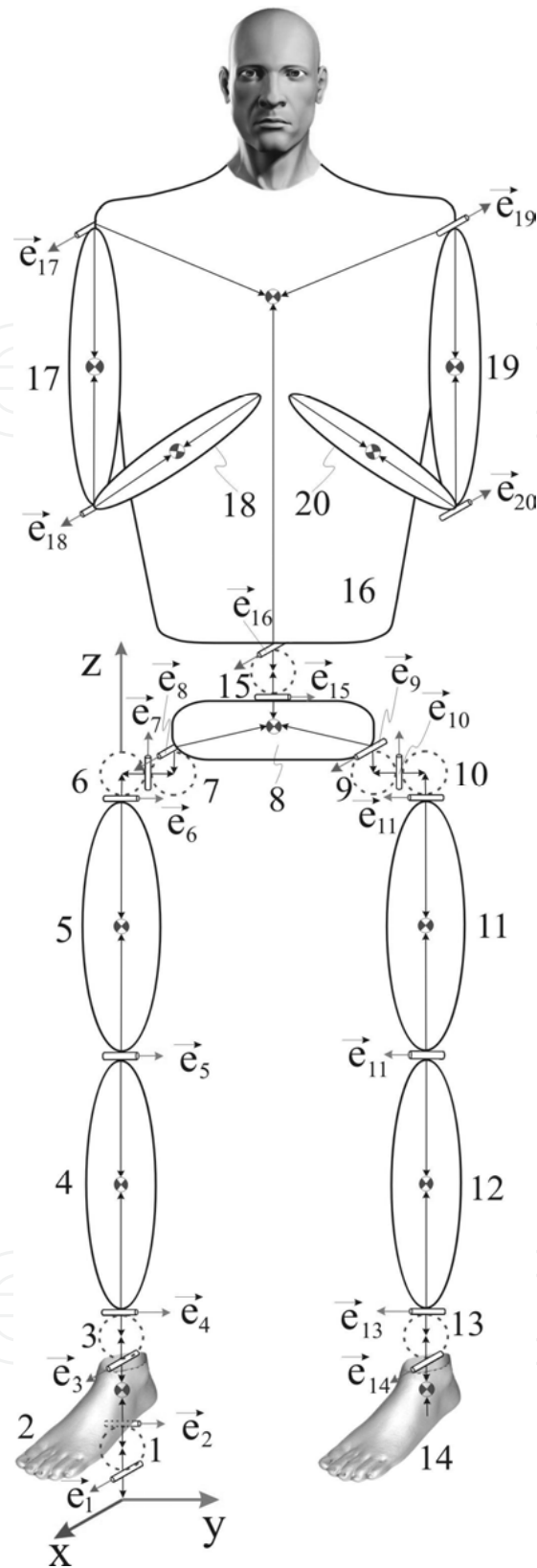


Figure 1. Scheme of locomotion mechanism

The possibility of the mechanism's overturning about the foot edge is modeled by two "fictitious" joints in the directions of the axes x and y to detect if the mechanism as a whole will rotate in the y - z or x - z plane. Each mechanism joint is powered by a DC motor except for joints 1 and 2 under the foot, which represent unpowered DOFs. All parameters of the mechanism can be found in [4]. The mechanism motion is synthesized using semi-inverse method, whereby dynamic balance is permanently ensured during the walk

(Vukobratovic et al. 1990). Legs' motion pattern was obtained by recording the performance of a human subject, and then, the trunk motion was synthesized in such a way to ensure that ground reaction force under the foot is in a certain predefined position (in our example this is the point O of the coordinate system Oxyz), ensuring simultaneously that horizontal components of the ground reaction moment are equal to zero, i.e. $M_x=M_y=0$. As was already said, this point is known as ZMP. Each change of the dynamics above the supporting foot causes displacement of the ZMP out of its nominal position. Walk synthesis has been carried out for one half-step of the single-support phase only. The mechanism walks in such a way that while one leg is in support phase the other one is transferred from the back to front position. When it reaches the position just above the ground floor the supporting foot is changed and the walk continues. Footprints of the mechanism nominal motion (ZMP nominal positions) are presented in Fig. 2.

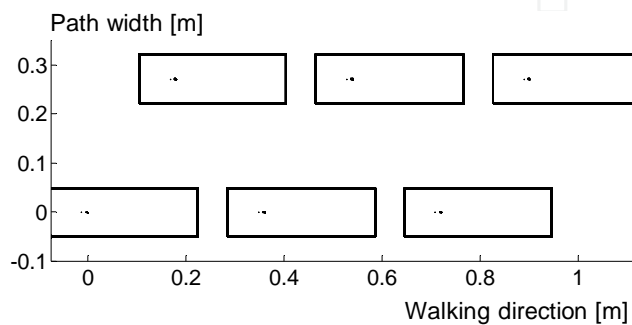


Figure 2. Mechanism footprints and ZMP positions during nominal motion

If during the walk the ZMP position comes out of the support polygon, this means that the mechanism is not performing dynamically balanced gait any more, and it collapses by rotating about the foot edge. ZMP position, being very sensitive to the changes of dynamics of the mechanism above the foot, is the best indicator of the overall mechanism dynamic balance. In Fig. 3. is shown a stick diagram of the mechanism performing nominal motion.

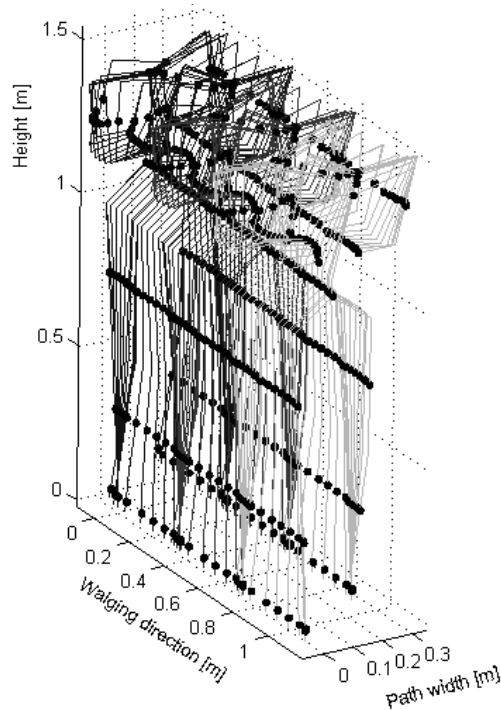


Figure 3. Stick diagram of the mechanism performing nominal motion

3. Modification of the Nominal Motion

3.1 Turning

The nominal motion modification to be considered first is the change of the walk direction. Namely, very often there arises a need to switch from a rectilinear motion to the right/left direction without interrupting the walk, so that it would be highly desirable to achieve such a gait by modifying the nominal rectilinear motion.

A first thing to be considered is how to perform turning. The angle α formed between the foot at the end of a single-support phase and the foot that up to that moment was in contact with the ground will be adopted as the measure of the extent of turning.

A smaller α corresponds to a “milder” and a larger to a “sharper” turning. Besides, care should be exercised as to the relative position of the mechanism’s feet (legs) with respect to the “body”. In the case of the mechanism used (see Fig. 2) the turning will be realized by rotation at joints 7 and 10, so that both joints are activated simultaneously. A simplest algorithm would be to perform turning so that in each half-step the leg being in the swing phase rotates so that the foot that is making contact with the ground forms an angle α with respect to the foot that was previously in contact with the ground. However, this algorithm did not perform well since the “outer” and “inner” leg followed the arcs of different lengths so that a situation evolved soon when the motion could not be continued at all.

A solution to this problem would be to perform deflection in the first half-step, and in the second half-step the correction of deviation due to the foot rotation, so that in the beginning of the next step the feet are not deflected with respect to the trunk.

The next thing to be considered is the way in which foot turning by the angle α will be realized – whether once or incrementally in the course of the whole half-step, so that at the end the foot deflects by the full value of the angle α . In the present work we chose gradual increase of the turning angle.

Let the desired value of foot deflection at the end of a half-step be defined by the angle α . If the number of integration intervals during a half-step is n_{int} the value of deflection angle to be realized in one integration interval is $\Delta\alpha = \alpha/n_{\text{int}}$. This value is halved and the value $(\Delta\alpha/2)$ is added to each of joints 7 and 10. Let us explain this on the example of turning to the left, as shown in Fig. 4. During the first half-step, the right leg is in the support and the left leg in the swing phase. The angles are added in the following way:

$$\begin{aligned} \text{angle}7 &= \text{angle}7_{\text{nom}} + i \cdot (\Delta\alpha/2) \\ \text{angle}10 &= \text{angle}10_{\text{nom}} + i \cdot (\Delta\alpha/2) \end{aligned} \quad (1)$$

where i denotes ordinal number of the integration interval while $\text{angle}7_{\text{nom}}$ and $\text{angle}10_{\text{nom}}$ are angle values for nominal motion. In the end of this phase, the left foot is deflected relative to the right foot by the angle α (note that first and second footsteps are not parallel). In the second half-step, to compensate for the deviation of legs' positions relative to the mechanism body, the hip positions change in the following way:

$$\begin{aligned} \text{angle}7 &= -(\text{angle}7_{\text{nom}} + i \cdot (\Delta\alpha/2)) \\ \text{angle}10 &= -(\text{angle}10_{\text{nom}} + i \cdot (\Delta\alpha/2)) \end{aligned} \quad (2)$$

In the end of the second half-step the right foot becomes parallel to the left foot. After that, the procedure continues and the left foot angle relative to its previous position increases again, the right foot compensates for this deviation, and so on.

