Zero Moment Point—Measurements From a Human Walker Wearing Robot Feet as Shoes

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***Abstract*—The anthropomorphic biped robot Bip is equipped with sensors for measuring the ground/feet forces in order to localize the center of pressure (CoP) and zero moment point (ZMP). This paper focuses on experimental results regarding the evolution of the ground contact forces, obtained from a human walker wearing the robot feet as shoes. First, one determines the influence of heavy and rigid metallic shoes on the gait of the subject, during experiments carried out on flat ground. Second, the evolution of the contact forces is studied while walking on parallel planes with different elevations (stairs), then one addresses the case where the feet are supported by two nonparallel planes (uneven terrain). The corresponding analysis is founded on the concepts of virtual supporting surface and pseudo-CoP-ZMP introduced in a companion paper, discussing the theoretical aspects of CoP and ZMP (Sardain and Bessonnet, 2004). Beyond the academic contribution, the data analyzed in this paper could constitute an incitement to design truly anthropomorphic feet, for Bip as well as for other biped robots, because all the current robot feet are functionally rather poor.**

***Index Terms*—Biped robot, center of pressure (CoP), force sensors, motion analysis, walking gaits, zero moment point (ZMP).**

I. Introduction

THIS WORK is part of a project for the development of an anthropomorphic biped robot, Bip, involving two French laboratories, LMS and INRIA Rhône-Alpes [2], [3]. The technological construction has been completed and the robot has performed some postural motions and slow static walks [4]. The next stage is the implementation of fast and dynamic walking gaits, in other words anthropomorphic gaits. A relevant dynamic equilibrium criterion is provided by the concept of zero moment point (ZMP), described in [5]. Controllers of a lot of biped robots implement this concept, in one way or an other, as described in [6].

In the previous paper [1], we dealt with theoretical aspects of the ZMP, which is also the center of pressure (CoP), depending on the ground contact forces. In the present paper, the purpose is to present and analyze experimental data about the evolution of ground/feet forces and CoP-ZMP. Literature provides data either about human gaits, or about biped robot gaits, but in this case, experimental walks are slow or very slow, and the soles of the robots remain generally parallel to the ground. The data presented in this paper are recorded for fast dynamic walks of a human subject wearing shoes fitted with the Bip soles. Other original analyses are also presented, concerning the double support phase when the feet are in contact with two sloping planes, and on stairs.

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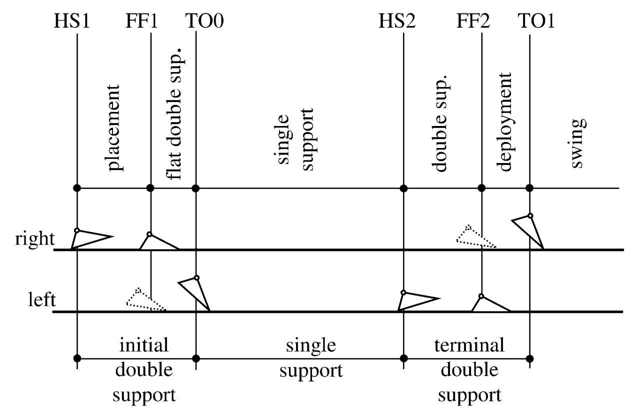

Fig. 1. Events and phases of the walk.

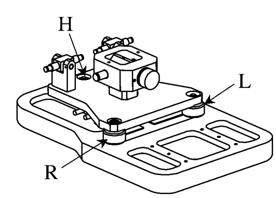

Fig. 2. Positions of the three sensors.

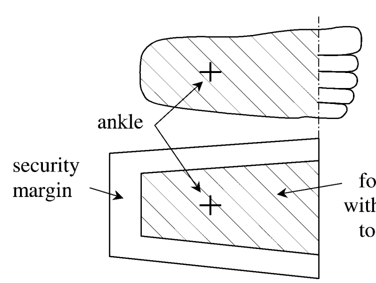

Fig. 3. Dimensioning principle of the robot sole.

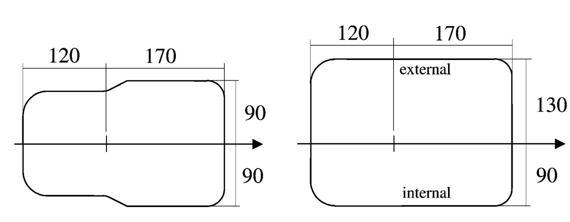

Fig. 4. (a) Bip foot. (b) Honda P2 dimensions (in millimeters).

Fig. 5. Human ankle situated at level of Bip one, front edge situated at metatarsi level.

In Section II, we define the events and phases of the walking gait that can be submitted to measurement. The experimental setup, comprising a human walker wearing the Bip soles as shoes and a force–motion analysis system, is described in Section III. The range of the results presented here is more general than the Bip case, because numerous biped robot feet look like Bip ones (rigid, wide and short). Sections IV and V are the heart of the paper. The comparison between "mechanical" and natural rapid gaits is carried out in Section IV from both the motion and the force points of view. The pressure forces are analyzed in different ways: evolution in time of forces and moments, CoP trajectories, with emphasis on the global CoP during the double support phase. Other gaits are studied in Section V, such as walk on stairs, and walk on two nonparallel planes, which are cases where the principle of CoP-ZMP is theoretically inconsistent because it relies on the existence of one single plane. The study is carried out thanks to the concept of virtual plane and pseudo CoP-ZMP we introduced in the companion paper [1].

As a conclusion, some slight modifications of the Bip feet are described, in order to get closer to natural gaits, and larger perspectives are proposed, concerning the community of biped robots developers: we hope that the data presented in this paper could be a starting point initiating the development of really anthropomorphic biped robot feet.

II. Definitions of Walk Phases

The terminology used to define the different phases of walking varies according to the disciplinary fields (such as medicine, prosthetics and orthotics, and biomechanics). The purpose of this section is to define the terms used in the analysis carried out in the paper. Walking is punctuated by events dividing the gait into different phases. Fig. 1 shows the two feet. *The comments below concern the right foot*. After the swing phase, the stance phase starts when the heel comes in contact with the ground. The walker then puts the sole flat on the ground. These two events, heel-strike and foot-flat, define the placement phase (sometimes called loading response or weight acceptance). After a rather long flat support phase (often called midstance), the walker deploys his foot, from the heel-off to the toe-off instants, this latter event marking the beginning of the swing phase (the deployment is sometimes called pushoff).

