

Dynamic simulation of a Humanoid robot with four DOFs torso

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Abstract— In this paper, we present the 3D dynamic simulation of walking gait of biped Robian II virtual manikin (25 kg weight, 1.10 m height). The biped has 16 degrees of freedom (dofs). Initially, a bio-mimetic approach is used to model a humanoid biped having 25 dofs based on common European male (75 kg, 1.78 m). Using, human being motion recording, foot/ground contact model and inverse kinematics, a 3D dynamic simulation of this humanoid is carried out. Scale factorization is used in order to reach Robian II weight and height. A 3D dynamic simulation of the Robian size humanoid gives the effort wrench exerted by the torso on the lower limbs. An analysis of the six components of this wrench shows the existence of two coupling relations. A study of four dofs mechanisms based on General State Equation (GSE) formalism leads us to an interesting result. Indeed, four dofs are necessary and sufficient to emulate the dynamic effects. An RPPP mechanism is presented in order to replace Robian upper part. Results of 3D simulation of the 16 dofs resulting biped are presented. ZMP control algorithm is used to ensure dynamic stability of the biped during walking gait.

Keywords— Humanoid robot, Biped robot, Bio-mimetic approach, Dynamic simulation.

I. INTRODUCTION

APPLICATIONS of walking robots, mainly the biped ones, are increasing due to technological progress in actuators, sensors and computer fields. They can operate in human environment more efficiently than other types of robots like wheeled ones. Assistance to humans in the accomplishment of domestic tasks, which are difficult or dangerous, consists in an important use for bipedal robots. In addition, a very useful application of research into bipedal robotics will be the enhancement of prosthetic devices development and testing.

Humans walking gaits are typically dynamic, as they are faster and more efficient than the static walking patterns. Therefore, research in bipedal robotics has progressed to study dynamic walking gaits [1] & [2].

Dynamic walking has been realized by some bipedal robots, most notably are the Honda P2 and P3 robots and the Wabian robot of the university of Waseda [3], [4], [5] & [6].

Most recently, Sony dream robot, a fully dynamic

humanoid robot shows quite impressive performances in carrying out human like tasks (walking, dancing,...) [www.sony.co.jp]

To carry out a useful biped robot prototype allowing the human locomotion system analysis, two main approaches can be developed. Generally, an anthropomorphic upper limb with arms and head is used in humanoid robots building. The other approach consists on ignoring the human like aspects of the prototype upper part.

Due to the fact that our main interest concerns significant contribution to the study of the human locomotion system, a multi-degrees of freedom (dof) biped prototype provided with flexible feet, called ROBIAN, is under development.

The Robian prototype major application will be the development of a real testing bed of active/passive prosthesis devices enhancing research on the locomotion mechanism handicap.

In this paper, we present, a 3D dynamic simulation of this biped virtual manikin. In section 2, we present the bio-mimetic approach used in order to model a virtual manikin of the human body based on a chosen kinematic structure having 25 dofs.

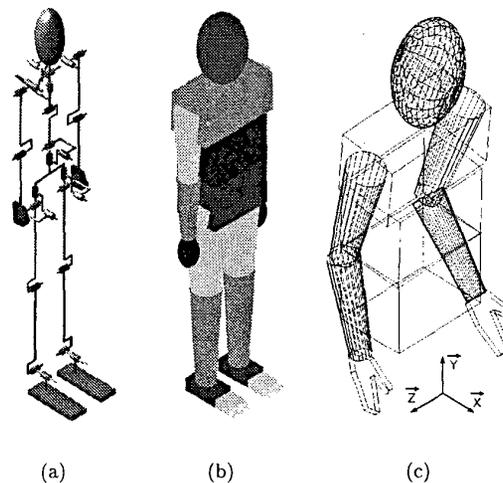


Fig. 1. Biped manikin and Torso with 13 dofs.

Section 3 deals with the virtual manikin of Robian

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II having 25 kg weight and 1.10 m height obtained by scale reduction of full size one. Emulation of realistic model torso of Robian II without any anthropomorphic consideration is then presented. Analysis of the human torso dynamic effects during walking gait is given. A minimum dofs mechanism able to reproduce these effects is then identified and verified using a method based on the General State Equation (GSE) formalism. Section 4 deals with the dynamic behavior simulation and analysis of the Robian II virtual manikin after replacement of human like torso by the simplified mechanism. In the last section, conclusions and further developments of this work are given.

II. BIO-MIMETIC APPROACH

A 25 dofs kinematic structure presented on figure 1(a) was chosen for the virtual manikin of our humanoid robot.