In the following figures are given examples of the algorithm application. In Figs. 4, 5 and 6 are presented footprints for the angle α of 5°, 15° and 25°, respectively, to illustrate how the change of walking direction affects dynamic balance of nominal motion. From Fig. 4 it is clear that the ZMP is close to its nominal position (far enough from the foot edge), and no compensation is needed. However, as is evident from Figs. 5 and 6 that, when the angle α increases the ZMP deviation from its nominal position increases too. In Fig. 5, it is very close to the foot edge, while in Fig. 6 it goes out of the support polygon and correction of ZMP position is necessary. To compensate for ZMP deviation we propose to add a permanent gravitational moment which can be produced by body inclination. Now, a question arises as to the choice of the joint most suitable for this operation. We investigated all possibilities (trunk, hip, and ankle) and found that the compensation by the ankle gave the best results.



Figure 4. Mechanism footprints when α is 5°. No compensation applied

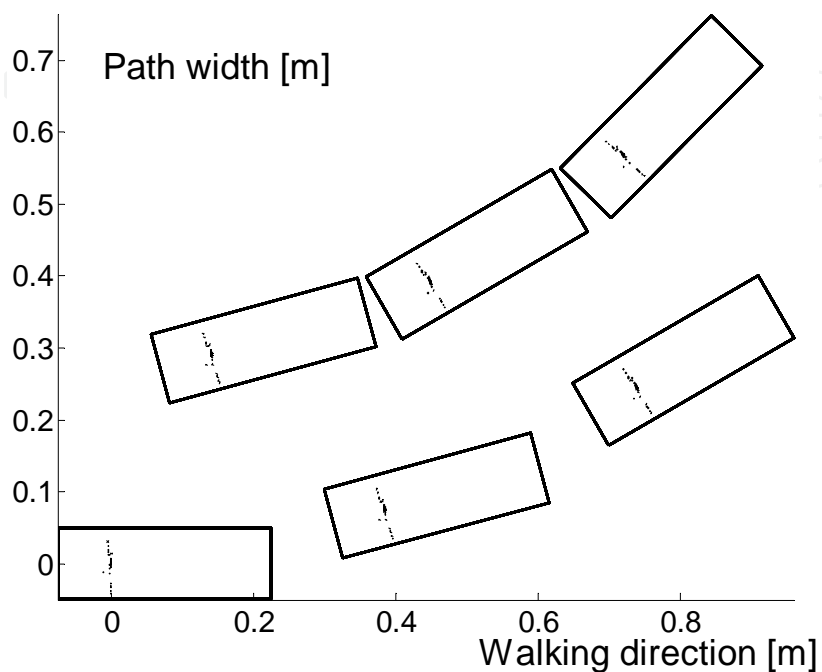


Figure 5. Mechanism footprints when α is 15°. No compensation applied.

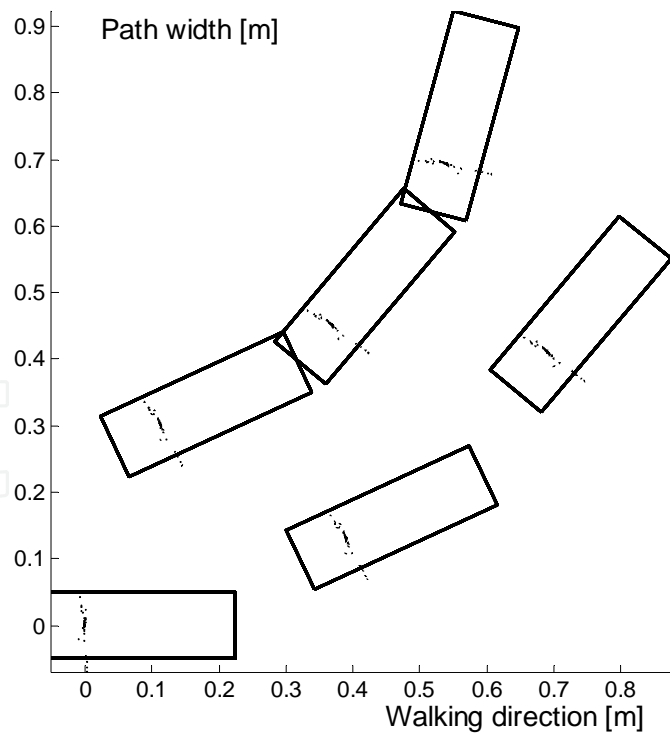


Figure 6. Mechanism footprints when α is 25° . No compensation applied.

In Fig. 7 are given footprints for the same case as shown in Fig. 6 ($\alpha = 25^\circ$) but with the compensation of 3° at joint 3. It can be seen that the ZMP position deviations are significantly reduced and that all ZMP positions are within the support polygon. Thus, by such compensation, dynamic balance is preserved and the walk continuation is ensured.

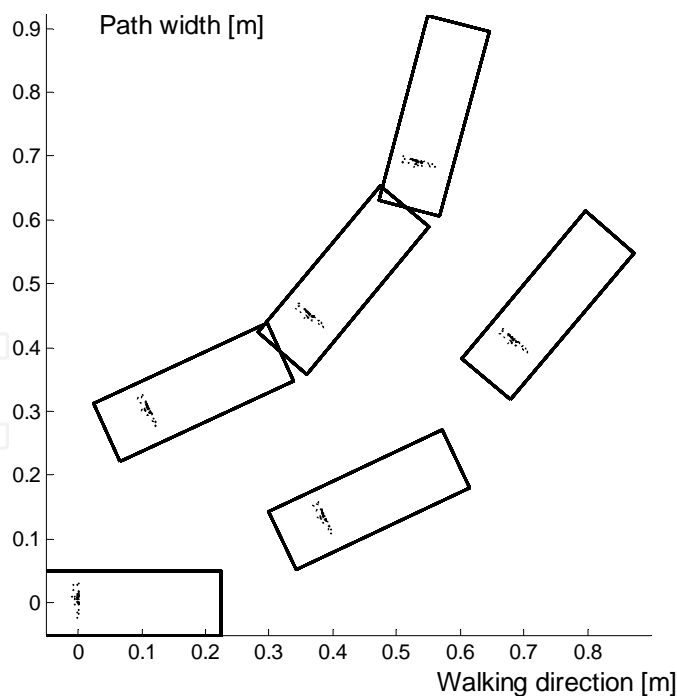


Figure 7. Mechanism footprints when α is 25° . Compensation at the ankle joint (joint 3) 3° .

3.1 Walk Speed-Up and Slow-Down

The next case we investigated was how to speed up and slow down the walk. Nominal motion was the same as before. To change walking speed, moments applied at all joints have to be changed. To avoid recomputing the complete dynamics we used the procedure

proposed by Hollerbach (1984) for changing robotic mechanism motion speed without recomputing completely its dynamics.

Let us remind that the mechanism dynamics is given in the following general form:

$$\tau = H(q)\ddot{q} + h(\dot{q}) + G \quad (3)$$

where τ is the vector of driving torques at joints; q , \dot{q} and \ddot{q} are the vectors of joint angles, velocities and accelerations, respectively; $H(q)$ and $h(\dot{q})$ are the inertial matrix and the vector that includes all velocity effects, while the vector G represents gravitational moments. Gravitational forces and their moments do not depend on motion speed. Thus, in (3) we can separate the moments that are acceleration and velocity-dependent from those which are not. If we denote by τ_n the acceleration- and velocity-dependent torques of non-accelerated motion and by τ_a those of accelerated motion, then the following relation (Hollerbach J. M. 1984) will hold:

$$\tau_a(t) = c^2 \cdot \tau_n(ct) \quad (4)$$

whereby $c > 1$ stands for the accelerated and $c < 1$ for decelerated motion.

We applied this method to investigate how the acceleration/deceleration of nominal (dynamically balanced) walk would affect its dynamic balance. In Figs. 8-12 are shown the cases of walk speeding up for various values of c .

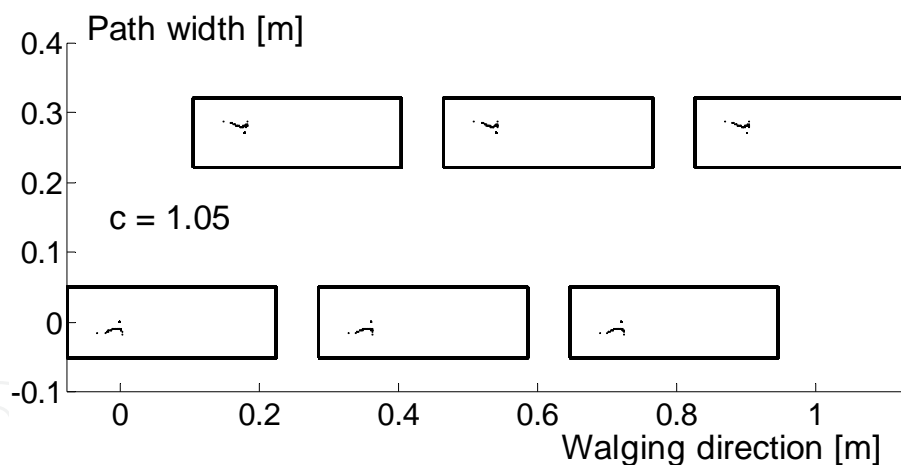


Figure 8. Mechanism footprints of accelerated motion for $c = 1.05$. No compensation applied.

