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# Design of a Mechatronic Device for Measuring Stump Stresses on Transfemoral Amputees

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**Abstract:** This study is devoted to the design of process for a low-cost mechatronic device intended for measuring the lower limb amputee stresses. This development is based on a biomechanical analysis and the force data obtained in a gait laboratory whereof a force and stress analysis over the stump-socket interface could be done. Later, gait critical conditions are simulated for acquiring the theoretical results needed to do a sensors selection (Flexiforce-Teckscan®). Once the selection is done, a sensors mesh is presented as a measuring device as well as the electronics for signal conditioning and the software for results analysis and presentation. This device is calibrated and validated by means. Finally, the device assembly is done with commercial prosthetic elements in order to proceed with the critical conditions tests and to get the experimental data. The data is compared with the theoretical results as the designed device validating stage.

**Key words:** Socket, stump, stress, biomechanics, interface, assembly

## INTRODUCTION

The rehabilitation process after an amputation is very important for victims and physicians play a key role. During rehab, patients use prosthetic devices and the socket is the part of them that allows transferring forces of the leg stump to the rest of the device. Therefore, this proposal shows a tool for diagnosis, through a device that measures the pressure on the leg socket-stump interface in order to improve rehab methods and support the best diagnosis for physicians and patients.

The gait could be described as a dynamic system where the reaction force and the contact surface change according to the patient cadence. During gait, from the back of heel to the lifting of forefoot there are forces widely higher than corporal weight and also generate a foot plantar pressure more elevated than the one at standing on natural and relaxed position (Lacuesta *et al*., 2005).

Several prosthetics researches have been developed on models which describe the behavior of socket stump through pressure analysis. Distributed pressure identification on the socket stump interface was proposed for people with lower limb amputation (above knee) they developed a socket model through Finite Element Analysis (FEA) (Tanaka *et al*., 1997). The stress identification was formulated for minimizing the elastic energy the most plausible stress was sought based on watched deformation.

A pressure measurement device was designed for the socket of 48 trans-tibial amputees, studying the behavior of the silicone as interface between stump and socket, analyzing statistically and concluding that pressure exerted by the stump over socket depends on the alignment made by physicians which allow defining the pressures on the front and the back of the residual member. The equipment used for pressure measurement was F-scan sensors from Tekscan. The sensor network is composed by four arrays distributed in the socket which carried out a biomechanical analysis that determined that the anterior, posterior and lateral surfaces showed higher pressure (Dumbleton and Buis, 2009).

**Dynamic of the interfase:** The devices used to measure pressure work with the mechanical concept of forces and moments. In this case of study, forces are produced by a prosthetic device with a rigid element (e.g., prosthetic foot with the ground where reaction forces and moments are generated by contact with the ground). This forces are reflected on the interface and therefore on the person. The dynamic event analysis is based on Newton's second law, with the calculation of forces and moments. By Jia *et al*. (2004), Fig. 1 shows the gait force and moment diagram at

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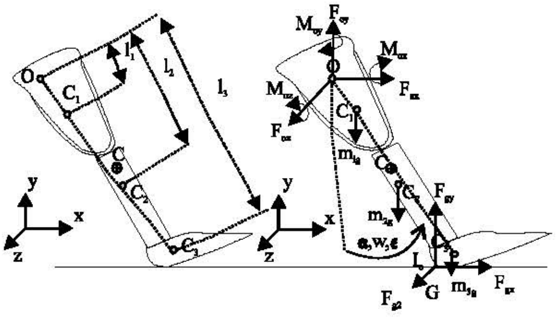

Fig. 1: Diagram of forces and moments

the back of heel phase on 3D Cartesian planes (x, y, z). The knee rotation as the sum of moments with respect to the origin O (Eq. 1):

$$M_{oz}\text{-}m_1g_{i1}\sin b\text{-}m_2g_{i2}\sin b - m_3g_{i3}\sin b+F_{gx}y_G+F_{gy}y_G = I_o f \quad (1)$$

Where:

b = The angular displacement on sagittal plane

$m_1$,-$m_3$ = The stump, socket-tube and prosthetic foot masses, respectively

$l_1$-$l_3$ = The distances from center of mass to origin

The sum of x and y moments regarding O (Eq. 2 and 3):

$$M_{0x}+F_{gz}y_G+F_{gy}z_G = 0 \quad (2)$$

$$M_{0y}+F_{gz}x_G+F_{gx}z_G = 0 \quad (3)$$

Equation 4-6 show the sum of forces on the different coordinated axis (x, y, z):

$$F_{ox}+F_{gx} = (m_1+m_2 + m_3)(r_f\cos b\text{-}r_{p2}\sin b) \quad (4)$$

$$F_{oy}+F_{gy} - (m_1+m_2 + m_3)g = (m_1+m_2+m_3)(r_f\sin b\text{-}r_{p2}\cos b) \quad (5)$$

$$F_{oz}+F_{gz} = 0 \quad (6)$$

Variable p is angular velocity, f is angular acceleration and r is the distance from the origin to the center of mass of entire model (Uriostegui *et al*., 2007).