Thus, four events (heel-strike, foot-flat, heel-off, toe-off) delimit four phases for each foot and therefore there are eight events for the two feet, delimiting *a priori* eight phases for the global gait. In fact, only four principal phases are often considered [7]: 1) initial double support, with weight transfer from left to right side, going from the right heel-strike to the left toe-off; 2) single support on the right leg; 3) terminal double support, with weight transfer from right to left side; and 4) swing of the right leg (single support on the left leg).

With our experimental material, heel-strike, foot-flat, and toe-off events appear clearly. Therefore, we suggest that six events for the two legs should be considered (see Fig. 1): 1) heel-strike of the right foot HS_1; 2) foot-flat of the right foot FF_1; 3) toe-off of the left (rear) foot TO_0; 4) heel-strike of the left (front) foot HS_2; 5) foot-flat of the left (front) foot FF_2; and 6) toe-off of the right foot TO_1. Notice that subscripts are related to successive supports (0: rear left foot, 1: right foot, 2: front left foot).

Thus, six phases are considered, both for the global gait, and for each leg separately (see Fig. 1): 1) placement (first subphase of the initial double support); 2) flat double support (second subphase of the initial double support); 3) single support; 4) double support (placement of the other foot, first subphase of the terminal double support); 5) deployment (second subphase of the terminal double support); and 6) swing.

III. Experimental Setup

A. Description of the Bip Feet

A solution for measuring the forces acting on the feet consists in using universal six-axis force-torque sensors (UFS) at the level of the ankle. However, the standard UFS, developed to equip wrists of industrial manipulators, have the disadvantage of

Fig. 6. Walker with reflective markers walking on the force-plate, and in the background one of the four CCD cameras.

bulky dimensions, unaesthetic in the case of humanoid robots, and, above all, implying a sole-ankle distance higher than the anthropometric one. A more compact solution in order to determine the pressure forces consists of inserting thin force sensors inside the foot at the level of the sole. Three sensors are sufficient to determine the three components of the pressure forces (the normal force plus the two tangential moments). As described in [8], in addition to this device, the friction forces can be deduced from a complementary system measuring the ankle torques (in the case of Bip, by means of strain gauges pasted on the rods of the transmissions). Fig. 2 shows the three traction-compression sensors, rather thin (14 mm), inserted between the sole and the upper part of the foot (which holds the universal joint of the ankle, and on which act the rods of the actuators, as described in [9]). One sensor (H) is close to the heel, behind the ankle, and two (R and L) are ahead, fairly far from the front edge.

Let us notice that the shape of the sole is nonanthropomorphic. Actually, some arguments can justify this geometry: the stiff mechanical foot has the same function as the quasi-stiff part

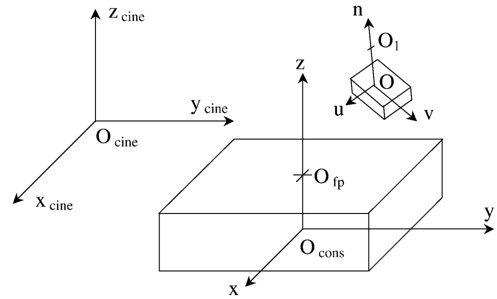

Fig. 7. Motion analysis (cinema), force-plate and foot frames.

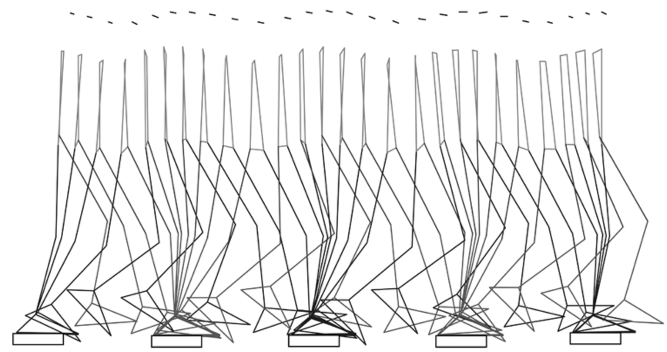

Fig. 8. Stick diagram plotted using marker images (1 image/120 ms).

of the human foot, i.e., from the heel to the metatarsi (without toes). This part has been reproduced for the Bip foot, with in addition a safety margin outside the lateral and rear edges, as sketched in Fig. 3. In this way, one gets a wide foot with a longer heel. The front part of the foot seems to be short but it has an anthropometric size since it has not the function "toes." This disposition of the foot is common to several biped robots, as for example, the Honda P2 [10] (see dimensions in Fig. 4).

B. Force–Motion Analysis System

The experimental setup comprised a human walker wearing the Bip soles as shoes and a force–motion analysis system. The experiments were done by three walkers, each gait (walk, stairs, etc.) being repeated nearly five times. The data presented in this paper come from a subject weighing 96 kg, which is similar to Bip weight. Each mechanical foot weighs 1.8 kg. The Bip soles are firmly screwed onto the shoes of the subject, as shown in Fig. 5, the front edge being situated at metatarsi level. Fig. 6 shows the tested subject walking on the force-plate. The technical characteristics are described in [8]. The walker is equipped with 14 markers. The forces are recorded at 2000 Hz, synchronized in time to the 50 Hz rate of the cameras.

The three frames used in the study appear in Fig. 7: motion-analysis reference $(O_{\rm cine}, \boldsymbol{x}_{\rm cine}, \boldsymbol{y}_{\rm cine}, z_{\rm cine})$, force-plate reference $(O_{\rm fp}, \boldsymbol{x}, \boldsymbol{y}, z)$ and foot reference $(O, \boldsymbol{u}, \boldsymbol{v}, \boldsymbol{n})$. Everyone agree to identify $(\boldsymbol{z}, \boldsymbol{x})$ as the frontal base and $(\boldsymbol{y}, \boldsymbol{z})$ as the sagittal one. According to conventions commonly used by mechanics people, we designate $\boldsymbol{y}$ as the frontal vector because it is perpendicular to the frontal base, and we designate $\boldsymbol{x}$ as the sagittal vector because it is perpendicular to the sagittal base. (One must warn that biomechanics people use generally an opposite convention).