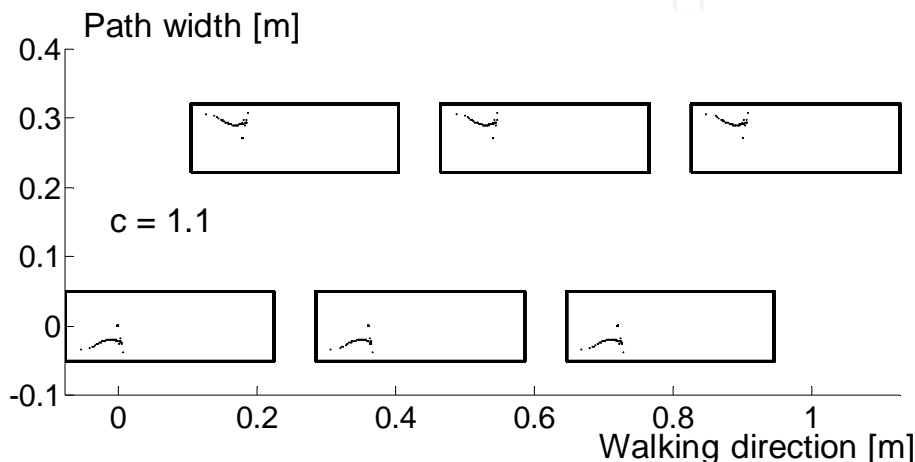


Figure 9. Mechanism footprints of accelerated motion for $c = 1.1$. No compensation applied.

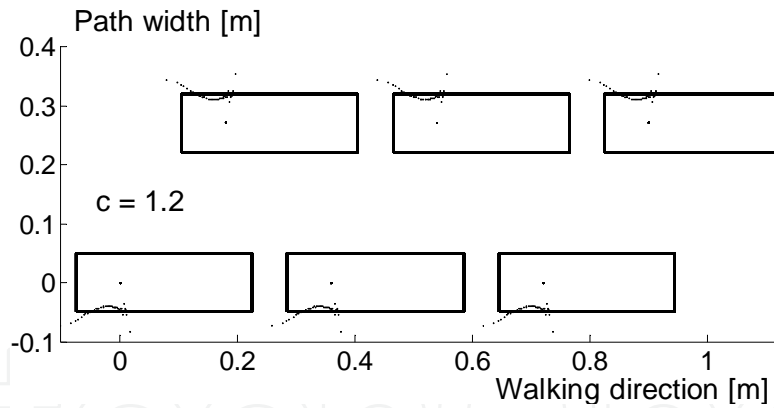


Figure 10. Mechanism footprints of accelerated motion for $c = 1.2$. No compensation applied.

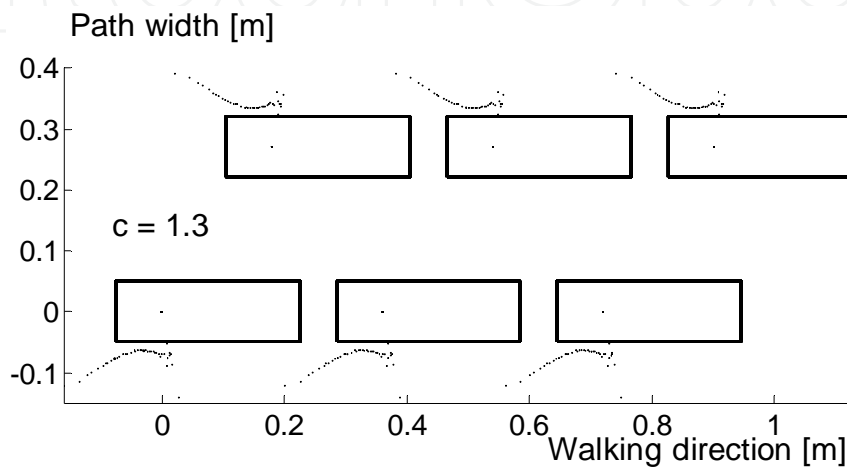


Figure 11. Mechanism footprints of accelerated motion for $c = 1.3$. No compensation applied.

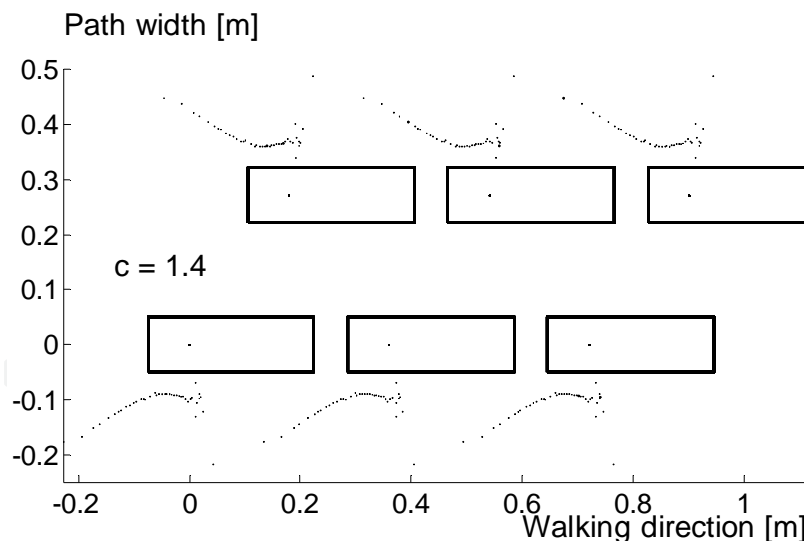


Figure 12. Mechanism footprints of accelerated motion for $c = 1.4$. No compensation applied.

The presented figures illustrate well the importance of the altered mechanism dynamics on the ZMP position. For $c > 1.1$ (Figs. 10 - 12) it is clear that the ZMP is out of the support polygon and that the mechanism's dynamic balance is not preserved. To make possible continuation of the walk it is necessary to correct the ZMP position.

To achieve this we applied the same strategy as before - inclination of the body. In Figs. 13-17 are presented the correction effects when compensation was performed by joints 3 and 4 (ankle). Joint 3 compensated for deviations in the sagittal and joint 4 in the frontal plane.

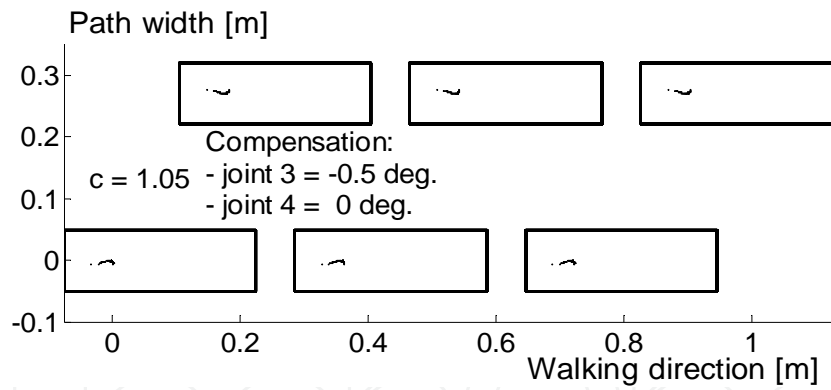


Figure 13. Mechanism footprints of accelerated motion for $c = 1.05$. Compensation of -0.5° applied at joint 3; no compensation at joint 4.

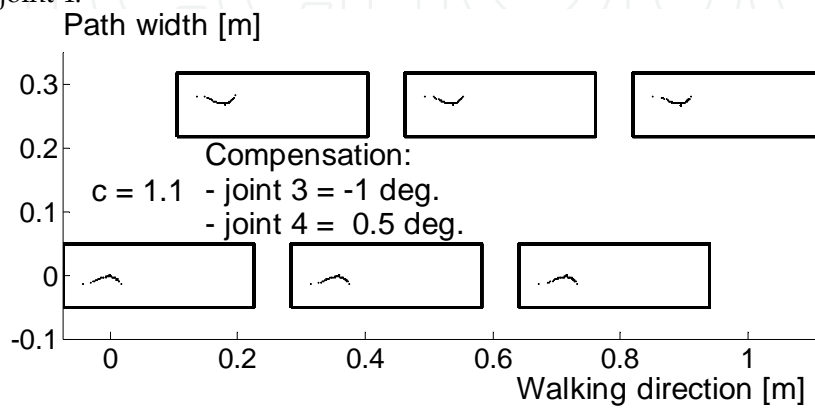


Figure 14. Mechanism footprints of accelerated motion for $c = 1.1$. Compensation of -2° applied at joint 3, of 0.5° at joint 4.

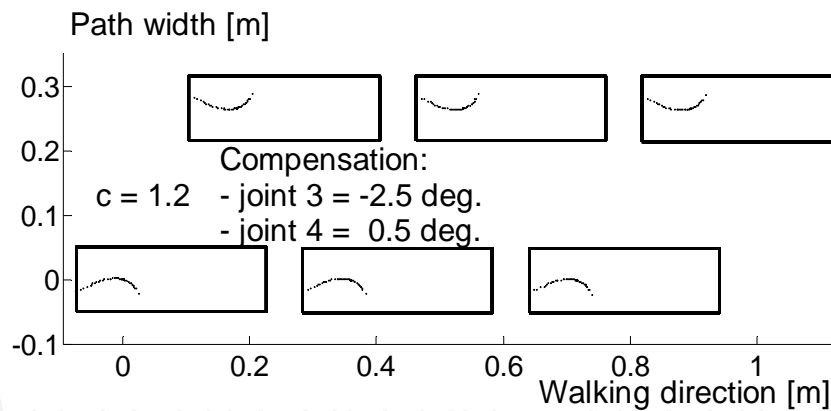


Figure 15. Mechanism footprints of accelerated motion for $c = 1.2$. Compensation of -2.5° applied at joint 3, of 0.5° at joint 4.

