Development of an Active Force Plate for Testing Lower-Limb Prostheses

Cristiano Marinelli, Hermes Giberti and Ferruccio Resta

Abstract In the recent past, lower-limb prostheses technological advancement mostly concerned the possibility of integrating ever smaller and more powerful electronic components instead of new materials and topologies. Although sophisticated, products currently on the market do not guarantee the same opportunities of their biological counterpart. According to authors' opinion this deficiency is principally due to the lack of suitable development and verification methods. As a consequence, our research group is developing a bench for testing transfemoral prostheses. The setup is briefly recalled in this paper. Then, attention is focused on the subsystem designed for reproducing the loads acting on the foot due to reaction with the ground.

Keywords Prostheses · Test bench · Gait simulator · Force plate

1 Introduction

Different solutions have been proposed in the last two decades for replacing the lower limbs after amputation surgery. On the one hand, developing a commercially viable prosthesis that is humanlike as well as economical is a challenging design problem. On the other hand, suitable development and verification methods are missing. Indeed, the legislation in force (ISO 2006:10328 [1]) merely identifies structural tests to verify the prosthetics strength properties. The ISO itself acknowledges the

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limits of the standard stating: *"Ideally, additional laboratory tests should be carried out to deal with function,. . . , and user activities as part of the evaluation procedure. There are no standards for such tests, so appropriate procedures will need to be determined. "*.

The need to introduce the user behavior in the development and verification process is not recent, several solutions have been proposed in the literature. Among these, in-vitro experimental procedures [2–4] demonstrate several advantages over in-vivo ones [5, 6] in terms of reliability, versatility and safety. It is therefore foreseen that robotic testing will play a greater role than human gait trials in the development process of prosthetics. However, there is no system yet able to completely achieve the aforementioned purpose. In particular, the possibility to apply full scale forces is still an open issue. As a consequence our research group is developing a novel bench for testing the functional properties of transfemoral prostheses considering working conditions more realistic than those achieved in the literature. The setup is briefly recalled. Further information may be found by the reader in [7]. Afterward, attention is focused on the innovative solution defined for reproducing the loads acting on the foot due to reaction with the ground.

2 System Mechanical Architecture

The gait simulator (Fig. 1) exhibits 8 degrees of freedom (DOFs) and consists of two main subsystems. These are respectively used to replicate the series of motion patterns performed by the residual segment of the limb and the trend of forces acting on the prosthetic foot due to reaction with the ground. The first task is accomplished through a 6-axis manipulator having suitable motion and payload capabilities. On the other hand, the second is accomplished through a custom 2-axis active force plate whose longitudinal and vertical progression are respectively driven through a toothed belt linear guide and an active air spring. The employment of this pneumatic actuator has not yet been evaluated by other authors even if two merits are related to its usage: the compressibility of the gas and the intrinsic stiffness of the bellows

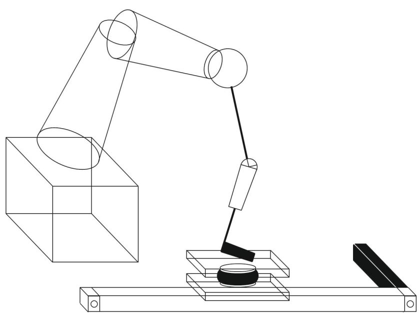

Fig. 1 Schematic representation of the gait simulator

ensure a smooth transfer of the load during the initial contact phase enhancing the stability of the system; the high power to weight ratio of this kind of solution guarantees a mass reduction and therefore a stress attenuation at the electric motor driving the longitudinal progression of the carriage.

From a functional point of view, the solution proposed allows to define two independent control strategies in longitudinal and vertical direction. On the one hand, the use of a linear guide determines the need to alternately implement two control logics: force and position control. The former is active during the entire stance phase in order to reproduce the correct value of the force acting on the foot due to reaction with the ground in the longitudinal direction. The latter contributes instead to return the carriage to its initial position before the beginning of the next cycle, that is, before the end of the swing phase. The contact force in the vertical direction allows to detect the walking phase, either stance or swing, and therefore to choose the control strategy to be applied. In addition, the vertical force itself is used to modulate the selection matrix so as to change the control mode as smoothly as possible [8].