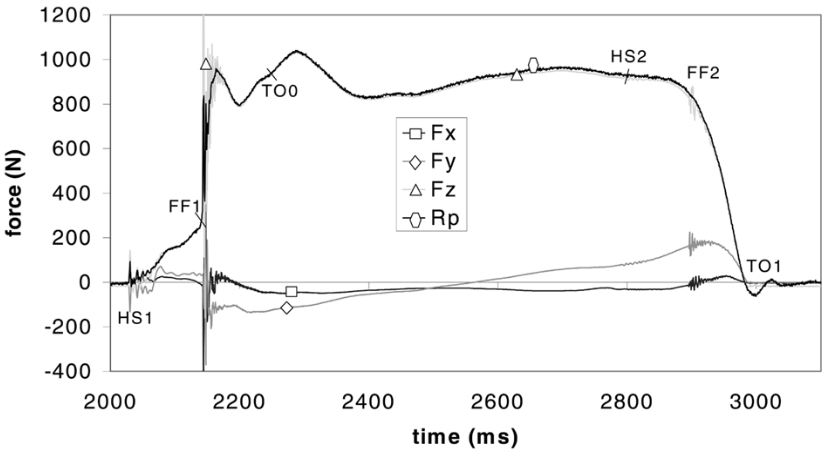

Fig. 9. "Mechanical" walk: forces. F_x, F_y, and F_z measured with the force-plate, R_p with the device integrated in the foot (R_p and F_z are very close).

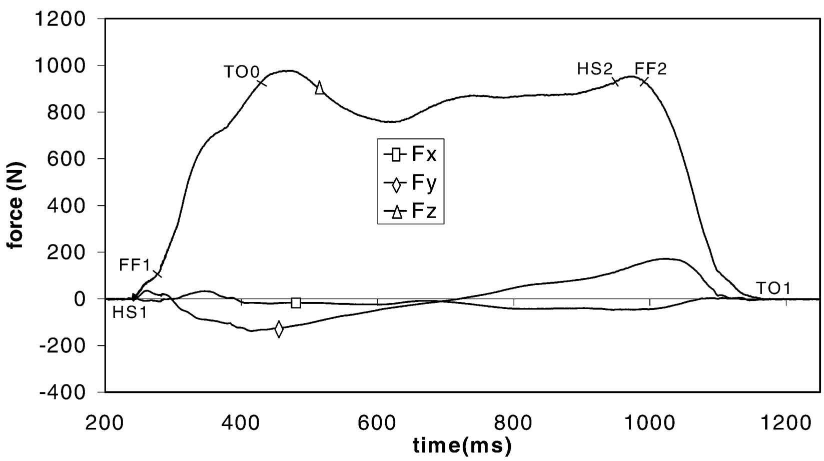

Fig. 10. "Natural" walk: forces (measured with the force-plate).

IV. Analysis of Ground/Feet-Contact Forces

The goal of this section is to characterize the evolution of the ground/feet forces from different points of view, such as that of CoP-ZMP, on each foot and globally for the double support phase. A question will be also answered. Is it possible to reproduce anthropomorphic gaits with "mechanical" feet?

A. Motion Analysis

The film presented in Fig. 8 (one image every 120 ms) seems to answer yes. All the determinants of gait (see, for example, [11]) are respected: pelvis rotation and pelvis tilt, stance phase knee flexion, leg valgum allowing a narrow walking base. With regards to the average speed, 1 m/s in the case of this example, the stride length is normal, 1.5 m, as is the period, 1.5 s. For further analysis, the marker data have been transformed into angular orientations. The trajectories of the angular coordinates of the "mechanical" walk and that of the walk with leisure shoes are quite similar (not presented here for lack of place). However, the frequency of the cinematographic data is small, 50 Hz. Some events could occur between two video frames (20 ms). In contrast, the frequency of the sthenic data, 2000 Hz, is much higher: the evolution of the forces is recorded every 0.5 ms. Therefore, the sthenic analysis may be more accurate.

B. Analysis of Local Contact Forces

First, let us compare the forces and moments of the "mechanical" walk (Bip feet) with the natural walk (leisure shoes). Fig. 9 is to be compared with Fig. 10 (forces), and Fig. 11 with Fig. 12 (moments). The global similarity between the forces on the one hand and the moments on the other hand is surprising. Indeed, walking with the Bip feet is anything but natural. This proves that the human being is endowed with great capacities of adaptability. However, some differences appear just after the foot-flat (FF_1), at nearly 2150 ms for the "mechanical" walk and 300 ms for the natural walk. In the first instance, the pressure force F_z and the sagittal moment $M_{\mathrm{Ou}}^{\mathrm{fp}}$ increase abruptly, in the second instance they increase smoothly.

Similar comments can be associated to the evolutions of the CoP. Fig. 13 shows the CoP trajectory of the "mechanical" foot, which is to be compared with Fig. 14 for the natural shoe. In both cases, between the heel-strike HS_1 and the foot-flat FF_1 (weight acceptance phase), the CoP is behind the ankle. In both cases, just after the foot-flat, the CoP goes in front of the ankle. The difference is that in the first case, this displacement occurs with a great velocity, as demonstrated by the jumps appearing between the successive marks of the CoP (marked every 0.5 ms) in Fig. 13.

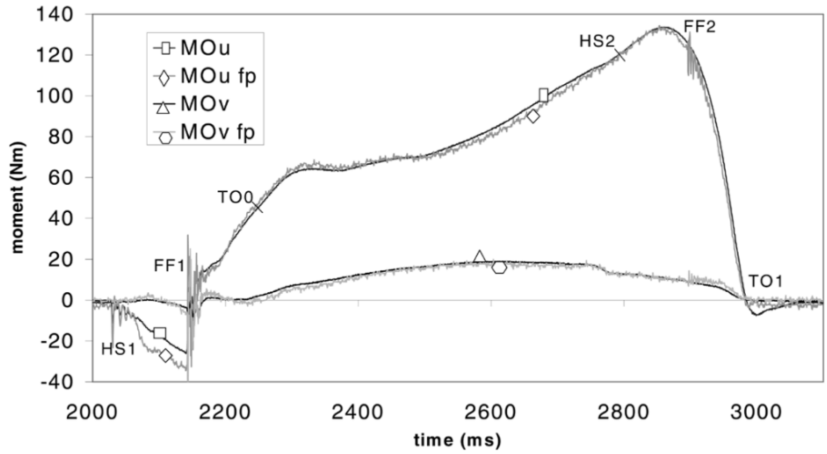

Fig. 11. "Mechanical" walk: moments. M_{0u} and M_{Ov} provided by the Bip measurement device, M_{Ou}^{fp} and M_{Ov}^{fp} by the force-plate after a frame change (respectively very close).