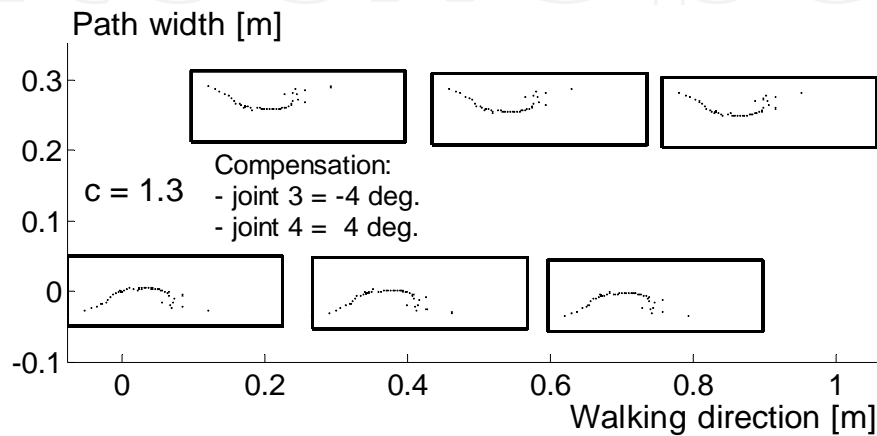


Figure 16. Mechanism footprints of accelerated motion for $c = 1.3$. Compensation of -4° applied at joint 3, of 4° at joint 4.

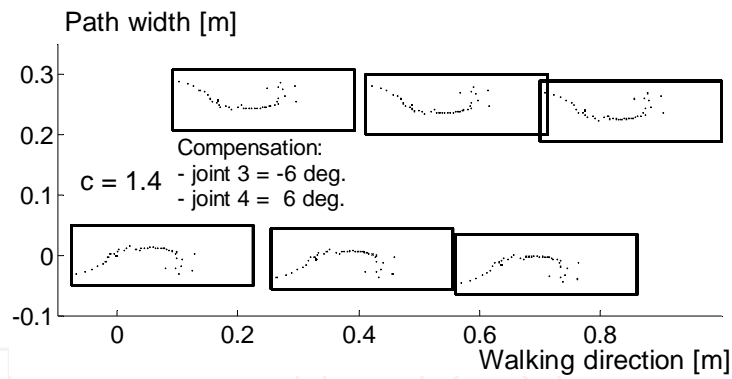


Figure 17. Mechanism footprints of accelerated motion for $c = 1.4$. Compensation of -6° applied at joint 3, of 6° at joint 4.

The presented examples show that the corrections made by the ankle joint brought the ZMP back to the support polygon. Figs. 18-22 illustrate the situations when the ZMP deviation was compensated by the trunk joints (joints 15 and 16).

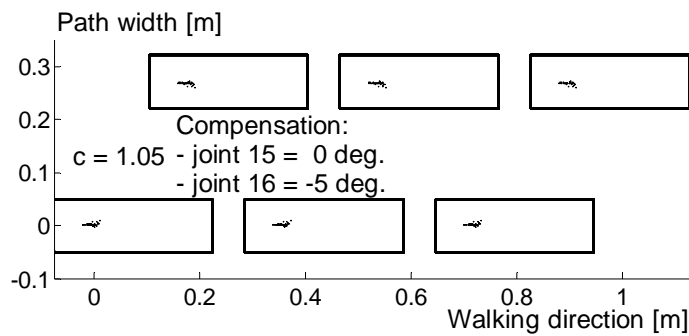


Figure 18. Mechanism footprints of accelerated motion for $c = 1.05$. Compensation of 0° applied at joint 15, of -5° at joint 16.

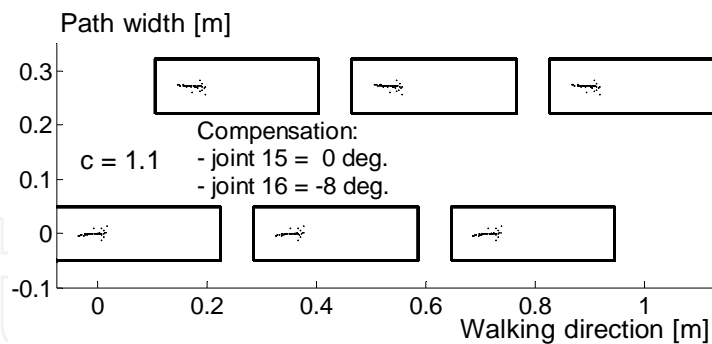


Figure 19. Mechanism footprints of accelerated motion for $c = 1.1$. Compensation of 0° applied at joint 15, of -8° at joint 16.

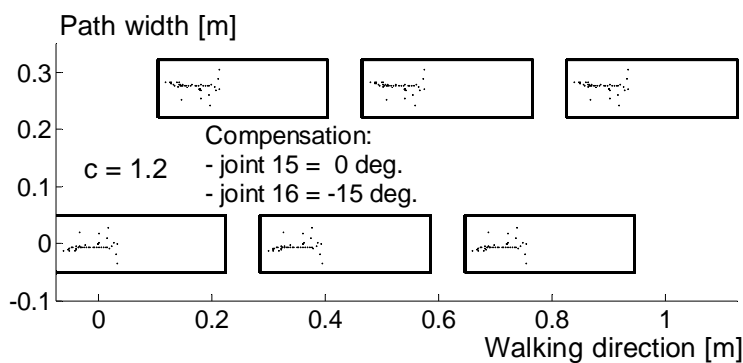


Figure 20. Mechanism footprints of accelerated motion for $c = 1.2$. Compensation of 0° applied at joint 15, of -15° at joint 16.

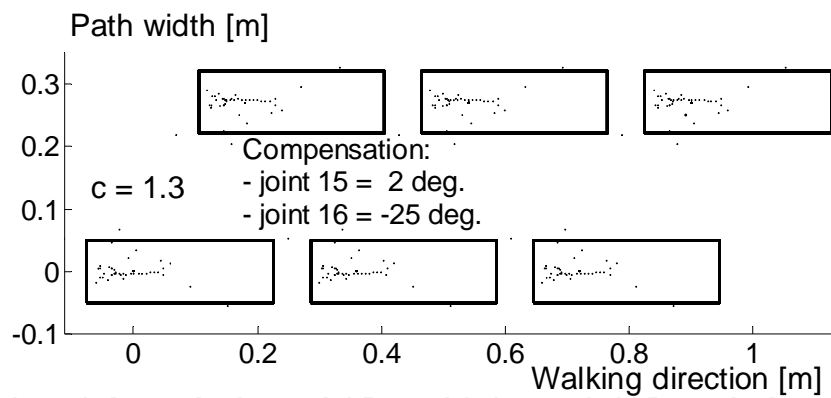


Figure 21. Mechanism footprints of accelerated motion for $c = 1.3$. Compensation of 2° applied at joint 15, of -25° at joint 16.

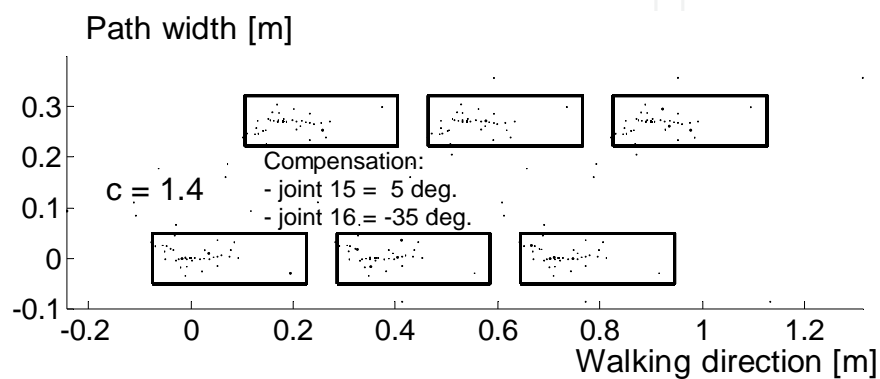


Figure 22. Mechanism footprints of accelerated motion for $c = 1.4$. Compensation of 5° applied at joint 15, of -35° at joint 16.

It is evident that much larger inclination angles are needed for compensation performed by the trunk compared to ankle joint (35° compared to 6° for $c = 1.4$). Such large compensation inclinations may jeopardize the anthropomorphism of the walk. Besides, in case of compensation by the trunk for $c = 1.3$ and 1.4 the ZMP positions were not brought completely back to the support polygon. Hence, it is clear that compensation by the ankle joint is more efficient.

In Figs. 23-27 are presented examples of decelerated motion ($c = 0.95 - 0.5$). It is evident that spatial dissipation of the ZMP trajectory is lower. This can be explained by the diminished overall influence of inertial forces, so that the ZMP trajectory converges to the trajectory of the system's gravity center, which is a sinusoid lying symmetrically between the mechanism's footprints.

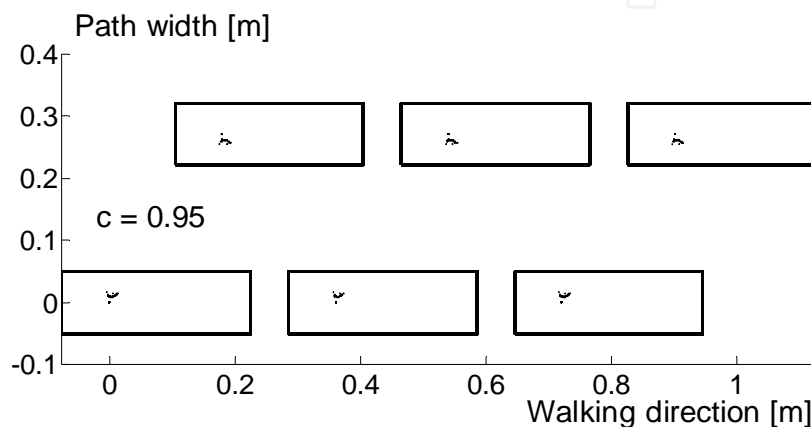


Figure 23. Mechanism footprints of decelerated motion for $c = 0.95$. No compensation applied.



