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DESIGN AND CONTROL OF AN ACTIVE HUMANOID LEG FOR TESTING LOWER-LIMB PROSTHESES

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ABSTRACT

The present paper deals with the development of a bench for testing different types of lower limb prostheses. Aim of the bench is to test the prosthetic devices considering working conditions as much as possible similar to the real ones with respect to methodologies provided by International Standards. These standards merely identify structural tests whose purpose is just to verify that the prosthesis, or their individual components, are able to ensure adequate strength properties during their use. The only functional test concern just the ankle-foot units. Test methods for the assessment of the functional performances of the whole prostheses are missing. There are no criterions for such tests and no benches. From this the need to build new test machines that, simulating both the stance and the swing phase according to sought gait standards, allow to assess the functional properties of different lower limb prostheses and to make comparison between them. According to this, the purpose of the present work is to assess the feasibility of such a bench, evaluating, by mean of a co-simulation executed considering a Multi-Body model of the bench developed using MSC ADAMS and a model of the control system developed using MATLAB/Simulink, its capability in guaranteeing the sequential replication of movements and loads that distinguish a leg during the execution of the stride. The obtained results demonstrate the feasibility of the machine, encouraging therefore the development of more refined models, considering technological solutions closer to reality.

Keywords: lower limb prosthesis, amputee, test bench design, Multi-Body model, co-simulation.

INTRODUCTION

The present work aims to provide to industries a support in the design and development of prosthetic devices, in an attempt to restore the complete rehabilitation of patients who suffered the amputation of lower limbs because of traumas, diseases or birth defects. The demand for ever more efficient devices by users induces in fact the need of more powerful design and verification tools in order to ensure ever higher performances ([1]). Up to now, International Standards ([2–4]) merely identify static and cyclic structural tests whose purpose is just to verify that a certain category of prostheses, or their individual components, are able to ensure adequate strength properties during their use. According to this, strength proofs are generally performed using simple servo-hydraulic testing systems. Test methods for the assessment of the functional performances of the whole prostheses are missing. As stated by International Organization for Standardization:

- “The tests specified do not provide sufficient data to predict actual service life.”;
- “Ideally, additional laboratory tests should be carried out to deal with function, wear and tear, new material developments, environmental influences and user activities as part of the evaluation procedure.”.

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There are no standards for such tests and no benches. From this the need to build new test machines that allow to assess the functional properties of the prostheses considering working conditions as much as possible similar to the real ones, that is simulating both the stance and the swing phase according to sought gait standards. Humanoid robots such this are mechatronic systems that require the development of sophisticated kinematic and mechanical design ([5,6]) and the definition of stable and adaptable control strategies ([7]). Many considerations must then be done upon the advantages of using different solutions in term of mechanism architecture and control algorithms before developing a reliable numerical model. The comparison with the literature in the area is very poor. Nevertheless, starting from the experience acquired during a previous work ([8]) and the knowledge that in recent past have been widely developed studying legged walking robots ([9, 10]), a primitive model of the bench is developed since this work is intended to be a feasible study of the machine. The intention consists in simulating the gait cycle of an amputee subject by reproducing the characteristics of the kinematics and dynamics of walking of the prosthetic leg. According to this, the machine must then be able to replicate by mean of its components the series of motion patterns performed by the segments of the leg and the trend of forces acting on the foot due to reaction with the ground. For reasons of clarity, a brief description of the kinetics aspects of walking, considered of interest, is reported below.

REQUIREMENTS

Walking uses a repetitious sequence of lower limbs motion to move the body forward while simultaneously maintaining stance stability ([11]). The sequence performed by a single limb is called a gait cycle and can be divided into two periods: the stance and the swing phase, namely the phases during which the foot is respectively in contact with the ground and that during which it is moving up in the air (Fig. 1).

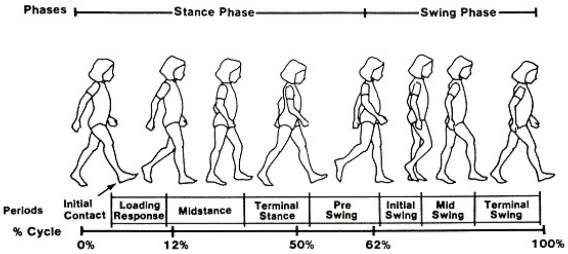


Figure 1. Representation of the phases of the gait cycle

This function is in particular the result of a series of motion patterns performed by the hip, knee and ankle in concomitance with the motion of the rest of the body. In general, these movements follow precise patterns even if varying from an individual to another, so that marked differences can be attributed to a pathology in progress. Simulating the entire gait cycle of a prosthetic leg consists then in reproducing all the kinematic and dynamic aspects that characterize periodically the limb motion of an amputee. By convention, the period of the cycle is generally taken as the amount of time that elapses between two impacts of the same foot with the ground. During this work the same convention is adopted. Trends in the sagittal plane of the angles to the joints of interest and the reaction forces exchanged with the ground, obtained from a gait analysis laboratory, are shown below (Fig. 3) with reference to the sign convention shown on the diagram of the leg (Fig. 2).