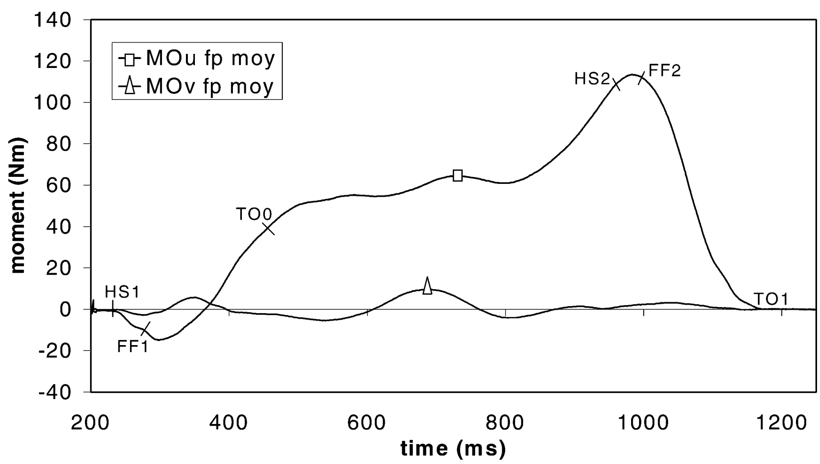

Fig. 12. "Natural" walk: moments (measured with the force-plate, with a post smoothing).

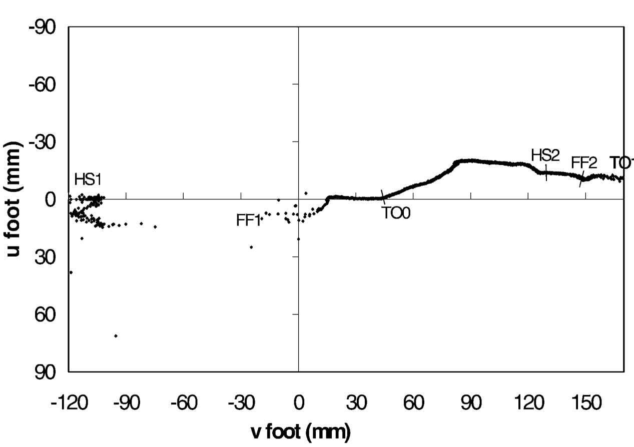

Fig. 13. "Mechanical" walk: CoP trajectory. The frame represents the foot size ($180 \times 290\ \mathrm{mm}^2$) and the origin represents the position of the ankle.

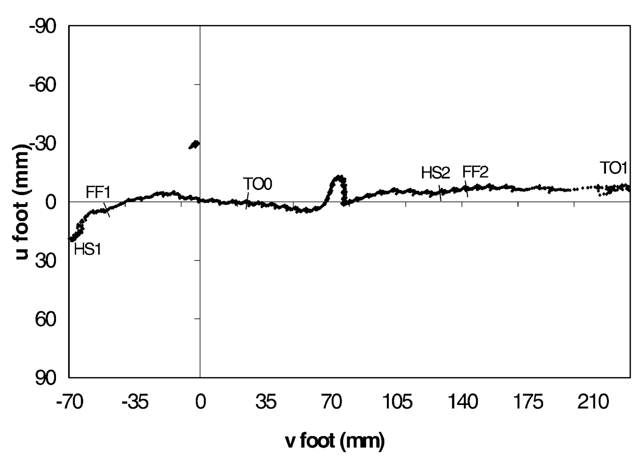

Fig. 14. "Natural" walk: CoP trajectory. The heel goes from -70 to 0, the foot from 0 to 170, and the forefoot from 170 to 220 mm.

We would like to emphasize a common point important in our eyes: the pressure forces begin to decrease between the heel-strike HS_2 and the foot-flat FF_2, which are close and situated exactly at the same distance from the ankle (nearly 140 mm) in both cases. This fact helps to validate our choice of locating the front edge of the Bip foot at the level of the metatarsi.

From our point of view, the similarities are more surprising than the differences we were expecting due to the anatomical gap between the Bip and the human feet. In particular, the single supports, from TO_0 to HS_2, are very similar. Effectively, the initial double supports $(\mathrm{HS}_1\text{-}\mathrm{TO}_0)$ as well as the terminal double supports $(\mathrm{HS}_2\text{-}\mathrm{TO}_1)$ are different. However, although they are

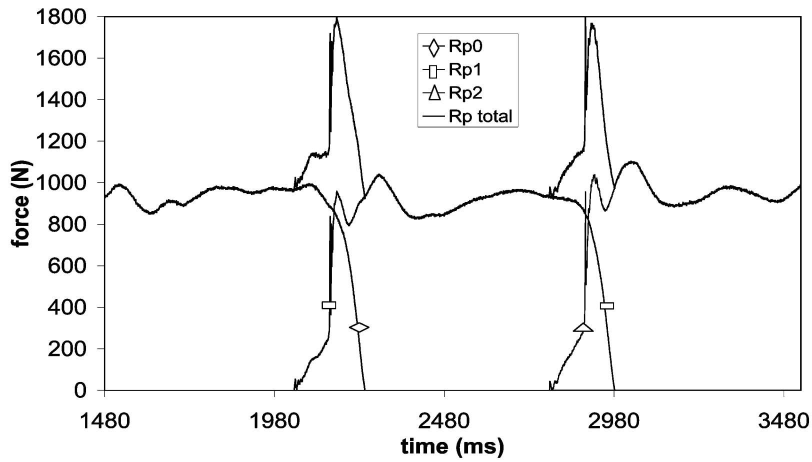

Fig. 15. "Mechanical" walk double support: sum of the pressure forces (R_{p1}: right foot, R_{p0}: left foot—rear, R_{p2}: left foot—front, R_p: left plus right feet).

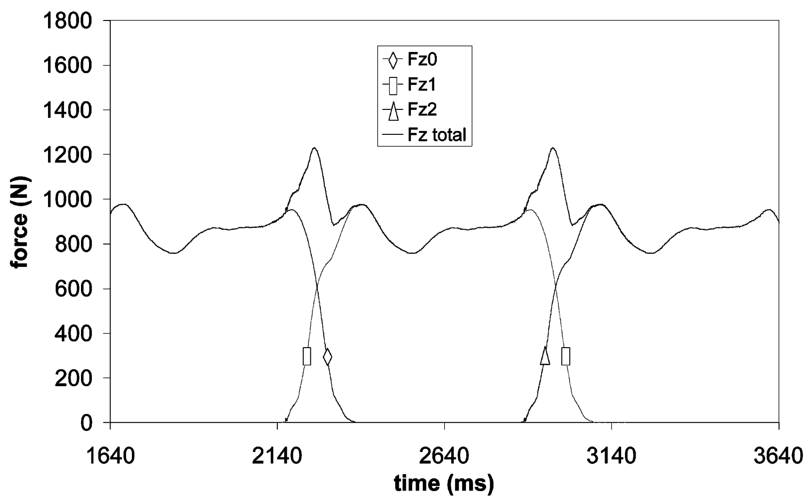

Fig. 16. "Natural" walk double support: sum of the pressure forces (F_{z1}: right foot, F_{z0}: left foot—back, F_{z2}: left foot—front, F_z: left plus right feet).