Figure 24. Mechanism footprints of decelerated motion for $c = 0.9$. No compensation applied.



Figure 25. Mechanism footprints of decelerated motion for $c = 0.8$. No compensation applied.

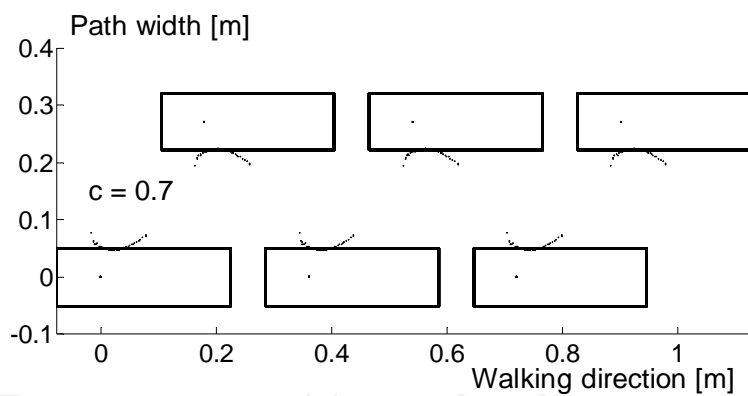


Figure 26. Mechanism footprints of decelerated motion for $c = 0.7$. No compensation applied.



Figure 27. Mechanism footprints of decelerated motion for $c = 0.6$. No compensation applied.

To compensate for ZMP deviations we applied again the same strategy, i.e. body inclination. As can be seen, in both cases compensation (by the ankle (Figs 28-32) and the trunk joint (Figs. 33-37)) was successful.

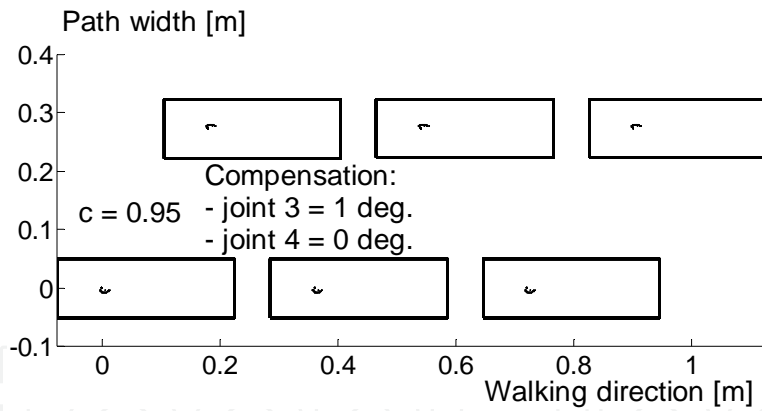


Figure 28. Mechanism footprints of decelerated motion for $c = 0.95$. Compensation of 1° applied at joint 3; no compensation at joint 4.

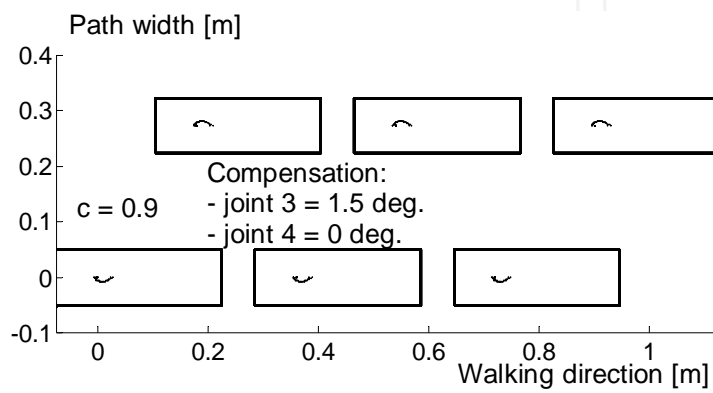


Figure 29. Mechanism footprints of decelerated motion for $c = 0.9$. Compensation of 1.5° applied at joint 3; no compensation at joint 4.

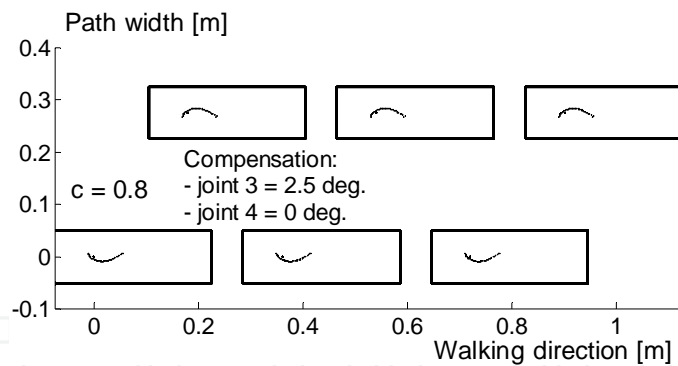


Figure 30. Mechanism footprints of decelerated motion for $c = 0.8$. Compensation of 2.5° applied at joint 3; no compensation at joint 4.

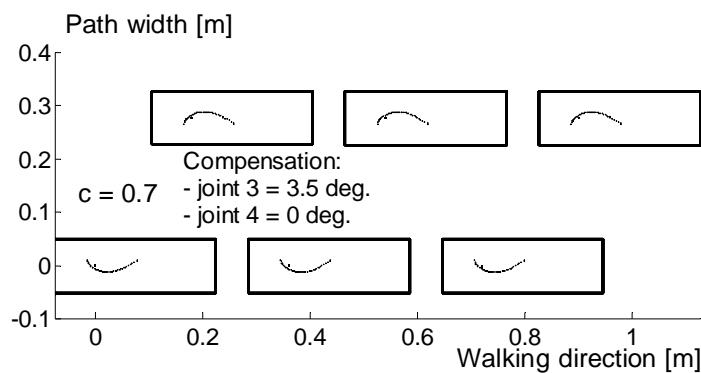


Figure 31. Mechanism footprints of decelerated motion for $c = 0.7$. Compensation of 3.5° applied at joint 3; no compensation at joint 4.

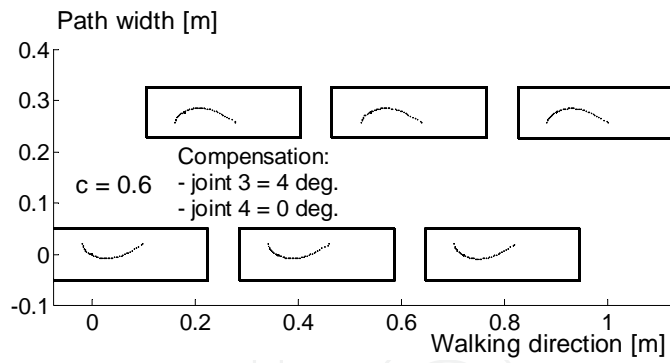


Figure 32. Mechanism footprints of decelerated motion for $c = 0.6$. Compensation of 4° applied at joint 3; no compensation at joint 4.

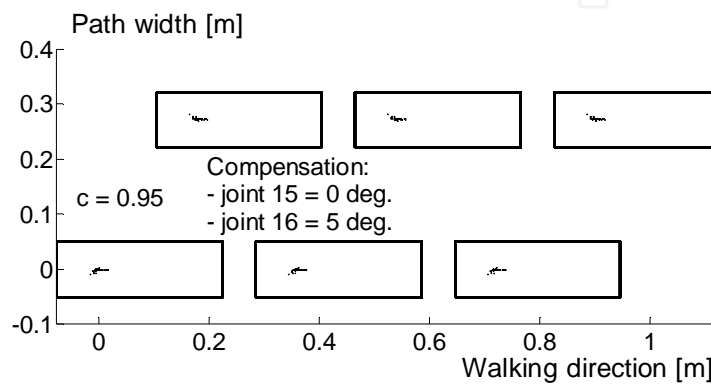


Figure 33. Mechanism footprints of decelerated motion for $c = 0.95$. Compensation of 0° applied at joint 15, of 5° at joint 16.

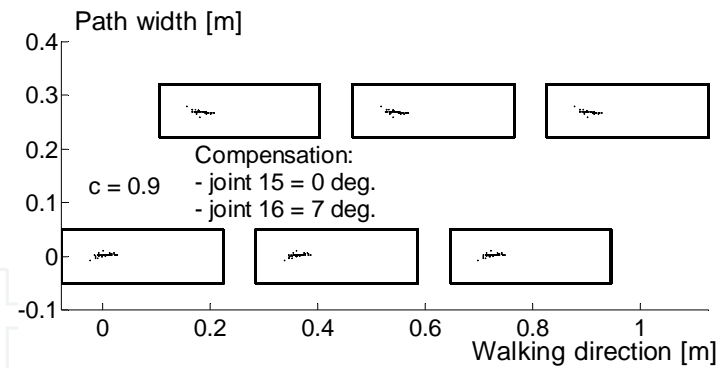


Figure 34. Mechanism footprints of decelerated motion for $c = 0.9$. Compensation of 0° applied at joint 15, of 7° at joint 16.