The human body is modeled by 16 solid primitives according to the Hanavan model as shown on figure 1(b). Using a description of the 3D-bio-mechanical data a mass distribution has been associated to each solid [7].

Faithful reproduction of human movements during walking gait is of a primary importance for dynamic simulation of a virtual manikin. Therefore, a series of measurements using VICON motion analysis system was carried out to obtain positions of 16 markers placed on a human being at points where relative motion between the skin and the bones are minimal during walking gait.

These markers positions are the input of the biped inverse kinematic model which allows us to obtain as output the time evolution of the 25 joint variables.

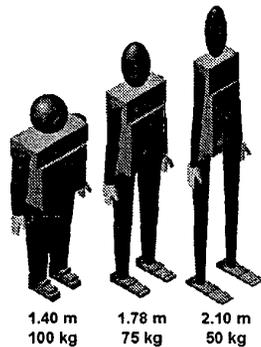


Fig. 2. Parametrical construction.

A distributed feet/ground contact model based on spring damper combination is used to include the external efforts in the dynamic model of the biped [8].

Under Adams software, the above model biped is

built using parametrical construction depending on total weight and height.

Figure 2 shows the efficiency of parametrical construction by presenting several model of the biped with different weights and heights.

Finally, the 3D biped manikin is simulated using Adams [9]. The simulation attempts to produce motions close to the recorded data. Joints are controlled using a proportional derivative controller giving joint torques according to its position :

$$\tau = K_p(q_d - q) + K_v(\dot{q}_d - \dot{q})$$

The biped achieves 3 stages during 4.8 seconds of simulation. A positioning stage (0-1.2 sec), a launching stage (1.2-2.4 sec) and two established walking cycles of period 1.2 sec.

III. ROBIAN II PROJECT MANIKIN

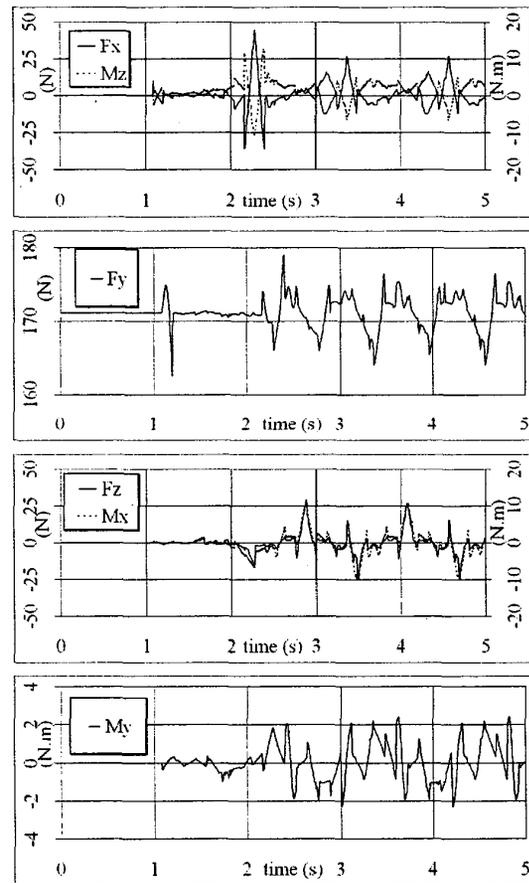


Fig. 3. Components of the wrench at embedding point of realistic model of torso during walking gait.

As the objective of Robian is the development of a simple testing bed of active/passive locomotion system

prosthesis devices, we intend to build a small biped with 1.10 m of height and no more than 25 kg of weight.

To this end, we proceed to a scale reduction of our humanoid according to these parameters.

In a first approximation, human aspects of the upper part which present 13 actuators (3 per arm, 3 for the neck, and 4 for the trunk) are not essential to accomplish this objective.

A minimal mechanism is, then, looked for in order to replace upper part of this model (presumed to be realistic) containing 13 dofs (figure 1(c)). This model should reproduce the dynamic effects on the lower limbs during walking gait.

A. Upper part dynamic analysis

The proposed approach is based on making equivalence in term of efforts between the selected model and the realistic one built under Adams. Initially, the upper part of the realistic biped built under Adams is isolated and embedded at the center of mass of the down-torso. Thereafter, the structure is animated with the time laws of the joint variables in order to extract, using a dynamic simulation, the 6 components of the effort wrench at embedding point (forces: F_x , F_y , F_z & moments: M_x , M_y , M_z).