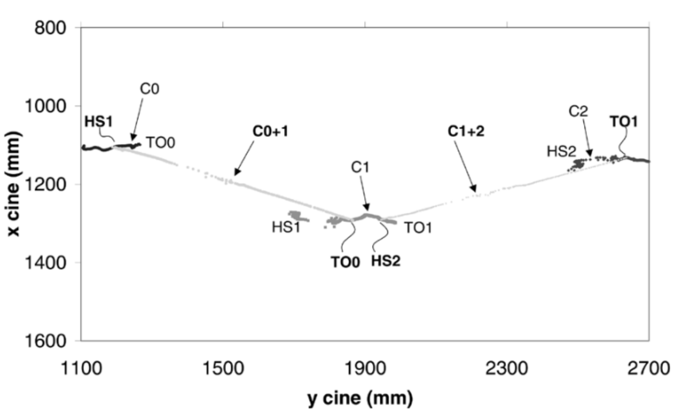

Fig. 17. "Mechanical" walk: global CoP trajectory (C_0, C_1, C_2: local, C_{0+1}, C_{1+2}: global).

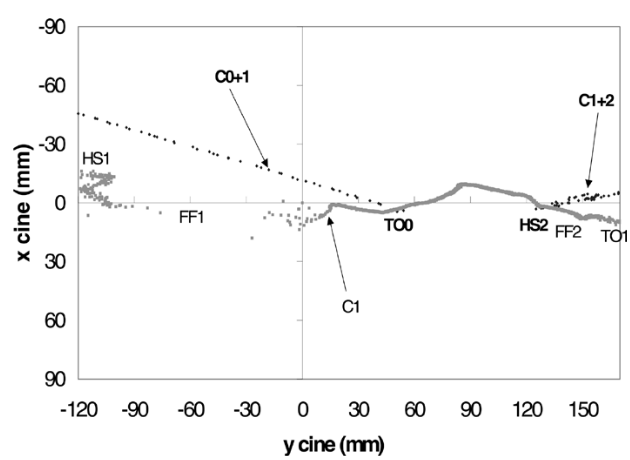

Fig. 18. Zoom of the global CoP trajectory on the sole (the frame represents the foot size).

different when each foot is considered separately, is it the case when the two feet in support are examined globally? This is the question examined in Section IV-C.

C. Double Support Analysis

As the data recorded by the two sensitive feet are synchronized, they can be edited as functions of time without any computation. As the ground is flat, the two feet are in the same plane and the pressure forces can be directly summed (see Fig. 15). The rough variations of the local forces, just after the foot-flat, are retrieved on the global pressure force. The resultant force reaches 1800 N, i.e., more than 180% of the weight of the subject. Here is a real difference from that of the natural walk, where

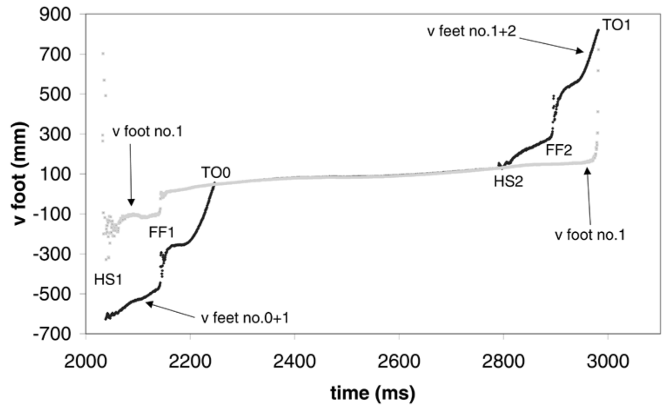

Fig. 19. "Mechanical" walk: evolution in time of the global CoP frontal coordinate.

the resultant represents about 130% of the weight of the subject, as shown in Fig. 16.

Let us pursue the analysis of the double support phase. Fig. 17 shows (in the reference "cinema") the trajectories C_{0+1} and C_{1+2} of the global CoP, superposed with the trajectories of the local CoP: C_0 = rear left foot, C_1 = right foot (idem Fig. 13), C_2 = front left foot. The jumps appearing locally after heel-strikes appear also globally: when the trajectory of the global CoP is interrupted (about 1400 mm for C_{0+1}, about 2200 mm for C_{1+2}).

Fig. 18 is a zoom on the local and global CoP trajectories, bounded by the line of the foot, where the origin of the axes is the projection of the ankle. C_1 is the local trajectory on the right foot. When the left foot is in rear support, the global trajectory is C_{0+1}. When the left foot is swinging, the global trajectory coincides with the local one C_1. When the left foot is in front support, the global trajectory is C_{1+2}. Globally, when the rear foot leaves the ground (TO_0), the global CoP C_{0+1} is widely in front of the ankle (nearly 50 mm), exactly at the same distance as in the case of natural walk.

To better analyze the motion of the global CoP, Fig. 19 shows the CoP frontal coordinate as a function of time. The movement along the global trajectory is fast during the double support, slow during the single support. More precisely

- initial double support: 648 mm during 205 ms, i.e., average velocity 3.2 m/s, with a maximum at 8 m/s;
- single support: 80 mm during 550 ms, i.e., average velocity 0.15 m/s, with a maximum at 0.5 m/s;
- terminal double support: 612 mm during 185 ms.

Walking is actually a dynamic motion! These peaks of velocity have to be examined with respect to the global velocity presented here, 1 m/s or 3.6 km/h, which is medium. Finally, it should be noted that the correlated velocity of the global center of mass is regular: in the case of the example, between 0.8 and 1.3 m/s (average 1 m/s).

D. Interpretation of the Results

To conclude Section IV, the principal difference between the "mechanical" and the natural gaits, just as well locally as globally, can be said to be the jump of CoP occurring after the "mechanical" heel-strike, correlated with a brief peak of force at foot-flat. The value 1800 N of the total force means that the vertical inertia effects amount to a maximal value nearly equal to the weight.