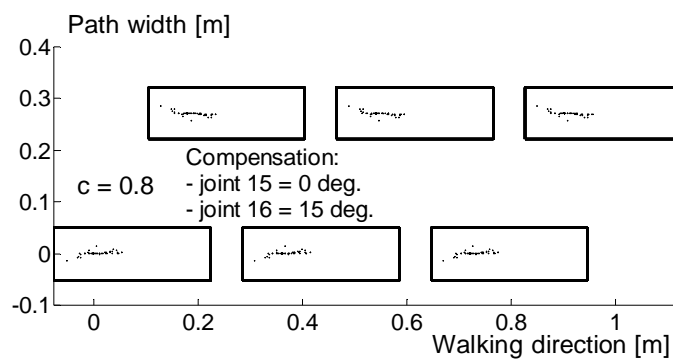


Figure 35. Mechanism footprints of decelerated motion for $c = 0.8$. Compensation of 0° applied at joint 15, of 15° at joint 16.

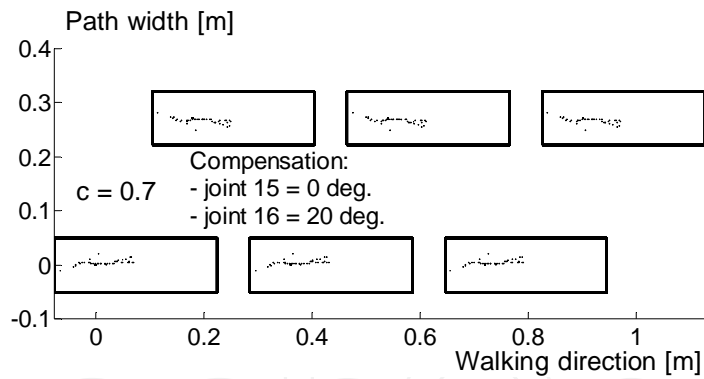


Figure 36. Mechanism footprints of decelerated motion for $c = 0.7$. Compensation of 0° applied at joint 15, of 20° at joint 16.

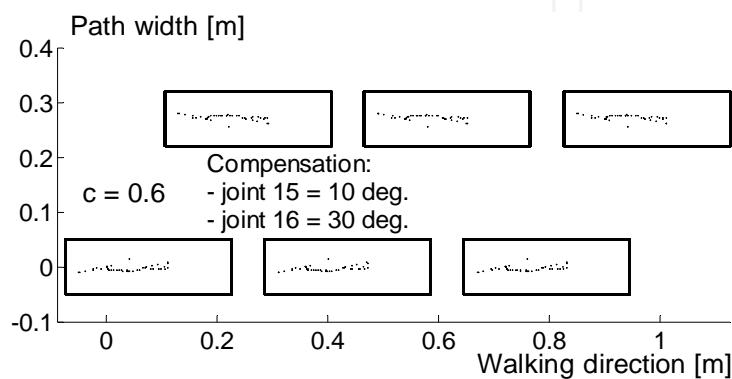


Figure 37. Mechanism footprints of decelerated motion for $c = 0.6$. Compensation of 10° applied at joint 15, of 30° at joint 16.

Dispersion of ZMP positions is smaller in case of compensation performed by the ankle joint. Thus, it can be concluded that although both joints are suitable for compensation in case of deceleration, the ankle is advantageous over the trunk.

3.3 Step Extension

The next basic modification of the nominal walk is change of step length. In this paper step extension will be considered, only. To extend step maximal angle between two legs for nominal step (in Fig. 38 denoted by β_{nom}) should be enlarged.

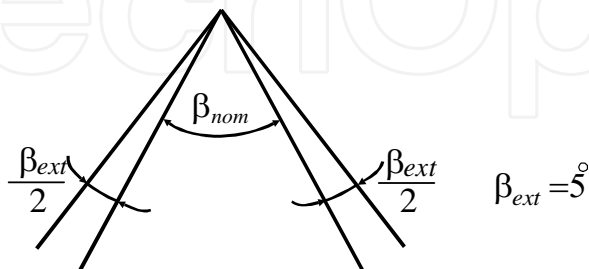


Figure 38. Angles β_{nom} and β_{ext}

Let us denote total value of the added angle as β_{ext} . Total amount of β_{ext} is divided between two hip joints (joint 6 for the right, joint 11 for left leg) and, accordingly, $\beta_{ext}/2$ is added per each leg. Thus, maximal angle between the legs for an extended step is $\Delta\beta = \beta_{ext}/n_{int}$. As in the case of turning, the angle beta should be enlarged gradually. This means that in each sampling time actual value of angles 6 and 11 is enlarged by

$\Delta\beta = \beta_{ext}/n_{int}$, where n_{int} is the number of integration intervals during a half-step:

$$\begin{aligned} angle6 &= angle6_{nom} + i \cdot (\Delta\beta/2) \\ angle11 &= angle11_{nom} + i \cdot (\Delta\beta/2) \end{aligned} \quad (5)$$

where, again, i denotes ordinal number of the integration interval while $angle6_{nom}$ and $angle11_{nom}$ are the angle values for nominal motion. Of course, to preserve position of the foot relative to the ground, ankle joints 4 and 13 should be corrected accordingly.



Figure 39. Extended step

In Fig. 39 are given footprints for such extended gait. Dashed line denotes the footsteps of the nominal gait, solid line of the enlarged stride. It can be noticed that the ZMP position deviates along the footprint axis and, actually, no correction is needed.

4. Combination of Basic Modifications of the Nominal Gait

4.1 Step Extension and Speed-Up for Rectilinear and Turning Motion

In the following section we will show how the basic modifications already described can be combined simultaneously.

In Figs. 40-47 are given examples of the combination of basic modifications for rectilinear motion: gait speed-up and step extension (the same as in the example shown in Fig. 39). In Figs. 40, 42, 44 and 46 are given examples of non-compensated and in Figs. 41, 43, 45 and 47 of compensated motion. Step extension was combined with gait speed-up, for $c = 1.1$, $c = 1.2$, $c = 1.3$ and $c = 1.4$.

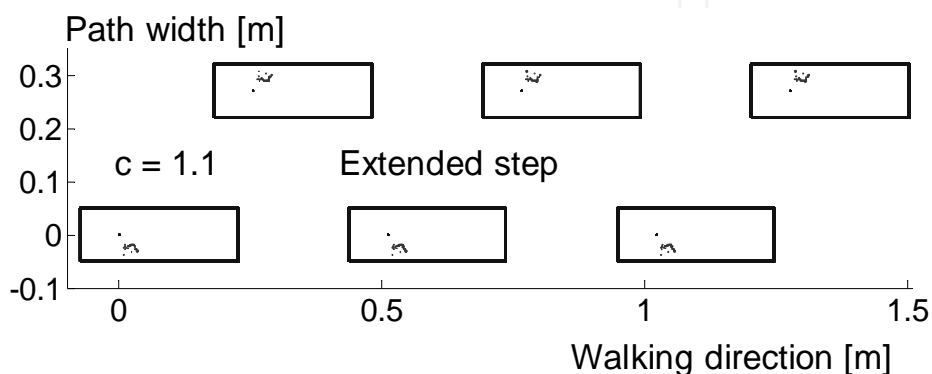


Figure 40. Mechanism footprints of extended step and accelerated motion for $c = 1.1$. No compensation applied.

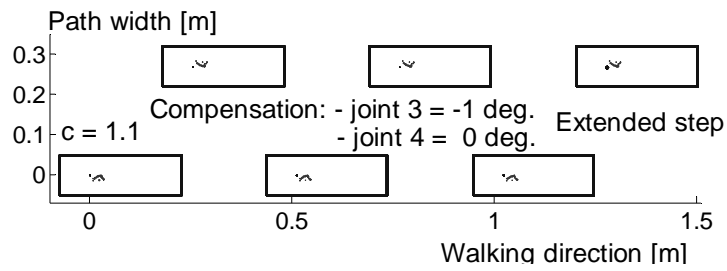


Figure 41. Mechanism footprints of extended step and accelerated motion for $c = 1.1$. Compensation of -1° applied at joint 3, of 0° at joint 4.

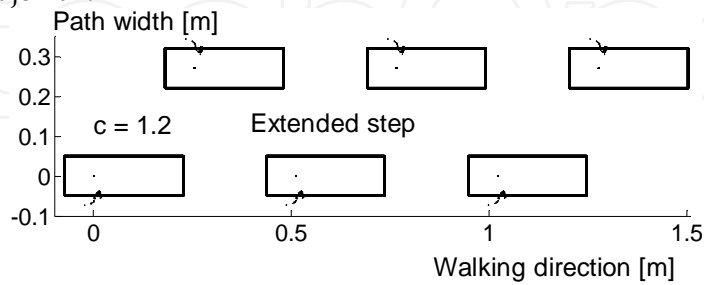


Figure 42. Mechanism footprints of extended step and accelerated motion for $c = 1.2$. No compensation applied.

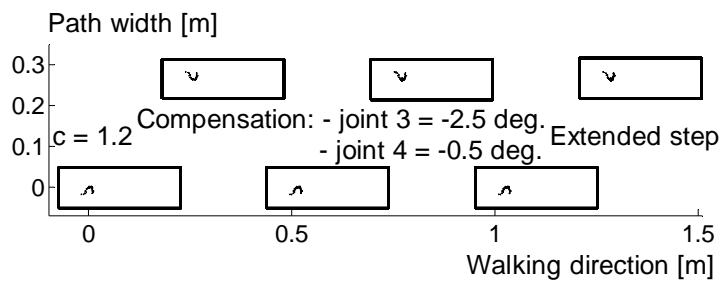


Figure 43. Mechanism footprints of extended step and accelerated motion for $c = 1.2$. Compensation of -2.5° applied at joint 3, of -0.5° at joint 4.