If the 6 components are independent, the equivalent system must have, at least, 6 dofs. The interest here is to determine the number of coupling relations between the wrench components in order to reduce the number of these necessary dofs. Figure 3 shows time evolution of the six components of this wrench.

The analysis of simulation results shows the existence of two coupling relations [10]. The first one relates the moment component M_x around the x axis (motion direction) to the force component F_z in z axis (lateral direction). The second relation concerns the moment component M_z and the force component F_x (axes are depicted on figure 1). In a first approximation, these relations can be written as follows:

$$\begin{aligned} M_x &= k_1 \cdot F_z \\ M_z &= k_2 \cdot F_x \end{aligned} \quad (1)$$

where, k_1 and k_2 are two constants ($k_1 > 0$ and $k_2 < 0$). Hence, the minimal equivalent mechanical system should be a four dofs spatial mechanism.

B. Proposed method - Dynamic equivalence

The proposed method is based on General State Equation (GSE) formulation. The objective is to identify a mechanism able to produce at its embedding point a required wrench which components are equal to those of the reference model (13 dofs torso system).

It is well known that a mechanism is capable to reproduce as much components of effort wrench as its number of independent actuated dofs. Nevertheless, the walking gait presents coupling relations between wrench components. These relations can be validated by changes on the mechanism geometrical and inertial parameters. At first, a mechanism topology, number of dofs (less or equal to 4) and joints kind (R for rotational joint and P for prismatic one) is selected. Due to the two coupling relations (eq. 1), a maximum number of four effort components are chosen among the six wrench components depicted on figure 3 as inputs according to the new equivalent kinematic structure. The outputs are the joint variables motion laws of the candidate mechanism. Dynamic equations based on Newton-Euler formalism are written for each mechanism link at the embedding point. This leads to get the motion equations of this system. The number of motion equations (n) is equal to the number of dofs of the system. These equations can be written in the general following form:

$$\begin{bmatrix} \ddot{q}_1 \\ \vdots \\ \ddot{q}_n \end{bmatrix} = \begin{bmatrix} g_1(q_i, \dot{q}_i, F_x, F_y, F_z, M_x, M_y, M_z, P_g, P_i) \\ \vdots \\ g_n(q_i, \dot{q}_i, F_x, F_y, F_z, M_x, M_y, M_z, P_g, P_i) \end{bmatrix}$$

where:

- q_i is the joint variable of the i th joint.
- $F_x, F_y, F_z, M_x, M_y, M_z$ are effort wrench components at embedding point.
- P_g, P_i are geometrical and inertial parameters of the mechanism.

These equations form a system of second order differential equations which can be grouped into a first order system called ordinary differential equations system or General State Equation (GSE). Analytical resolution is impossible for the complex systems with more than 2 dofs. The numerical resolution of this type of equations is carried out using Adams software. The GSE is build as follows:

$$\frac{d\vec{X}}{dt} = \begin{bmatrix} f_1(x_1, \dots, x_{2n}, u_1, \dots, u_m, P_g, P_i) \\ \vdots \\ f_{2n}(x_1, \dots, x_{2n}, u_1, \dots, u_m, P_g, P_i) \end{bmatrix}, \vec{Y} = \begin{bmatrix} q_1 \\ \vdots \\ q_n \end{bmatrix}$$

where:

- $\vec{X} = [x_1, \dots, x_{2n}]^T$ is the state vector with $x_1 = q_1$, $x_2 = \dot{q}_1, \dots, x_{2n-1} = q_n$, $x_{2n} = \dot{q}_n$.
- $\vec{U} = [u_1, \dots, u_m]^T$ is the input vector whose components are chosen among $F_x, F_y, F_z, M_x, M_y, M_z$ of the realistic torso.
- \vec{Y} is the output vector.
- $f_1 = x_2, f_2 = g_1, \dots, f_{2n-1} = x_{2n}, f_{2n} = g_n$.

C. Four dofs RPPP model

In a recent work we showed that no more than two coupling relations exist between wrench components

which means that a four dofs mechanism is necessary and sufficient to ensure dynamic equivalence with human upper part during walking gait [10].

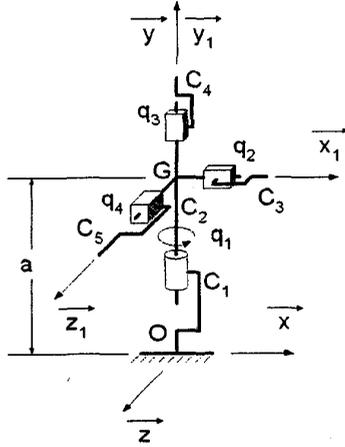


Fig. 4. RPPP Model.