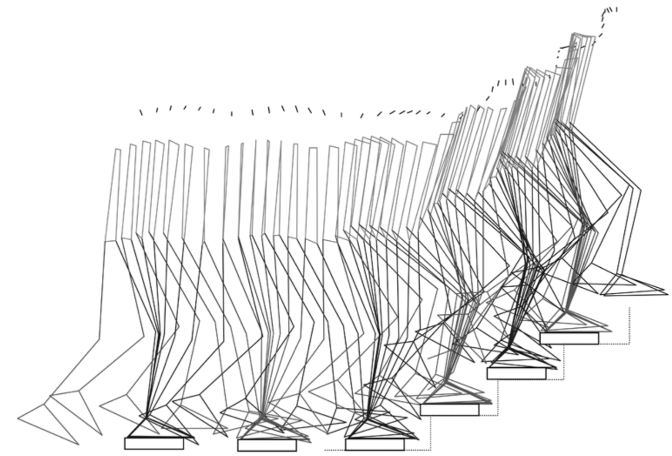

Fig. 20. Stick diagram plotted using marker images during the walk on stairs.

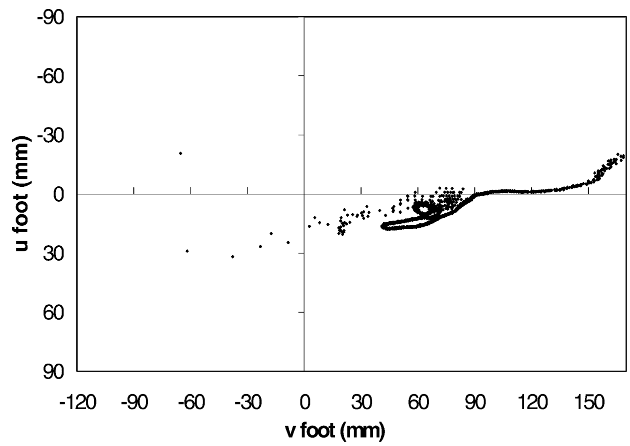

Fig. 21. Walking on stairs: CoP trajectory.

An explanation of a similar phenomenon encountered during fast walks and runs is proposed in [12]. A model made of a large mass and a small one represents the body minus the foot on the one hand and the foot on the other hand. The two masses are connected by a spring representing the leg, and under the small mass, a device comprising a spring plus a dashpot represents the fatty pad of the human foot (plus perhaps a rubber sole). Effectively, dynamic simulations carried out with this simple model give brief force peaks after impacts. However, the fact that the phenomenon appears in our case during the double support phase of nonfast walks relativizes the relevance of the interpretation. Nevertheless, it is an indication that the phenomenon we examine is in connection with 1) an impact of 2) a foot without ankle. Experimental results [13] seem to confirm this explication. The walking gaits of subjects were examined, with free and fixed (by short leg braces) ankle joints. In the latter case, small peaks in the vertical force were measured after heel-strike.

The foot has an important role in avoiding impact, as a shock-absorbing mechanism. The Bip feet perform this role correctly at heel-strike, but not at foot-flat. In fact, it would be more correct to say that the "mechanical" feet with a long heel are not

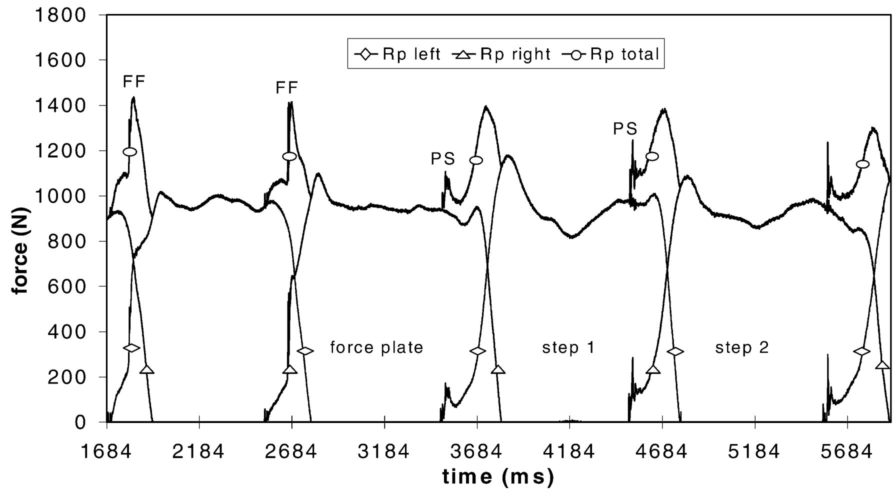

Fig. 22. Walking on stairs: evolution in time of the local and global pressure forces (FF: foot-flat, PS: plantar strike).

well adapted for the human being. Indeed, the ankle muscular system is capable of developing large torques in flexing, but not in stretching. Let us imagine a subject whose soles are fixed on the ground: he could bend forward, but not backward, because his ankle torques can balance the moment of his weight in the forward direction, but not in the backward one. A further look at Figs. 11 and 12 shows that the flexing moments are nearly 120 Nm, versus − 20 Nm for the stretching ones just before foot-flat. A greater negative torque would be necessary to control the placement phase in order to avoid impact at foot-flat, in other words in order to retain the foot during the placement or weight acceptance phase. Actuation systems of robots have the ability to generate torques in one direction as well as in the other, and for this reason, biped robots have capabilities that the human being does not possess. They can therefore be animated with a mixed motion and force control (as for example in [14]), and it is possible to control the complete movement of the feet, i.e., foot-flat and deployment, but also placement.

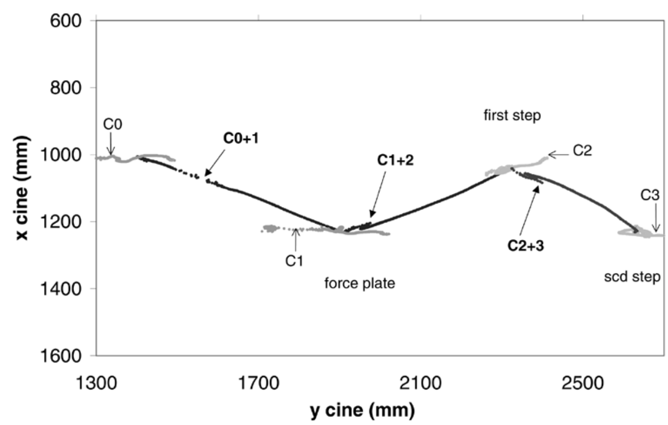

Fig. 23. Walking on stairs: double-support virtual-CoP trajectories $(C_{0+1}, C_{1+2}, C_{2+3})$ and single-support local ones (C_0, C_1, C_2, C_3).