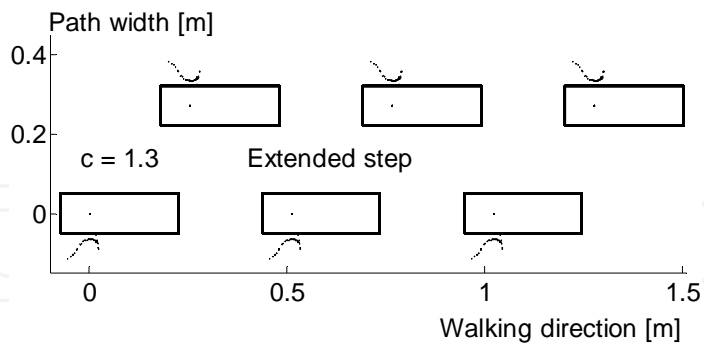


Figure 44. Mechanism footprints of extended step and accelerated motion for $c = 1.3$. No compensation applied.

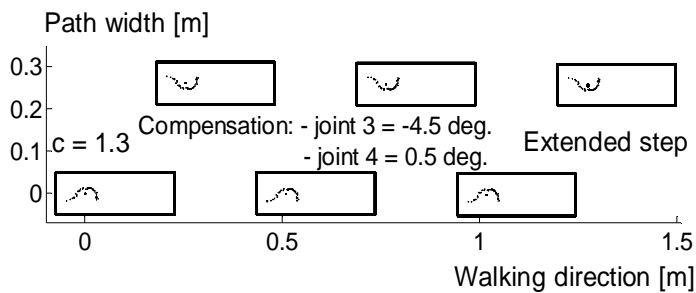


Figure 45. Mechanism footprints of extended step and accelerated motion for $c = 1.3$. Compensation of -4.5° applied at joint 3, of 0.5° at joint 4.

It is again demonstrated that simple inclination at the appropriately selected joint (the ankle joint is again used for compensation) can ensure dynamic balance in spite of the ZMP displacement, even in the case of such step extension as shown in Fig. 46.

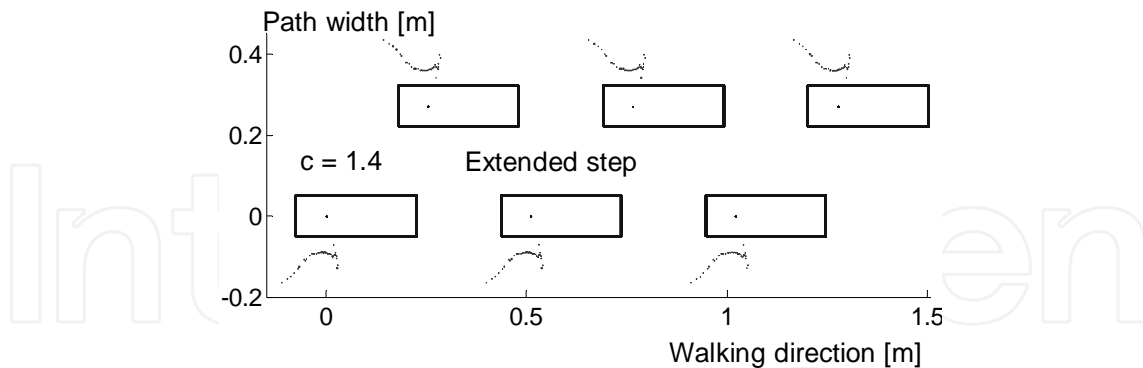


Figure 46. Mechanism footprints of extended step and accelerated motion for $c = 1.4$. No compensation applied.

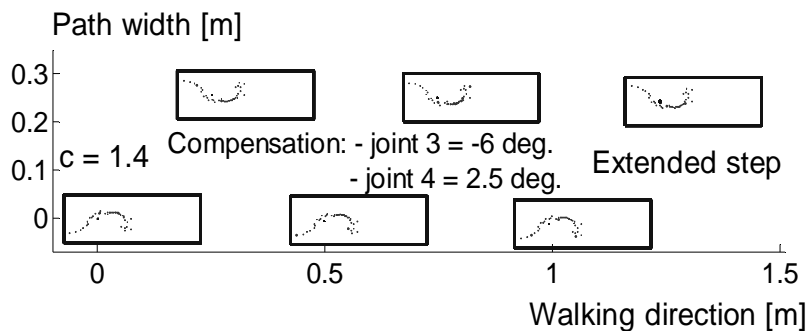


Figure 47. Mechanism footprints of extended step and accelerated motion for $c = 1.4$. Compensation of -6° applied at joint 3, of 2.5° at joint 4.

Let us investigate now the influence of the combination of combined modifications of the basic nominal. Once more, the nominal position of the ZMP is the point just below the ankle joint and any deviation from it is easily visible. Mechanism will preserve its dynamic balance (it will not fall down) if the ZMP position is within the support polygon, which in the considered examples corresponds to the footprint area. In Figs. 48-50 are shown examples of the combination of extended step and turning left with different intensities of turning without ZMP displacement compensation because the ZMP is still within the support polygon. In Figs. 51 and 53, to gait extension and turning left, accelerations of $c = 1.2$ and $c = 1.3$ are added.

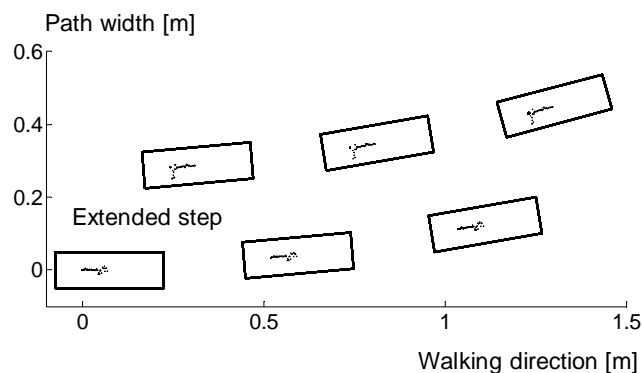


Figure 48. Mechanism footprints of extended step in turning left when α is 5° . No compensation applied.

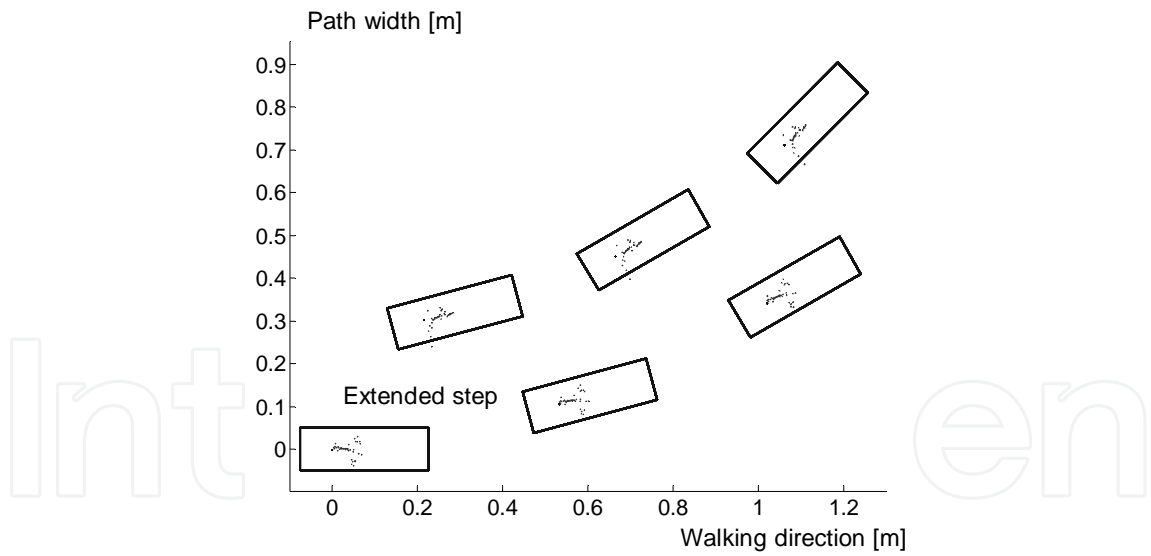


Figure 49. Mechanism footprints of extended step in turning left when α is 15° . No compensation applied.

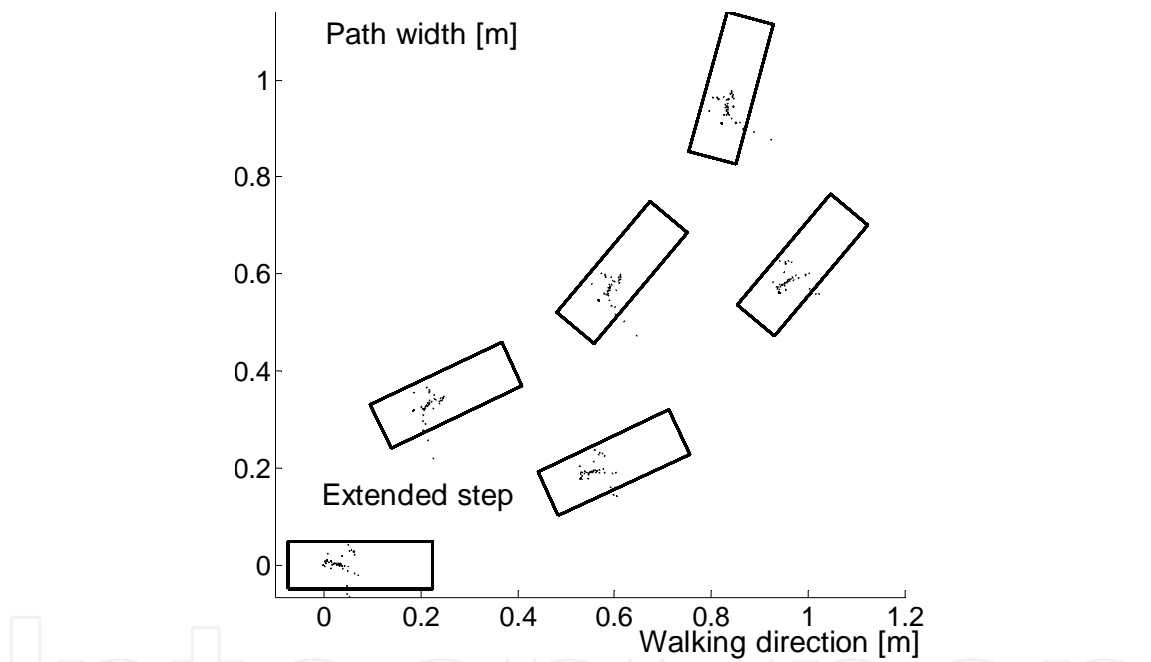


Figure 50. Mechanism footprints of extended step in turning left when α is 25° . No compensation applied.