## MATERIALS AND METHODS

**Sensor network design:** Based on Eq. 4-6, it was determined that the maximum force exerted on the interface was 26.1 N and corresponds to the force (Jia *et al*., 2004) $F_{ax}$. Besides, the previous work results established that gait pressures of a transfemoral amputee correspond to the 32% of the amputee bodyweight per cm. Hence, the proposal is to use the Flexiforce A301 sensor (120 N of nominal pressure), considering that the measuring area (0.2827 cm$^2$) implies 9.04% of bodyweight. This sensor works as a variable resistance on an electric circuit, so that, its value is higher than 5 MΩ when there is no load applied and it decreases when applying (Mejia *et al*., 2010).

A network sensor was designed to allow measuring pressure in the socket. This design has 5 force sensors which established a hotspot for estimate the pressure on the grid made of a sheet of acetate, due to its flexibility and low thickness, Fig. 2a shows dimensions of the grid.

The electronics for signal conditioning was based on manufacturer's recommendations which states that an operational amplifier must use at inverter configuration by adjusting the resistance $R_2$ to determine the gain configuration. Figure 2b shows the electronic network sensor circuit. A simulation was made to determine $R_2$ as 85 kΩ and thus, the sensor voltage output as (0-8 V).

$$(\sum y_u\text{-}n)^2)\,/_{\sigma^2 \sim x_n^2} \quad (7)$$

An experiment was designed to assess the measurement error, based on statistical analysis, according to sensors hysteresis. This allows calibrating each sensor using ji-square method, Eq. 7 (Box *et al*., 2008).

**Test bench:** A machine for structural testing of prosthetic devices was performed, following the international standard ISO 10328 which determines the critical load conditions which lower limb prostheses must be submitted. A pneumatic system with closed loop control system for testing was implemented, according to the standard requirements. The standard establishes different test arrangements which recreate the configurations in which the maximum pressure occurs (Jimenez *et al*., 2012).

In this research, a user interface was designed for performing the tests according to standard where there was a heel-support static test setup, allowing reproducing a critical moment in the amputee gait. In order to understand the test, it was defined an amputee with 80 Kg of weight.

According to Lacuesta *et al*. (2005) there is a value of 120% of weight during gait. Therefore, the pneumatic actuator force was established to a maximum value equivalent to 960 N (100% is 80 kg of weight). Being this one of the parameters for the design of the control system of the test bench.