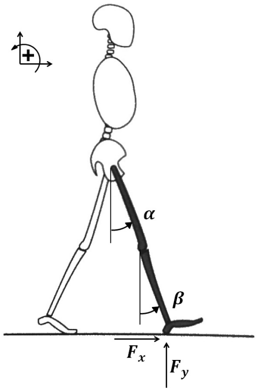
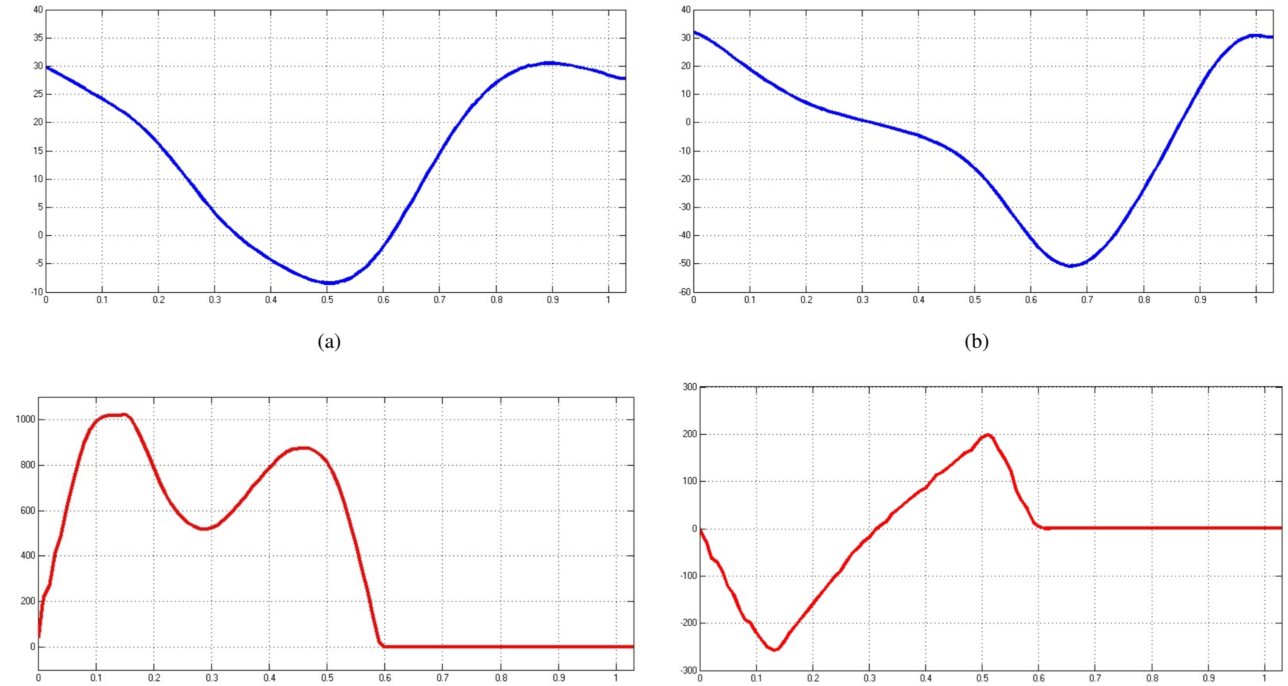


Figure 2. Assumed conventions

Trends refer in particular to the limb of a patient with trans-tibial amputation.