Several models with four dofs are possible. Nevertheless it is necessary to have a thought about the realization of this model. Indeed, it is very difficult to build then to control certain types of joints (e.g. spherical joints). Figure 4 presents the kinematic structure of a decoupled RPPP mechanism which was chosen to satisfy the requirements of simple design and control.

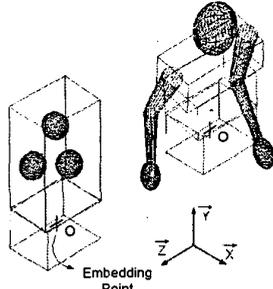


Fig. 5. Simulation of RPPP Model.

For the RPPP model, dynamic equations at point O can be reduced to:

$$\begin{aligned}
 M_y &= I_y \ddot{q}_1 + m_3 (\dot{q}_1 \dot{q}_2^2 + 2\dot{q}_1 \dot{q}_2 \dot{q}_2) - m_5 (\dot{q}_1 \dot{q}_4^2 + 2\dot{q}_1 \dot{q}_4 \dot{q}_4) \\
 F_x &= m_3 \{ (\ddot{q}_2 - q_2 \dot{q}_1^2) \cos(q_1) - (q_2 \dot{q}_1 + 2\dot{q}_1 \dot{q}_2) \sin(q_1) \} \\
 &\quad + m_5 \{ (\ddot{q}_4 - q_4 \dot{q}_1^2) \sin(q_1) + (q_4 \dot{q}_1 + 2\dot{q}_1 \dot{q}_4) \cos(q_1) \} \\
 F_y &= (m_1 + m_2 + m_3 + m_4 + m_5) g + m_4 \ddot{q}_3 \\
 F_z &= -m_3 \{ (\ddot{q}_2 - q_2 \dot{q}_1^2) \sin(q_1) + (q_2 \dot{q}_1 + 2\dot{q}_1 \dot{q}_2) \cos(q_1) \} \\
 &\quad + m_5 \{ (\ddot{q}_4 - q_4 \dot{q}_1^2) \cos(q_1) + (q_4 \dot{q}_1 + 2\dot{q}_1 \dot{q}_4) \sin(q_1) \}
 \end{aligned}$$

where, m_i is the link C_i ($i = 1 \dots 5$) mass and I_y is the sum of inertia of the 5 links around the vertical axis.

The four motion equations are obtained as follow :

$$\begin{bmatrix} \ddot{q}_1 \\ \vdots \\ \ddot{q}_4 \end{bmatrix} = \begin{bmatrix} g_1(q_1, \dots, q_4, \dot{q}_1, \dots, \dot{q}_4, F_x, F_y, F_z, M_y, P_g, P_i) \\ \vdots \\ g_4(q_1, \dots, q_4, \dot{q}_1, \dots, \dot{q}_4, F_x, F_y, F_z, M_y, P_g, P_i) \end{bmatrix}$$

where:

- q_i is the joint variable of the i th joint.
- F_x, F_y, F_z, M_y are chosen wrench components at embedding point.
- P_g, P_i are geometrical and inertial parameters of the RPPP mechanism.

The related GSE is given as follows :

$$\vec{X} = [q_1, \dot{q}_1, q_2, \dot{q}_2, q_3, \dot{q}_3, q_4, \dot{q}_4]^T, \vec{U} = [M_y, F_x, F_y, F_z]^T,$$

$$\vec{Y} = [q_1, q_2, q_3, q_4]^T, \frac{d\vec{X}}{dt} = [f_1, f_2, f_3, f_4, f_5, f_6, f_7, f_8]^T$$

with $f_1 = \dot{q}_1, f_2 = \dot{q}_2, f_3 = \dot{q}_3, f_4 = \dot{q}_4, f_5 = \ddot{q}_1, f_6 = \ddot{q}_2, f_7 = \ddot{q}_3, f_8 = \ddot{q}_4$.