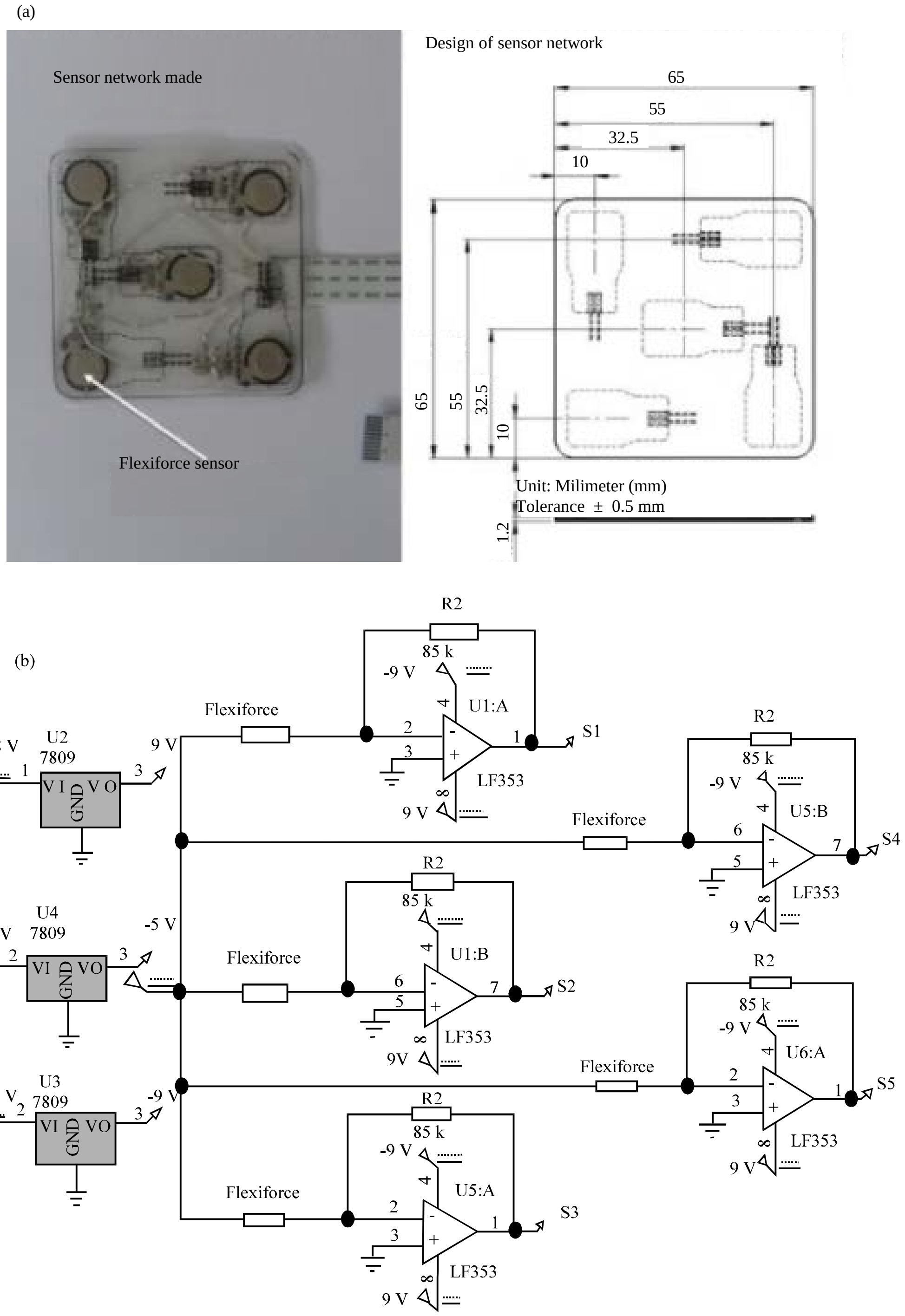

Fig. 2: Sensor scheme and electronics: a) Design and sensor network made and b) Electronic network sensor circuit

The close loop control was design base on advance control theory where was implemented a sliding mode control with differential flatness, considering the pressure in the pneumatic actuator as the nonlinear variable to controller.

For this variable, it's necessary realize an identification the plant for complete modelling test bench in two parts for simplification the process design controller. The first part was an open loop identification where the input is a step to the system is observed that the actuator does not pause in a position nor in a pressure intermediate on the contrary, according to the magnitude of the step arrives faster to final position (mechanical limit) and the pressure of feeding of 600 kPa by the previous thing, it is not possible to realize an identification process in open loop of the system because the dynamics are only stabilized by mechanical limits (Monje, 2006).

To perform an identification process that reproduces the dynamics of the system, a pre-stabilization process is performed where it is identified in closed loop using a PID controller by auto-tuning (Bueno, 2011).

The second part is closed loop identification where a PID is proposed with a tuning of the constants in order to achieve an intermediate pressure value, initially neglecting the establishment time, the steady state error and the type of response. The control loop is closed by feedback of the pressure difference in the actuator chambers to evaluate the error according to the desired pressure reference in Fig. 3. The data obtained for the identification of the plant are observed in Fig. 4.

The pre-stabilized system permit the identification with MATLAB® ident tool which provides a parametric model from the experimental input and output data of the system (off-line) to design an advanced control for the ystem identified as the real system, so that, the control signal can be used for both plants which will have a similar dynamic.

For the selection of the appropriate identification model, several parametric models of 4th and 5th order (according to the theoretical model of Jimenez *et al*. (2012) were evaluated that consider both measurement noise and load disturbances, comparing the transient response, the relation of the output and the model of the waste. This type of perturbations and considering that its structure is not complex as the system, we use ARX process models which are autoregressive with exogenous input and are based on the method of least squares optimization (Rodriguez and Bordons, 2005). The representation of states of the linearized and identified model is shown in Eq. 8:

$$\tilde{x} = \begin{bmatrix} -530.6\times10^{4} & -8.4\times10^{4} & -1.1\times10^{6} & -3.8\times10^{6} \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} u \quad (8)$$

$$\tilde{y} = \begin{bmatrix} 0.83e4 & 30.16e4 & -1.08e6 & 3.90e6 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}$$