On the other hand, the intrinsic stiffness of the bellows allows to control the air spring exclusively in terms of force during all the phases of the test. During the swing phase the pneumatic actuator supply the force necessary to hold the force plate at the maximal vertical height, i.e. the force necessary to support the weight of the plate itself and the elastic return of the spring bellows. The same force is supplied during the initial contact stage while being dragged downward by the movement of the foot, which is subjected to an increasing force due to the simultaneous return of the spring to its resting length. When the force is high enough to ensure a stable contact condition the inner pressure is modulated so as to reproduce the correct gait analysis trend of vertical force. Finally, when the force drops below the predetermined offset value, the application of the initial constant force results in a gradual decrease of the load applied to the foot and the return of the platform to the initial height.

3 Mechanical Design of the Foot Loading Subsystem

Once identified a linear guide (NC Componenti LPA RH80-15) and an air spring (Norgren PM/31041) suitable for the application the active force plate is designed in order to: accommodate the air spring, fit the shape of the carriage of the linear guide and introduce the measurement equipment. In particular, the main quantities to be collected during the procedure are the contact force between the foot and the plate representing the ground and the vertical displacement of the plate itself. Apart from being useful parameters for evaluating the performance of the prosthesis under test, these quantities are indeed essential in terms of control purpose. In particular, it is necessary to design and build a force plate that can separately collect data along 2 axes in order to avoid measurement interferences.

The final solution satisfying these needs follows from the equipment presented in [9] for identifying the mass matrix of people standing in a quiet upright position. It consists of a horizontal rigid plate and two vertical flexible foils designed

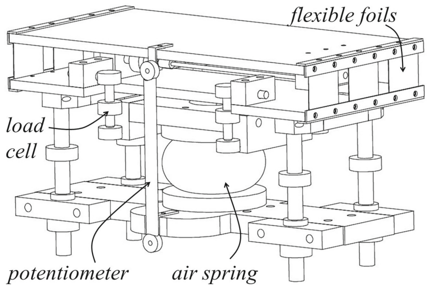

Fig. 2 Perspective view of the active force plate architecture

to offer high rigidity in vertical direction and low rigidity in longitudinal one. As a consequence, the solution ensures complete transmission of the vertical force so that it can be successively measured, and access to the longitudinal force starting from the deflection of the structure. Both the force components are measured by means of strain gauge load cells (Honeywell Precision Miniature Load Cell). On the other hand, the vertical displacements is measured through a linear potentiometer (DSPM Industria CLS1322). A schematic representation of the solution is shown (Fig. 2). The dimensions of its structural components are assessed by performing finite-element (FE) simulations in SolidWorks.

4 Mathematical Model

The system may be modelled as a mass moving in the sagittal plane under the effect of the force supplied by the air spring and the linear guide as well as the load applied by the foot both in vertical and longitudinal direction. The equations are given below with reference to the following scheme (Fig. 3). The first term is significantly affected by the dynamic behavior of the air within the pneumatic circuit. In this case the use

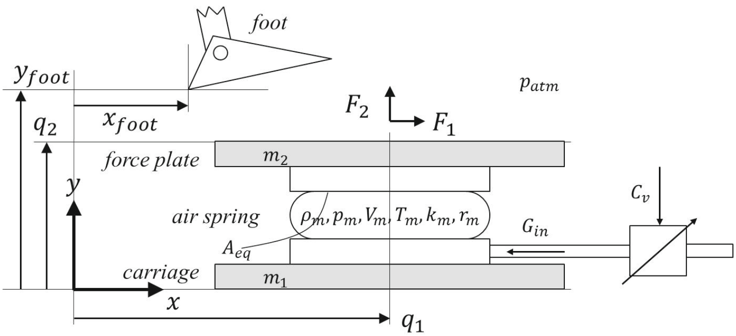

Fig. 3 Schematic representation of the problem under study

of reservoirs, compressors and long pipes is not expected. As a consequence, only the thermodynamic transformations of the gas within the air spring [10], the physical characteristic of the bellows and the mass flow-rate in the servo-valve are considered [11–13]. Their behavior is described by the following set of equations:

$$
\begin{aligned}
F_m = A_{eq}\left(p_m - p_{atm}\right) - k_m\left(q_2, p_m\right)\left(q_2 - q_{20}\right) - r_m\dot{q}_2 \\
\dot{p}_m V_m + k p_m \dot{V}_m = k G_{in} R T_m \\
V_m = A_{eq} q_2 \\
T_m = \left(\frac{p_m}{p_{m0}}\right)^{\frac{k-1}{k}} T_{m0}
\end{aligned}
$$