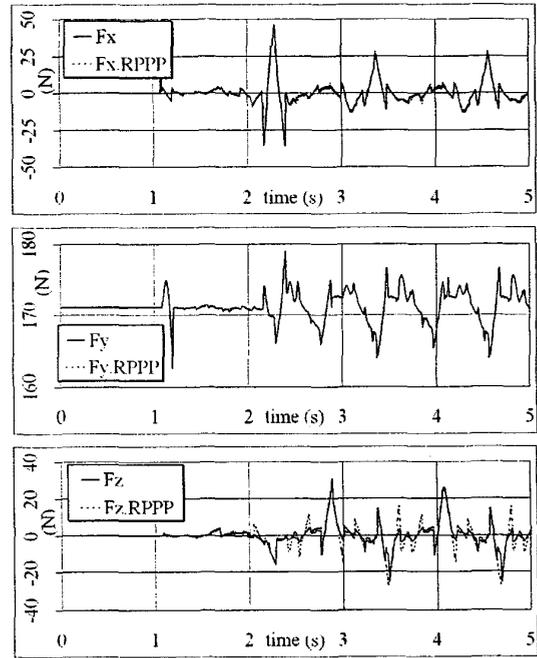


Fig. 6. Results of the RPPP model forces.

During simulation (figure 5), realistic torso wrench components are extracted and given as an input on line for the GSE. The GSE computes the joint variables which are applied on line to Robian upper part four joints.

TABLE I
PARAMETERS OF THE RPPP MODEL.

Parameter	a	$m_1 + m_2$	m_3
Value	0.25 m	9.77 kg	3.1 kg
Parameter	m_4	m_5	I_y
Value	1.82 kg	2.76 kg	0.295 kg.m ²

Dynamic behavior simulation results using parameters depicted on table I show that all 6 components of the realistic torso effort wrench are reproduced by the RPPP model (figures 6 and 7). This confirms the dynamic equivalence between the two mechanisms. Figure 8 shows resulting motions of the four parts. Masses of the three prismatic moving links were chosen in order to have motions within dimension of the prototype to be build. These movements are periodic having the same period as the walking gait which is 1.2 sec. Velocities and accelerations of these links are also taken into account due to their importance in the actuators choice.

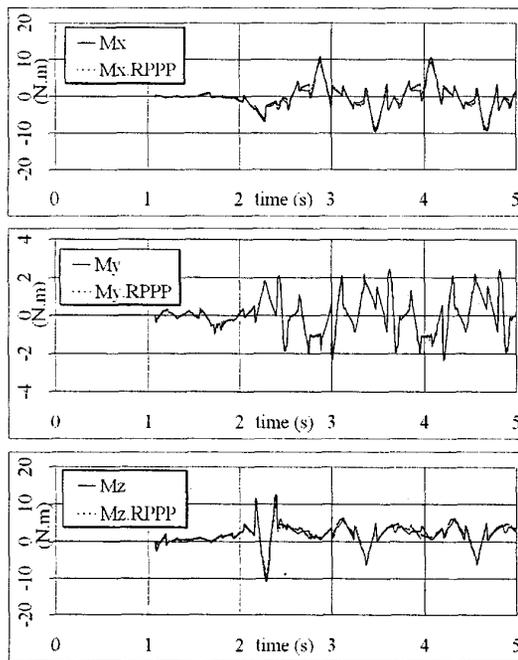


Fig. 7. Results of the RPPP model moments.

IV. DYNAMIC SIMULATION-DISCUSSION

In the previous section, we identified a four dofs mechanism dynamically equivalent to the human shape torso having 13 dofs.

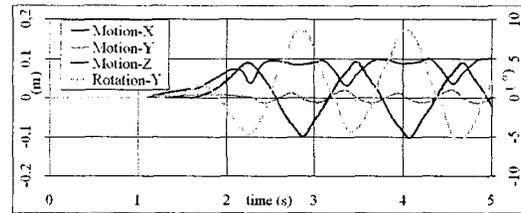


Fig. 8. Movements produced by the RPPP model.

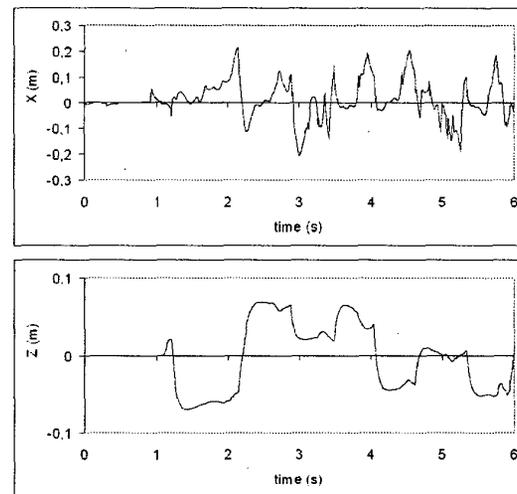


Fig. 9. ZMP coordinates.