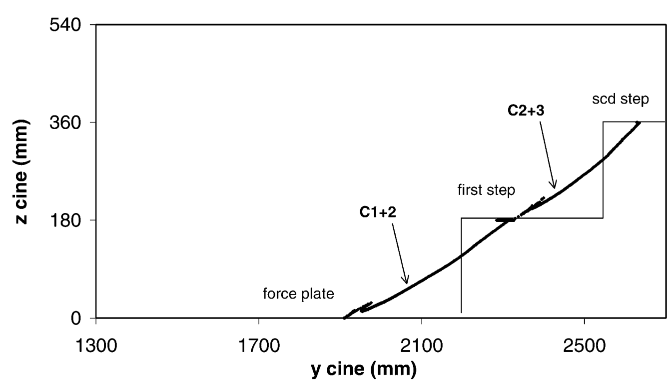

Fig. 24. Walking on stairs: virtual-CoP trajectories in sagittal view.

V. Other Experiments

In the companion paper [1], dealing with theoretical aspects of CoP-ZMP, we examined special cases when the two feet do not lie in the same single plane: first, when walking on stairs, and second, when walking on uneven terrain. Because in these cases, the classical definitions of CoP-ZMP are inconsistent, we have proposed and defined the concepts of virtual surface and pseudo-CoP. The experimental results presented in this section are founded on these propositions and definitions.

A. Walking on Stairs

When a human being walks on stairs, the contact with the steps occurs near the middle of the sole. In other words, the heel-strike is replaced by a plantar strike. What is the gait on stairs like with the Bip feet?

The film of Fig. 20 presents one image every 120 ms. The force-plate is just in front of the first step. The velocity is low: 0.55 m/s on horizontal ground, then 0.35 m/s on stairs (in comparison, the velocity of walks on level ground analyzed in the previous part of the paper was 1 m/s).

The CoP trajectories on the horizontal part are similar to the previous ones, going from heel to toe. They are not presented here. On the stairs, the first contact with the steps occurs in front of the ankle (nearly 60 mm ahead, see Fig. 21), then the CoP goes forward and backward when the subject tries to keep its balance (quasistatic because of low velocity), and finally leaves the sole at the level of the toe (the deployment section is similar to that of walks on level ground).

Fig. 22 presents the pressure forces recorded by the two feet plus the total resultant force during the double support phases.

Fig. 25. Double support on two secant planes.

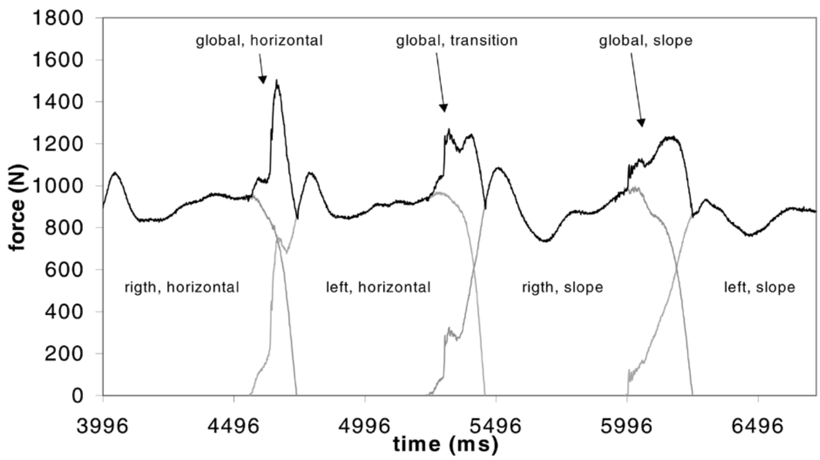

Fig. 26. Walking on nonparallel planes: evolution in time of the local and global pressure forces.

The first two stances of the figure, before the force-plate and on the force-plate, exhibit the characteristics of the walk with the Bip feet: impactless at heel-strike, the pressure forces increase abruptly at foot-flat. These rises are visible on the resultant, just at the level of the peaks. The peak values are about 1400 N, less than the 1800 N of Fig. 15 ("mechanical feet" with long heel, exactly as here), because here the walk is slower (0.55 m/s versus 1 m/s). The last two stances of Fig. 22 occur on the first two steps of the stairs. The plantar strike is translated by a small impact (about 200 N) then the pressure forces increase gradually, as can also be seen in the total resultant during the double support phases (the peaks are rounded off).

For the double support phase on stairs, the determination of the global CoP is based on the concept of pseudo-CoP we have proposed in the companion paper [1]. The horizontal trajectory of the global CoP, shown in Fig. 23, is slightly different from that on horizontal ground (Fig. 17). Indeed, the global CoP joins the local trajectories at a point, then it leaves it close to the same point. In other words, the single support trajectories begin and end at about the same point. This is true on the stairs, and also on the force-plate just before the stairs. One can observe that the global CoP shows a jump on flat ground (C_{0+1}), whereas on the contrary backward oscillations appear on stairs (C_{1+2} and C_{2+3}), corresponding to the phases of quasistatic equilibrium research. The sagittal trajectory of the global CoP is shown in Fig. 24. One can observe a slight inflexion of the curve for each step. The backward oscillations we have previously discussed can again be observed.

B. Walking on Uneven Terrain

The concept of CoP-ZMP is intrinsically related to walking on one single plane surface. So, the traditional definitions are inconsistent for the double support phase when the biped feet are contacting two noncoincident surfaces. This situation occurs when the walker goes from a plane surface Π_1 (for instance horizontal) to an other one Π_2 (inclined). It also occurs when walking on uneven surfaces.

In the previous paper [1], we have defined a virtual surface Π passing through the intersection line of Π_1 and Π_2, as well as a pseudo-CoP-ZMP within Π. This section presents corresponding experimental data, recorded for a transition from a horizontal plane surface to an inclined one, whose slope is steep (22% gradient), as shown in Fig. 25.