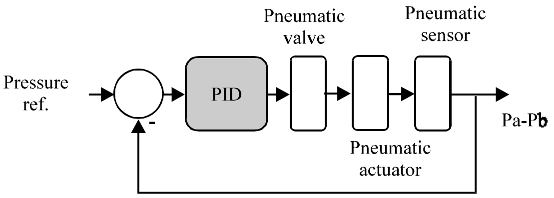

Fig. 3: Closed loop identification scheme

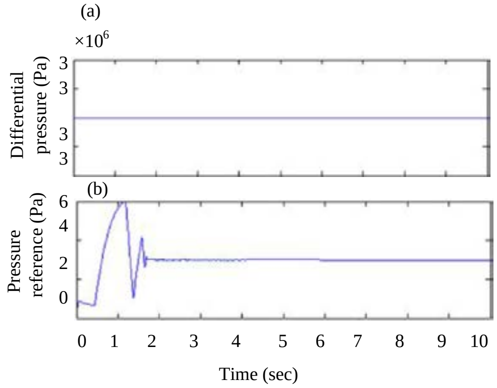

Fig. 4: a) Input and b) Output of the identified model

where, the states of the identified system are obtained which do not have a direct relation with the states of the real system allowing the output to describe the same dynamics.

Once the identified model has been obtained and the parameters of the amputee, the controller for the pressure difference and areas of actuator (Piston), according to Eq. 9 is designed.

$$F_0 = F_A - F_B = P_A A_A - P_B A_B \quad (9)$$

where, $F_0$ is the output force, $A_A$, $F_A$ and $P_A$ are the area of the piston, force and pressure in chamber 'A' and $A_B$, $F_B$ and $P_B$ are the area of the piston, force and pressure in the camera 'B', respectively.

The advanced control is made up of two techniques, the first is differential flatness where according to Morillo, the concept of differential flatness indicates that the states and inputs of a system can be expressed as functions of a set of differentially independent outputs, so that, problems such as stability, transition between points and trajectory tracking are easier to solve because they are not subject to any dynamics.

Therefore, a pressure controller is proposed by sliding modes in the space of the flat outputs whose reference variable is designed by means of a Bezier interpolation polynomial that allows to smooth the transition between desired values, so as to reduce sudden peaks in the control signal (Flores *et al*., 2011). This polynomial describes a curve composed of a proportional relationship between the initial and final points of the transition ($y_1$, $y_2$) and a Spline polynomial which passes through all the control points that define the shape of the curve and are created in the order of Polynomial defined by Eq. 10 and 11 (Pina, 2001):

$$P(t) = a_1 t^{n+1} + a_2 t^{n+2} +,\dots,\ a_{n-1} t^{2n+1} \tag{10}$$

$$F^{\square} = y_2 + (y_2 - y_1)p\left(\frac{t}{T}\right) \tag{11}$$

Where:

P(t) = The spline polynomial
n = The order of the system
t = The time
T = The transition period
$a_i$ = Constants that are calculated according to the order of the system
F = The controller reference

According to Ramirez and Agrawal (2004) and Conde *et al.* (2009), if a SISO system is controllable, it is differentially flat and its flat output is obtained from the last line of multiplication of the inverse matrix of controllability by the state vector. In this way, we obtain the flat output and its n-1 derivatives for the linear system of Eq. 12:

$$F = x_4;\dot{F} = x_3;\ddot{F} = x_2;\dddot{F} = x_1;F = A_{1.1}x_1 + A_{1.2}x_2 + A_{1.3}x_3 + A_{1.4}x_4 \tag{12}$$

For sliding mode control, the sliding surface based on the integral reconstruction of non-measured state variables is proposed as shown in Eq. 13, where it is also observed that a second integral term is added to compensate for the error in steady state:

$$\sigma = \dddot{F} + k_4\ddot{F} + k_3\dot{F} + k_2F(F-F^{\square}) + k_1\int(F-F^{\square}) + k_0\iint(F-F^{\square}) \tag{13}$$

where, σ leads to a dynamics of the fifth order, so, when a characteristic polynomial of Routh-Hurwitz is proposed, a system of compatible equations is considered and the constants $k_i$ are determined. From the resulting equation and from equation of mass flow of piston, we obtain the equivalent controller as the means to restrict the system dynamics to the sliding surface (Eq. 14):

$$u \in q = -(A_{1.1} + k_4)\dddot{F} - (A_{1.2} + k_3)\ddot{F} - (A_{1.3} + k_3)\dot{F} - A_{1.4}F - k_1(F-F^*) + \int(F-F^*) \tag{14}$$