Dynamic simulations of new virtual biped show that open loop walk using the identified RPPP mechanism motions presents instability during launching stage. Indeed, human walking center of mass average velocity variations are small in such a way that we can neglect inertial effects during established walk. During launching stage inertial effects are predominant and they have not been taken into account when we embedded the upper part to find equivalent mechanism.

Nevertheless, this model can easily reproduce this neglected effects. To do so, we used Zero Moment Point (ZMP) control method. During the walk, ZMP coordinates are determined and used to compute the required accelerations to be applied to the two moving masses in X and Z directions. In this case, the center of mass of the biped tends to be positioned on the ZMP vertical line.

Numerical fluctuation during on line integration computing may be another instability reason. To prevent this numerical variations, we used first order low pass filter.

Filtered ZMP coordinates are shown on figure 9. Simulation of stable walk of Robian II manikin using

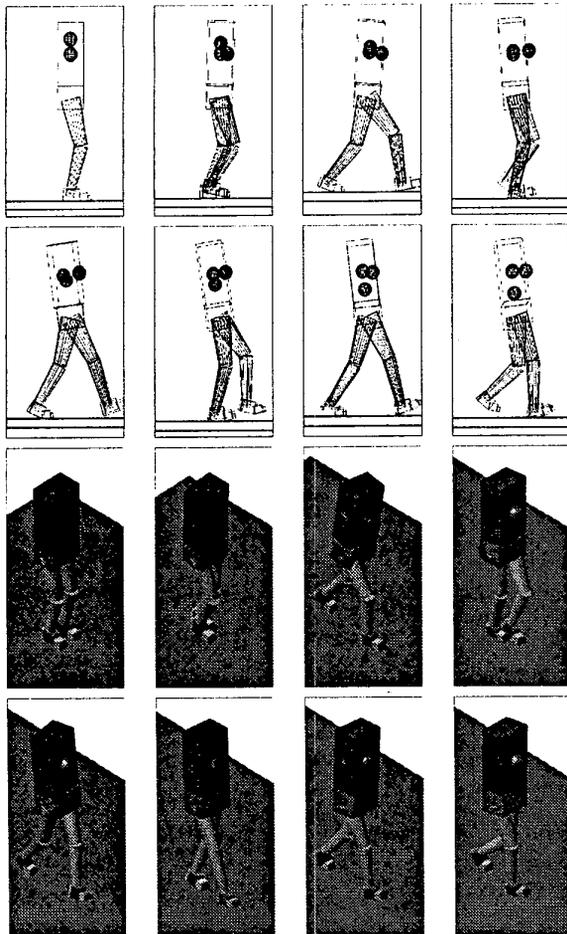


Fig. 10. Dynamic Simulation.

ZMP control is shown on figure 10.

V. CONCLUSIONS

The aim of this work was to carry out fully dynamic simulations of the virtual manikin of Robian II. This biped has 16 dofs, 25 kg of weight and 1.10 m height.

Based on bio-mimetical approach, motion recording, foot/ground contact model and inverse kinematics of a standard human being, a 3D dynamic simulation were used to build virtual manikin having 25 dofs.

The objective of Robian project is to build a real testing bed of locomotion system prosthesis devices. In this spirit, human like upper part is not of a primary importance. Only human upper part dynamic effects on the locomotion system are needed to be evaluated.

First of all, scale reduction was used to obtain values of the Robian II prototype weight and height. Then, dynamic analysis of human like upper part (having 13 dofs) was carried out in order to extract effort wrench

components exerted by the upper part on the locomotion system. This analysis showed the existence of two coupling relations between wrench components which led us to an interesting result. Indeed, a four dofs mechanism is able to emulate dynamic effects of the 13 dofs upper part system.

A generic method based on General State Equation formalism was developed in order to check dynamic equivalence between two mechanical systems.

An RPPP mechanism dynamically equivalent to human upper part was presented in order to replace Robian II upper part. Simplicity of realization and control of this mechanism were the main reasons which led us to chose a such kinematic structure.

A first order low pass filter and ZMP control were used to solve walk stability problems.

Finally, results of 3D stable walking gait dynamic simulation of the resulting biped manikin having 16 dofs and flexible feet were presented.

A complete design of the presented RPPP model in order to be manufactured will be one of the further developments of this work.

This mechanism combined with the locomotion mechanism which is under manufacturing will lead to the global Robian II biped prototype.

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