For the transition between the two surfaces, the vertical dynamical perturbation occurring after the foot-flat is lower than that occurring for the horizontal double support, however its shape is the same, as shown in Fig. 26, as well locally as globally. After the transition, when the two feet are on the slope, then

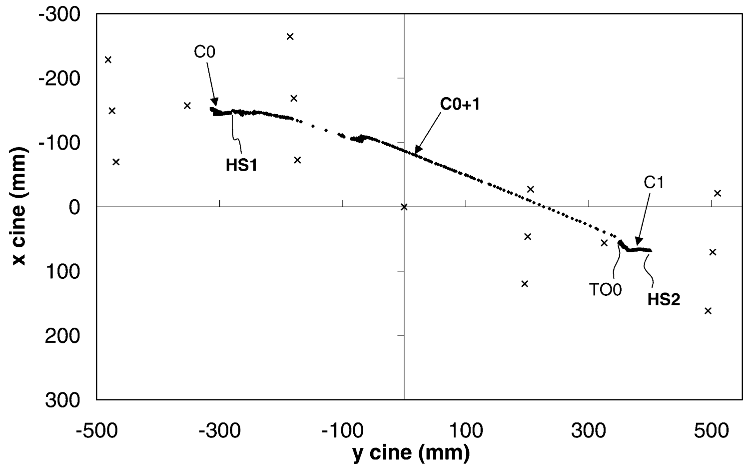

Fig. 27. Walking on nonparallel planes: double-support virtual-CoP trajectory (C_{0+1}) and single support local ones (C_0, C_1).

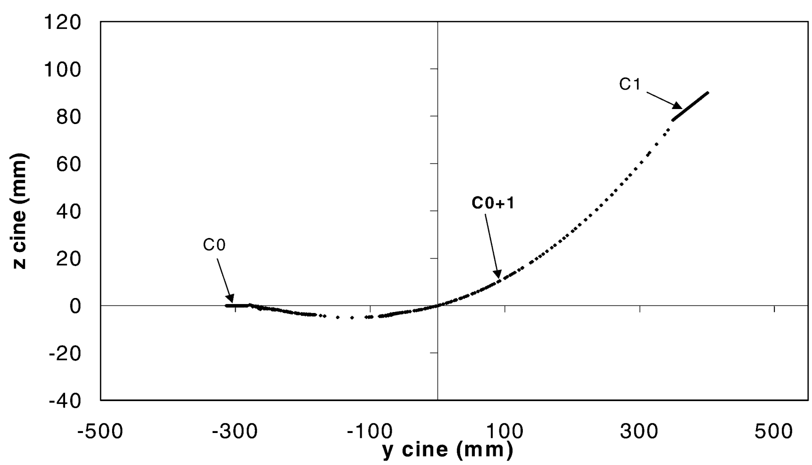

Fig. 28. Walking on nonparallel planes: virtual-CoP trajectory in sagittal view (warning: z-scale is larger than y-scale).

the hell-strike and foot-flat of the left foot occur quasi-simultaneously, and the peak disappear.

Figs. 27 (horizontal projection) and 28 (sagittal view) focus on the evolution of the pseudo-CoP-ZMP for the transition phase. In Fig. 27, the rear and front edges of the mechanical shoes are indicated with six points. The seventh point (central) indicates the position of the ankle. The virtual CoP-ZMP goes from HS_1 (end of the local single support trajectory C_0) to TO_0 (beginning of the local single support trajectory C_1). The positions of these points with regard to the ankle are similar to the horizontal case (see Fig. 18). Fig. 28 shows the virtual trajectory C_{0+1} in the sagittal plane. One can observe a very proper continuity with the local single trajectories C_0 and C_1. The jumps appearing near -150 mm and about $+150$ mm between successive marks (CoP positions are marked every 1 ms) attest that the CoP displacement is very rapid for the double support phase. This phenomenon is proven in Fig. 29, showing the pseudo CoP frontal coordinate as a function of time. The forward progression is quasi-zero for the single support phases ("foot no. 0" then "foot no. 1"), since it occurs largely for the double support phase in a very short time ("feet no. $0+1$," 635 mm from HS_1 to TO_0 in exactly 260 ms). In our mind, the knowledge of the phenomena occurring for the double support phase are fundamental, justifying the introduction of the concepts of virtual surface and pseudo-CoP-ZMP, allowing the corresponding study.

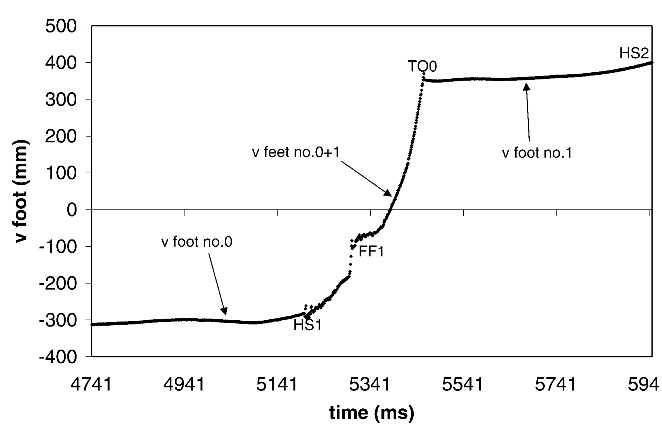

Fig. 29. Frontal coordinate of the virtual CoP as a function of time for the transition phase (foot no. 0 horizontal, foot no. 1 on slope).

VI. Conclusion and Perspectives

The tests described in this paper have proven that a human being is able to walk with robot mechanical shoes, generating gaits little different than natural ones. The main kinematic determinants of walking are reproduced. Further analysis of force data has shown some more similarities. In particular, with the Bip feet as well as with light shoes, the CoP is at the same place in front of the ankle after the placement of the foot, and is at the same distance from the ankle when the heel leaves the ground. However, real differences exist during the double support phases. Placement with light shoes is smooth, whereas when wearing the Bip feet, the CoP jumps from the heel to the front of the ankle and the pressure force increases sharply at foot-flat. In both cases, the maximal forces supported by each foot are hardly greater than the subject's weight, but globally, the total force as regards the two feet in support is abnormally greater with metallic shoes. Slight modifications could be implemented immediately to improve the behavior of the current Bip feet: first, replacing the current rubber fixed under the sole by a softer material, and second, shortening the heel and rounding off the back edge of the sole. However designing a real anthropomorphic foot would be a more exciting perspective. This task will no doubt be difficult, because the human foot is functionally very sophisticated. The results presented in this paper are a starting point to motivate reflection in this direction, for research and development teams whose biped robots are expected to reproduce anthropomorphic walking gaits, with medium or rapid velocities. Some works going in this direction have to be referred to, such as [15] and [16] for instance.

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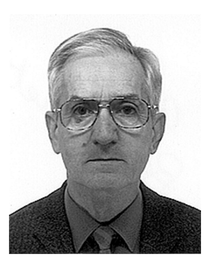

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