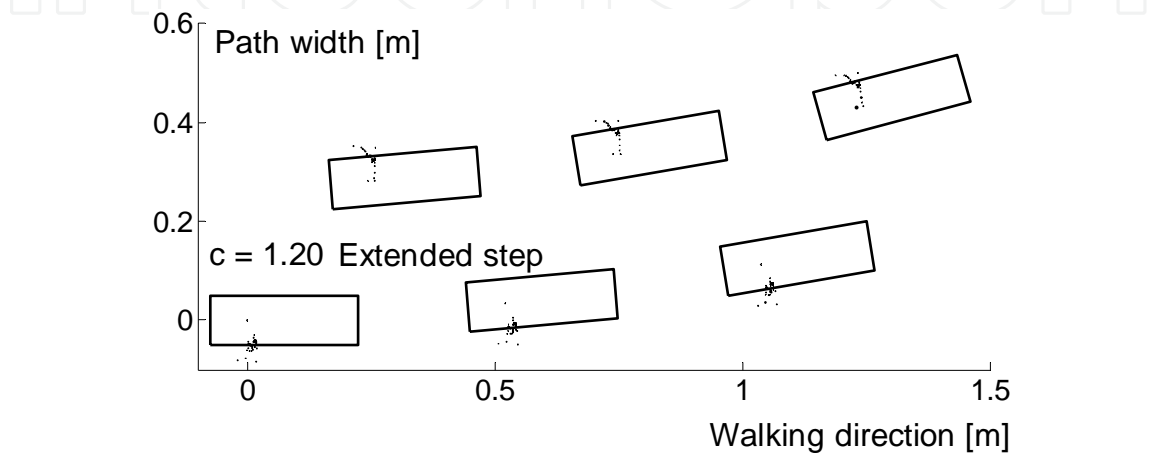


Figure 51. Mechanism footprints of extended step in turning left when α is 5° and accelerated motion for $c = 1.2$. No compensation applied.

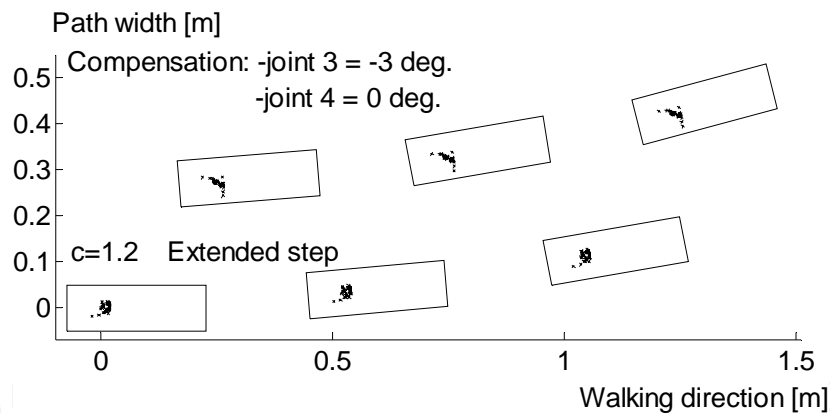


Figure 52. Mechanism footprints of extended step in turning left when α is 5° and accelerated motion for $c = 1.2$. Compensation of -3° applied at joint 3, of 0° at joint 4.

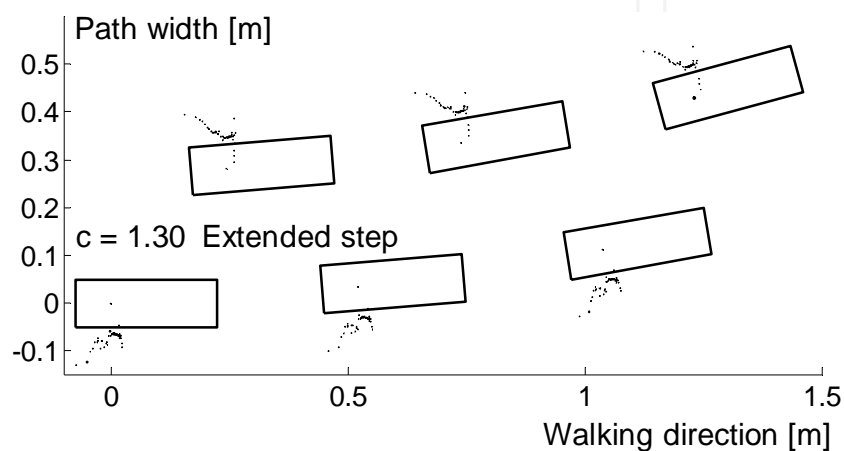


Figure 53. Mechanism footprints of extended step in turning left when α is 5° and accelerated motion for $c = 1.3$. No compensation applied.

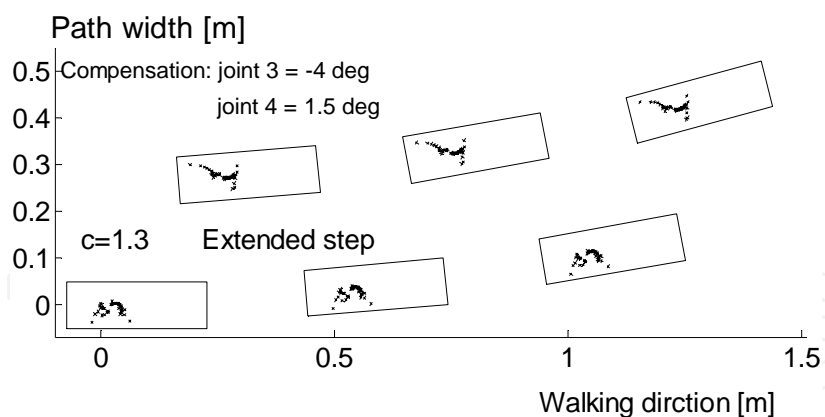


Figure 54. Mechanism footprints of extended step in turning left when α is 5° and accelerated motion for $c = 1.3$. Compensation of -4° applied at joint 3, of 1.5° at joint 4.

In Figs. 52 and 54 is shown the situation when the same compensation strategy was applied again. Ankle joint (joints 3 and 4) was employed for compensation in both the frontal and saggital planes. It is demonstrated again that such simple compensation strategy works well in this case too.

5. Conclusions

The future will bring about the growing application of humanoid robots, which will be increasingly more engaged in the close living and working environment of humans. This

fact inevitably leads to sharing their common working environment and the need of “working coexistence” of man and robot. Besides, the human environment, which is highly adapted to humans, is not static but a very dynamic one, so conventional procedures of planning motion trajectories will not be applicable for biped locomotion. Hence, the motion trajectories will have to be determined on the basis of a global plan of motion and instantaneous situation on the scene. Therefore, a new approach to planning biped gait is needed, which will be characterized by the possibility of fast reacting to the newly arisen situations by modifying the planned system motion, while constantly preserving its dynamic balance.

The paper describes a new approach to solving this task. One gait pattern is adopted as the basic one, and all the other gait realizations are obtained by its modification. The basic gait pattern adopted was the dynamically balanced walk (obtained by semi-inverse method) on a flat ground along a straight line, considered as a nominal gait. By appropriate modifications of the nominal gait at particular joints we achieved turning, speed-up, and slow-down motion and a combination of these basic manoeuvres. As a consequence of the modification of the basic pattern, the ZMP position changes so that even the dynamic balance of the overall system is endangered. We showed that the deviations of the ZMP position could be to a large extent compensated for simply by appropriate inclining the body. However, this inclination can jeopardize the anthropomorphism of the locomotion system, so that it is very important to select the appropriate joint for the modification realization, that is joint that will yield the dynamic balance with the least disturbance of the system anthropomorphism. Hence, this issue has received the special attention in the presented study.

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This book is the result of inspirations and contributions from many researchers worldwide. It presents a collection of wide range research results of robotics scientific community. Various aspects of current research in robotics area are explored and discussed. The book begins with researches in robot modelling & design, in which different approaches in kinematical, dynamical and other design issues of mobile robots are discussed. Second chapter deals with various sensor systems, but the major part of the chapter is devoted to robotic vision systems. Chapter III is devoted to robot navigation and presents different navigation architectures. The chapter IV is devoted to research on adaptive and learning systems in mobile robots area. The chapter V speaks about different application areas of multi-robot systems. Other emerging field is discussed in chapter VI - the human- robot interaction. Chapter VII gives a great tutorial on legged robot systems and one research overview on design of a humanoid robot. The different examples of service robots are showed in chapter VIII. Chapter IX is oriented to industrial robots, i.e. robot manipulators. Different mechatronic systems oriented on robotics are explored in the last chapter of the book.

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