In addition, the intention is to meet other requirements, namely the desire to eliminate the main limitations of a previous version of the machine developed according the same purposes ([8]). Indeed, instead of using an active system control, the movement to the joints (hip and knee) was passively reproduced by imposing the motion to the foot when in contact with the guide (soil) and by exploiting the inertial and stiffness properties of the system components when moving up in the air. Thus, the motion completely depended on the dynamic characteristics of the stride resulting in a tool that did not guarantee the correct reproduction of the desired movements and furthermore did not allow to integrate different patterns of movement than that for which it was designed. The major resulting limitations verified through proper sensors ([12]) are listed below:

- inability to properly and simultaneously apply the rotations to hip and knee as it actually happens in real conditions during both the stance and swing phases;



(a) (b)

(c) (d)

Figure 3. Trend with respect to time (sec) of the angle (deg) α (a), the angle (deg) β (b), the vertical force (N) F_y (c), the horizontal force (N) F_x (d)

- obvious dynamic instability of the leg during the swing phase due to the behavior of the integrated passive elastic elements at joints.

For more details see ([8]). Nevertheless, some of the previous simplifications are maintained to avoid construction limitations:

- only the plane of walking (sagittal plane) is taken into consideration despite the motion is three-dimensional, since the movements and forces outside of the plane may be considered minor;
- the hip and knee joints are reduced to simple hinges in the same plane of walking;
- the ankle joint is not reproduced in the light of the degrees of amputation considered, and consequently of the prosthesis under studying.

Starting from these requirements the first primitive model of the bench is developed.

DEVELOPMENT OF THE MODELS

The kinematic scheme of the system is defined being known the movements and loads that distinguish a normal leg during the execution of the stride and considering the other previously mentioned requirements. In general there are various solutions that can be exploited to reproduce the type of sought function. However, not all of them satisfy the construction requirements. Among these in particular, there is the need to place the drive motor units, sources of clutter and heat, away from the prosthesis mounted on the machine. This problem can be faced by exploiting four-bar mechanisms to bypass the rotations at the joints even if this trick imposes the need of reproducing the stride in place taking advantage of the support provided by a frame fixed to the ground. However, since this is a feasible study of the system, for reasons of simplicity, the introduction of aspects that unnecessarily increase the complexity of the system, such as this, is postponed to other research activities. In light of this, the mentioned solution is applied just to reproduce the vertical motion of the hip (Fig. 5) and not the rotations to the joints, assuming for simplicity that the electric engines can be mounted on site. The resulting scheme is shown in figure 4. Once the kinematic scheme is defined, the selection of the actuators and the assessment of the capability of the designed test rig in simulating the work cycle (i.e. the step) are achieved numerically by mean of two different Multi-Body (MB) models. The first one is developed in MatLab/SimMechanics to perform the inverse dynamics study and estimate the torques to be applied to the joints to overcome the inertia loads of the structure and the reaction forces applied to the foot, once assumed the geometric and inertial characteristics

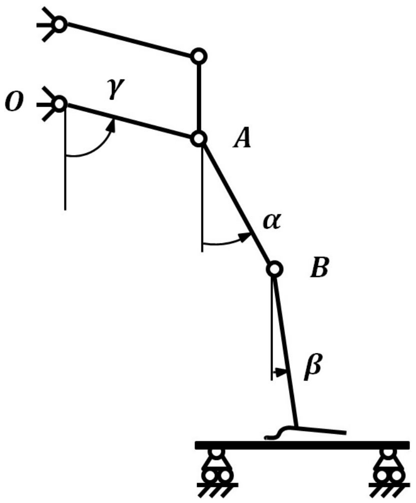


Figure 4. Kinematic scheme of the bench

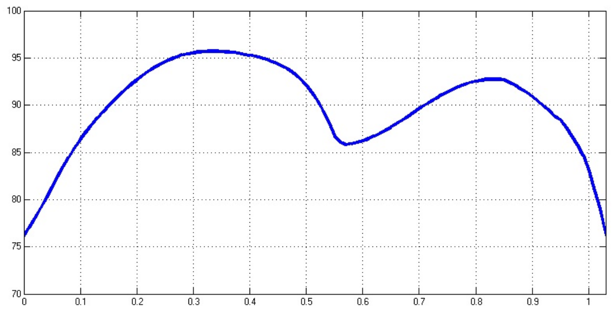


Figure 5. Trend with respect to time (sec) of the angle γ (deg)

of the components (all components are rigid). Therefore, during this phase the inertial contributions of the engines are not considered in any way. A representation of the model (Fig. 6) and the trends of the results obtained are shown below (Fig. 7).

Once assessed the possibility of reproducing the torques and chosen the appropriate gear motor units via the techniques described in ([13–15]), the second numerical model is developed. Besides taking into account the inertia of the engines, the control system required to carry out the study of the direct dynamics is implemented. It is decided in particular to run a co-simulation using ADAMS/view to develop the Multi-Body Model of the bench and MatLab/Simulink to develop the control part. The choice of using ADAMS is due to the need of implementing some aspects not otherwise considerable through SimMechanics, that is the flexibility of the prosthetic foot and the contact between the foot itself and the slide simulating the soil. The mechanical model is shown in figure 8.