$$
G_V = \begin{cases} C_V p_1, & if\ \left(p_2/p_1\right) \le b_v \\ C_V p_1, \sqrt{1 - \left(\frac{(p_2/p_1) - b_v}{1 - b_v}\right)^2} & if\ \left(p_2/p_1\right) > b_v \end{cases}
$$

where F_m is the air spring thrust force, p_m, V_m and T_m are the spring inner pressure, volume and temperature, k_m and r_m are the intrinsic stiffness and damping of the bellows, q_{20} is the spring length when $p_m = p_{atm}$, the atmospheric pressure, A_{eq} is the equivalent area, G_{in} is the mass flow-rate entering the air spring, C_V represents the valve opening, p_1 and p_2 are the upstream and downstream pressures of the valve, b_v is the critical pressure ratio, k is the specific heat ratio and R is the gas universal constant.

The second contribution is modeled neglecting many aspects that unnecessarily complicate the issue. For example, the model of the electric motor is not considered. Similarly, the dynamic effect of the flexibility of both the belt and the transmission is neglected as well as the backlash in the reducer unit. The force applied by the motor to the carriage can therefore be computed simply as $F_e = T_{ml}/R_p$ where T_{ml} is torque applied at the load shaft and R_p is the radius of the pulley. Finally, the reaction force due to contact of the foot with the plate are modeled. The Karnopp friction model is introduced in order to define the longitudinal force component [14]. The following set of three ordinary differential equations is considered:

$$
F_{fric} = \begin{cases} -|F_t| sign(F_t), & if\ v_s = 0 \wedge |F_t| \le F_{lim} \\ -\mu_s |F_n| sign(F_t), & v_s = 0 \wedge |F_t| > F_{lim} \\ -\mu_d |F_n| sign(v_s), & else \end{cases}
$$

where F_t is the net force applied tangent to contact surface, F_n is the net force applied normal to contact surface, μ is the friction coefficient, $F_{lim} = \mu_s \left|F_n\right|$ is the static friction limit, v_s is the sliding velocity and v_{th} is the threshold velocity.

A penetration contact model is exploited instead to compute the vertical one. In particular, the vertical component is calculated as the sum of an elastic and a viscous contribution as follows:

$$F_c = -k_c d - r_c(d)\dot{d}$$

where k_c and r_c are the stiffness and damping contact coefficients and $d = q_2 - y_{foot}$ is the penetration value. The parameters and coefficient useful from the implementation point of view are obtained starting from the literature [15]. The gravitational and inertial forces are finally introduced to definitely compute F_1 and F_2, i.e. the total amount of force acting on the system respectively in longitudinal and vertical direction:

$$F_1 = F_e + F_{fric} - (m_1 + m_2)\ddot{q}_1$$
$$F_2 = F_m + F_c - m_2(g + \ddot{q}_2)$$

The total mass is estimated starting from the CAD model of the force plate (Fig. 2) being known the density of its components: $m = m_1 + m_2 \approx 15\,\text{kg}$.

5 Results

The nonlinear numerical model of the problem under study is developed using both the Simulink and SimMechanics. SimMechanics is used to model and simulate the mechanical properties and the motion possibilities of the bodies constituting the system, that is, the foot and the force plate. Simulink is used instead to implement the equations describing the behavior of the pneumatic actuator, to estimate the reaction forces according to the aforementioned contact model, to apply the PID controller, and to compute both the force and position reference signals online as a function of the current state of the system. During the experimental test procedure the behavior of the prosthetic device may indeed vary from cycle to cycle preventing the possibility to implement standard reference signals. In particular, during the stable contact condition the vertical reaction force is simply reproduced through a sine function. The longitudinal force is computed instead on-line as a function of the vertical reaction force based on a linear correlation found between the two components:

$$dF_x(t)/dt \approx AF_y(t) - B$$

Finally, the law of motion necessary to take the carriage back to the initial position is computed as a function of the actual position and velocity of the carriage itself at the end of the stance phase. Figures 4 and 5 show the trend of the reaction forces achieved respectively in vertical and longitudinal direction. These are comparable only qualitatively with the physiological trends reported in the literature about gait analysis. Despite small, the deviations are principally induced by the techniques used for computing the approximated force references on-line as a function of the state of the system. Anyway, greater affinity might be achieved using different strategies.