In addition, the sliding surface is globally attractive by the continuous approximation by Ramirez (1993) for the discontinuous dynamics of the controller, i.e., it is forced to comply with the dynamics of the equivalent control by Eq. 15 which depends on a constant 'L' tunable:

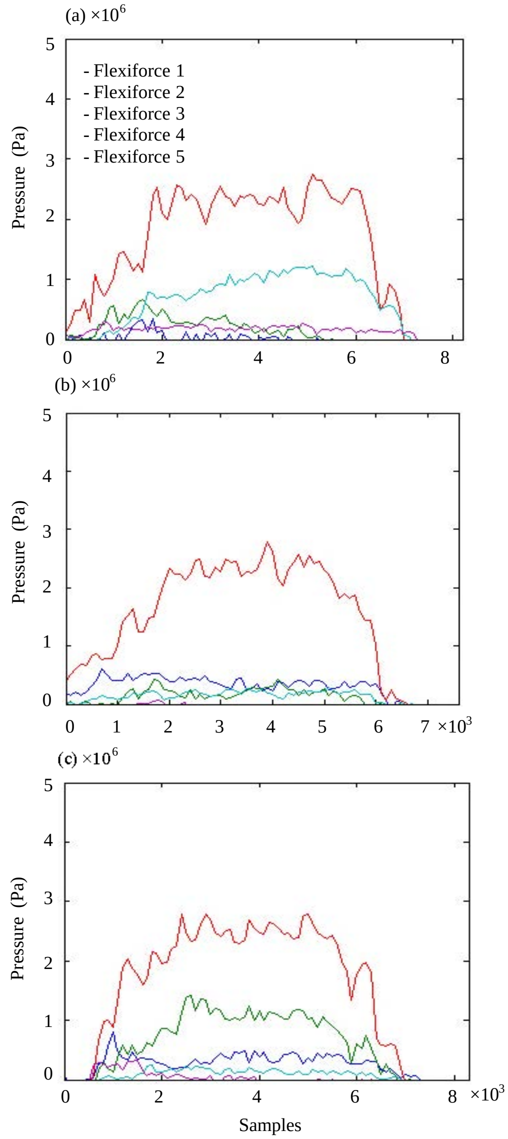

Fig. 5: Pressure chart of device: a) Test 1; b) Test 2 and c) Test 3

$$u_N = -L\operatorname{sgn}(\sigma) \tag{15}$$

Finally, it will be assumed that, the control signal supplied to the pneumatic system and to the reference system is the sum of the equivalent control and the attractive control. With the above the test of the device to measure pressure was realized and thus obtain the results to determine if it works the design raised in this project, the test assembly shown in Fig. 5 was performed.

Fig. 6: Assembly on the test machine

## RESULTS AND DISCUSSION

As a result, the pressure was recorded with the prosthetic device in the test bench with 3 static tests performed over the stump anterior surface and 960 N of applied force. For each test a socket for transfemoral amputee was used. Based on the foregoing an artificial stump was fabricated with human skin characteristics according to the state of the art (ballistic gel). Figure 6 shows the values recorded by the network which shows that central sensor has the greatest pressure.

The maximum pressure is generated in the anterior region in a 1 $cm^2$ area of pressure sensing at a maximum value of 32% of body weight. Therefore, it was established that pressure is equal to 2.51 MPa with an error of 0.12. Performing the calculation recorded by the device designed, it was established that the area of pressure is equal to 0.2827 $cm^2$ and the perceived weight percentage of the sensor network in this area is equivalent to 9.04% of bodyweight. The value obtained was 2.53 MPa with an approximate error of 0.13. The comparison between the results of the studies reported in the literature and the device designed, determine that the device is consistent and their measurements are accurate.

## CONCLUSION

Added value to the device as designed is its low cost, also serve to support the medical diagnosis in terms of the pressures on the interface. It shall identify possible errors in the manufacture of the socket or pathologies of the amputation. These anomalies in the stump-socket interface can cause skin damage or interfere with the rehabilitation of an amputee patient. It was also determined that the device, its physical properties will not affect the progress of an amputee when used.

## IMPLEMENTATIONS

The implementation of a controller with advanced control and identification techniques allows manipulating and solving systems where the behavior of the system is non-linear. Also, laboratory test of the device for pressure measurement under conditions simulating the progress of a transfemoral amputee was provided, giving an approximation of the actual behavior in patients of the pathology described above.

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