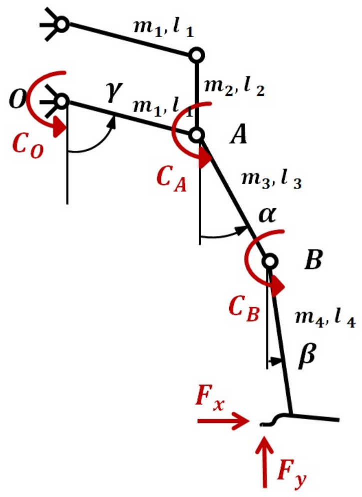


Figure 6. Dynamic scheme of the bench

Mechanical features of the model

The main features of the model are given below.

All the bodies constituting the system are rigid with the exception of the foot.

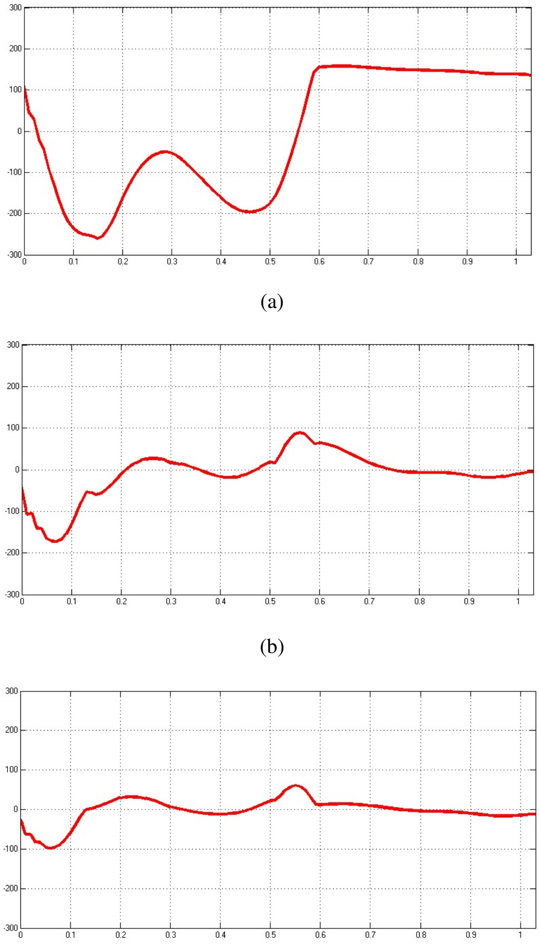
The connection between the links that simulate the tibia and femur, as well as that between the femur and the four-bar mechanism, are obtained by mean of simple planar hinges. On the other hand, the remaining connections are defined in order to avoid redundant constraints.

The reaction forces to be applied to the foot are defined by imposing appropriate contact properties between the prosthetic component and the sled that simulates the soil. The vertical component is reproduced exploiting the action of the four-bar mechanism engine and the surfaces impenetrability. The horizontal one is reproduced, instead, by introducing a Coulomb friction law between the same elements as stated in [16]. The friction coefficient is set in order to avoid slippage between the foot and the sled that could affect the proper force curve trend. Anyway, the actual technological solution, that would effectively prevent relative sliding between the two components, is not analyzed.

To simulate the weight and the inertial behavior of the engines, the corresponding masses and the appropriate inertial torques are applied respectively to the mounting points and on the bodies which act as stators.

Characteristics of the control system

Defining the control algorithms that best fit the mechanical model is the most tricky part of modeling. In particular, the different operation phases of the bench require dedicated control logics. Thus, the need to switch among different PID controllers depending on the simulation time holds. The implemented strategies are analyzed below distinguishing each phase of the stride.



(a)

(b)

(c)

Figure 7. Trend with respect to time (sec) of the torques (Nm) C_O (a), C_A (b), C_B (c)

Since the intention is to simulate the functioning of the machine starting from a rest initial condition even the initial transient phase is taken into account:

- Transient: $t = 0 - 0.5 sec$;
- Gait Cycle, Stance phase: $t = 0.5 - 1.1 sec$;
- Gait Cycle, Swing phase: $t = 1.1 - 1.53 sec$.