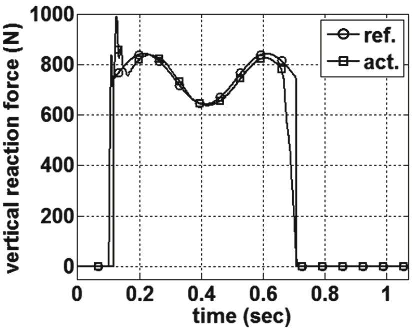

Fig. 4 Trends of the reference and actual vertical reaction force

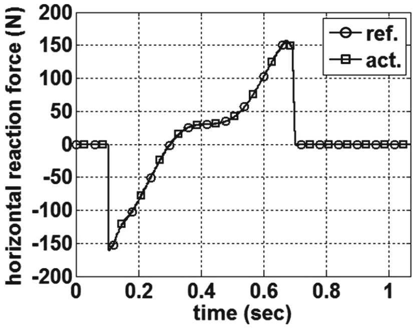

Fig. 5 Trends of the reference and actual longitudinal reaction force

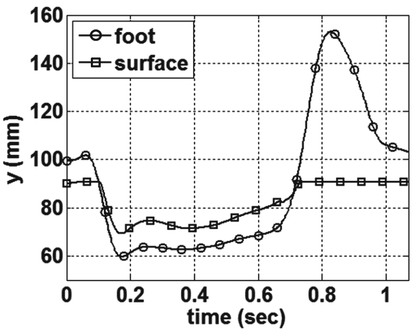

Fig. 6 Trend of the foot and contact surface vertical displacement

On the other hand, the hardware solution implemented allows to successfully reproduce the force components both in terms of amplitude and duration. Moreover, the pneumatic actuator allows to restrain the force peaks at the beginning of the contact stage.

Results are good also in terms of position. The subsystem is indeed able to recover both the vertical and longitudinal initial position before the beginning of the next cycle (Figs. 6, 7). Finally, the trend of the air spring inner pressure (Fig. 8) and the trend of the torque supplied by the motor (Fig. 9) are shown. Both the trends are

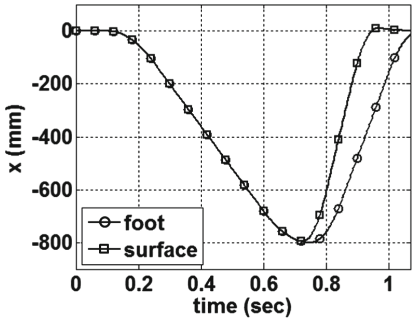

Fig. 7 Trend of the foot and contact surface longitudinal displacement

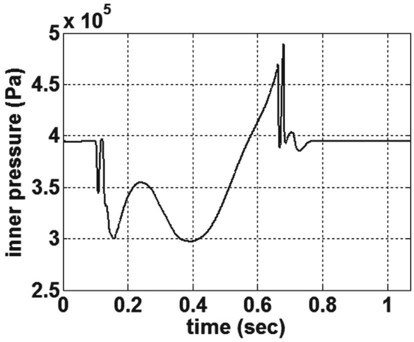

Fig. 8 Air spring absolute inner pressure

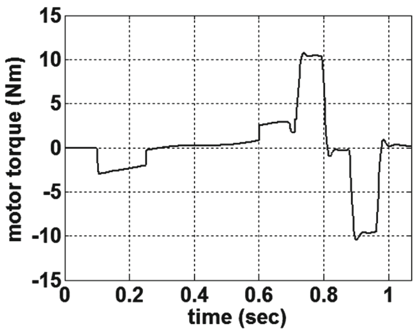

Fig. 9 Torque supplied by the motor

compliant with the commercially viable equipment. In addition, Fig. 9 demonstrates the ability of the selection matrix implemented in longitudinal direction to avoid sudden reference changes and therefore spikes that may jeopardize the stability of the system.

6 Conclusions

The research activity presented in this paper dealt with the development of a novel bench for assessing the functional performances of lower limb prostheses. The mechanical architecture of the rig was first introduced. Thereafter, the attention was focused on the mechanism necessary for reproducing the loads acting on the foot due to reaction with the ground during normal walking. Both the mechanical design and the operation procedure were reviewed. Then a numerical model was set up in order to assess the merits and limits of the proposed solution.

From this point of view the decision to reproduce the vertical reaction force through a pneumatic actuator resulted successful. Besides restraining the force peaks, the air spring has indeed a bandwidth wide enough for the application. Deviations from the physiological trend are more evident in longitudinal direction. However, better results may presumably be achieved by changing the strategy for computing the reference on-line as a function of the state of the system.

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