Throughout the transient the whole system is controlled in position. Then, during the gait cycle, the engines regulating the links rotations, via the hip and knee joints, are controlled in position to reproduce the correct kinematics known from the literature. On the other hand, the engines of the four-bar mechanism and the slide are controlled in force in the course of the stance phase and in position in the course of the swing phase. The need is in fact to reproduce the trend of the correct reaction forces during the former and to restore the system initial configuration before starting a new cycle during the latter. In addition, the performance of the four-bar mechanism control system is improved by combining the feed-back PID control with a feed-forward one. In light of these considerations, the controlled variables are: the angles α, β and γ, the horizontal displacement of the sled, the horizontal and vertical forces, i.e. F_x and F_y.

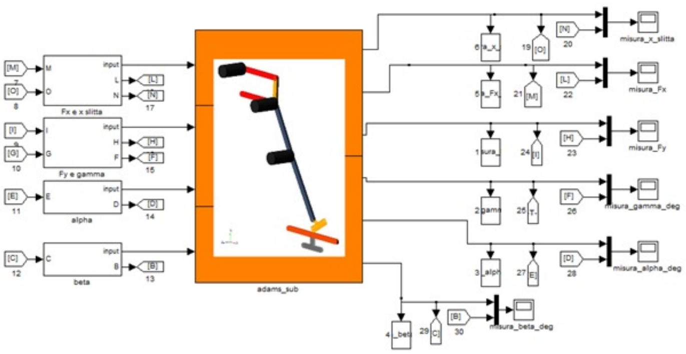


Figure 8. Representations of the Multi-Body model developed using ADAMS/view and of the control plan developed using MATLAB/Simulink

SIMULATION RESULTS

The graphs of the reference (pink) and the measured signals (yellow) of the controlled variables are shown below (Fig. 9,10,11). Given a chart, comparison between curves is meaningful depending on whether the control is performed either in position or in force.

Position control

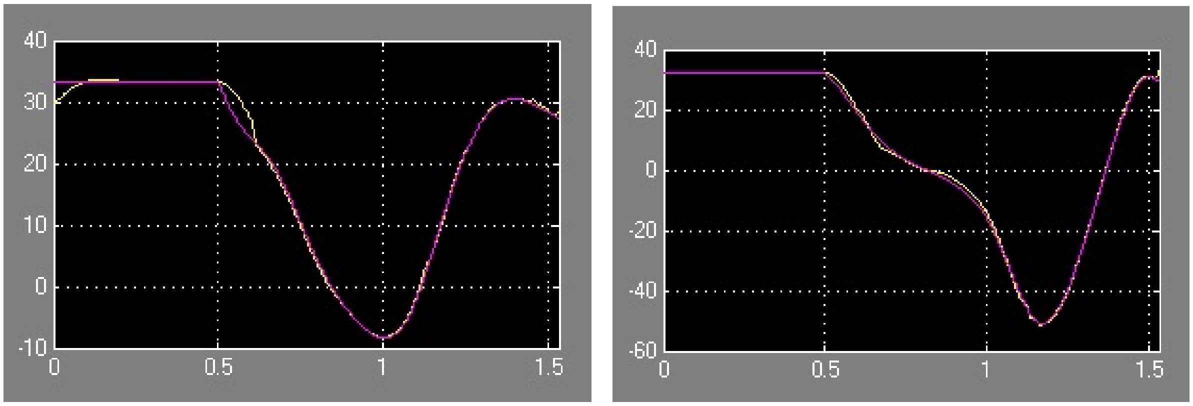
Concerning α and β, it is possible to carry out the abovementioned analysis by considering the entire duration of the simulation, since the corresponding engines are controlled just in position.

On the contrary, it makes sense performing the same comparison just during the transient (0 - 0.5 sec) and the swing phase (1.1 - 1.53 sec) when dealing with γ and the sled horizontal displacement.

Graphs show that the control system manages to follow the reference in a satisfactory manner, despite in some cases the feedback loops are in conflict with each other. For instance, the four-bar mechanism acts in contrast to the engines to the joints, augmenting α and β, early in the stance phase.

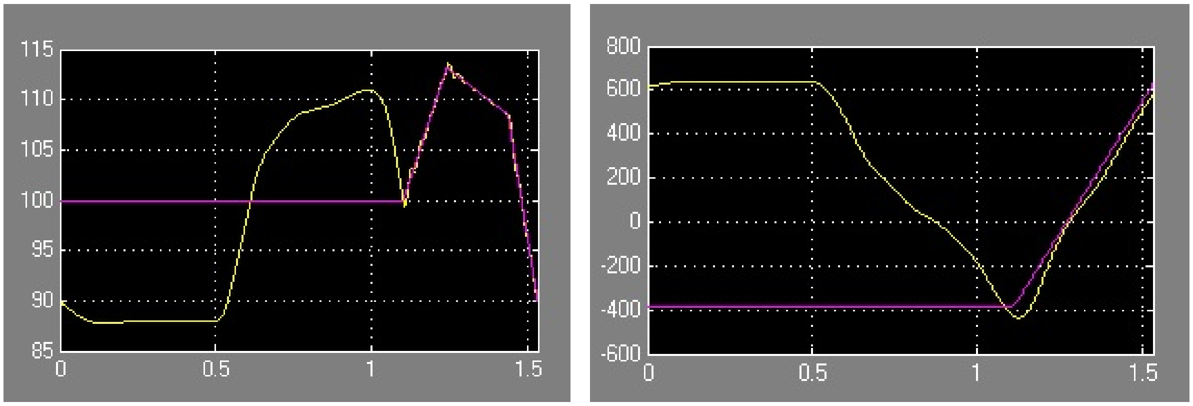
Force control

In light of the above considerations, in this case, comparison



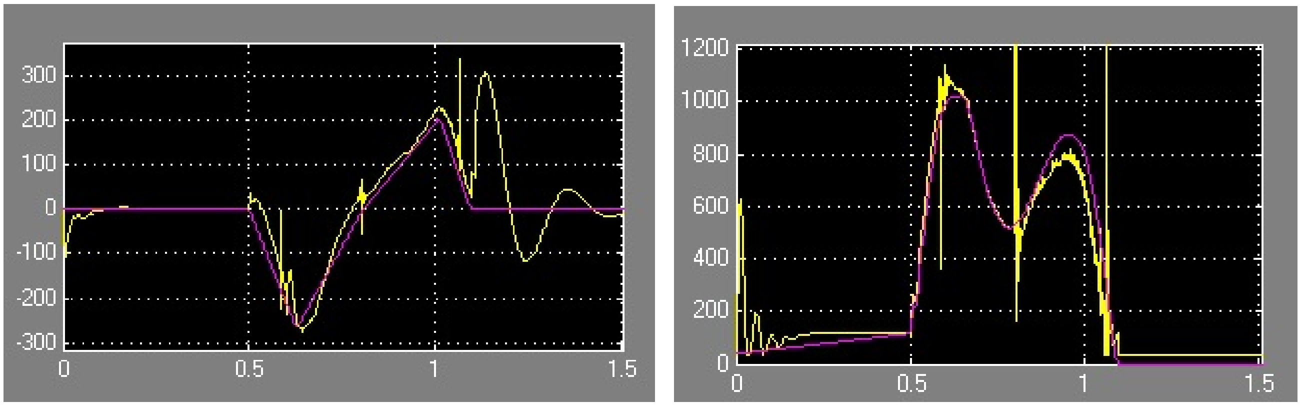
(a) (b)

Figure 9. Trend with respect to time (sec) of the reference (pink) and the measured signal (yellow) of the angles (deg) α (a) and β (b)



(a) (b)

Figure 10. Trend with respect to time (sec) of the reference (pink) and the measured signal (yellow) of the angle (deg) γ (a) and the horizontal displacement (mm) of the sled (b)



(a) (b)

Figure 11. Trend with respect to time (sec) of the reference (pink) and the measured signal (yellow) of the horizontal force (N) F_x (a) and vertical force (N) F_y (b)

makes sense only during the stance phase (0.5 - 1.1 sec), that is, when the slide is effectively controlled in force.
Compared to the previous cases, the deviations of the measured signals with respect to the references are rather obvious. These phenomena are due to slippage between the foot and the sled.

CONCLUDING REMARKS

The demand of ever more functional lower limb prostheses by patients who suffered the amputation of the lower limbs leads to the need of ensuring ever higher performances by industries. From this the need to build new test machines that allow to assess the functional performances of the prostheses, to make comparisons between them, and in general to support industries in the design and development of more powerful prosthetic devices, arises. According to this, the study of a test bench for testing lower limb prostheses is presented in this paper. A set of numerical models is developed in order to assess the feasibility of such a machine. Despite the obvious problems encountered in the reproducing the reaction forces trends to be applied to the prosthetic foot, achieved results encourage the development of more refined models. Therefore, the intention is to proceed with the design of the machine considering technological solutions closer to reality in an attempt to reproduce the walking aspects of interest.

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