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REAL-TIME ADAPTIVE SUSPENSION USED FOR LOWER LIMB PROSTHESIS

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Abstract: *The suspension system of the lower limb prosthesis has the main role of maintaining the permanent and safety contact with the limb during the daily activities even though there are some significant changes of volume, circulatory diseases, mechanical stress and so on. It has been designed the system based on pneumo-mechatronic components that has to assure the contact force acting on the skin. The suspension system comprises a network of dry-air inflated cells with very well controlled pressure. A detailed analysis was made, so that when the working conditions may influence the values of this force the pressure will be increased or decreased accordingly. The results of the tested system revealed the short time needed for control and the adaptive performances were proven.*

Key words: *lower-limb prosthesis, prosthesis control, adaptive system, mechatronic system, pneumotronic*

1. INTRODUCTION

There are many surveys indicating the increased number of amputees during the last years, and it should be analyzed as a worldwide problem, so that the demanding for mechatronic systems design applied to the lower limb prosthesis has become essentially. Consequently, especially for the suspension system as the most important subassembly, because of the role of assuring the safety and the normal life after the experienced trauma, the newest research has found their place. There are many efforts and studies that have conducted to the development of real-time adaptive suspension, including smart actuation, sensors, and transducers to improve the performances.

Some factors could influence the safety contact between the limb and the socket, such as limb volume variation during the daily activities, or alternatively during the day and night, changes in the body weight, and even the edema that may influence the size of the limb. Even though the socket fits properly at the beginning, we must analyze it as a complex process considering the objective causes affecting the health and the life quality of the patient, so we may mention unbalanced lower-limb prosthesis and human body system, material friction coefficient, irregular external shape of the limb, whose effects could produce ulcers, dermatitis infections, and some other diseases.

Therefore, we aim to permanently control the way the contact with the skin is done and to find out some properly solutions adapted to each patient. The paper [1] described a solution for preventing the limb volume variation by providing the real-time measurement and the most useful information regarding the concept of electromagnetic suspension.

The electromagnetic suspension is embedded in the socket and a feedback loop was implemented to control the attractive force. The microprocessor controls the electromagnets according to the pressure sensor output from within the sockets. The most important advantages of this solution are the opportunity of preventing the loss of contact with the limb, not only to accommodate it with the attachment, as well as the benefits of controlled pressure values. The authors of the paper [2] have used the bioimpedance analysis based on the elevated and no elevated vacuum sockets. Bioimpedance takes the advantages of the difference in response of different biological structure to electrical current that will pass through cell-free biological fluid with frequencies between 5kHz and 1MHz. By processing the very sensitive measured data based on this technique, the extracellular and intracellular fluid volume could be determined. The decreasing of residual limb volume could conduct to increasing the stress of bony prominences. Meantime, the increasing of volume will increase the pressure and the blood flow will be restricted. The elevated vacuum, also termed vacuum assist could be a solution for reducing limb fluid volume especially for people who otherwise may experience the consequences of this process during the day. The paper [3] revealed the way the fluid volume changes in the residual limb were affected by resting, standing, and walking. The bioimpedance method was used for measuring the extracellular fluid volume. This study with 24 volunteers has had the following results: the highest mean fluid volume was during stand. On average, subjects gained fluid volume during walk and rest. Not all participants lost fluid volume during walk, so eight of them have lost while sixteen gained. Not all participants gained fluid volume during rest, so fifteen participants gained fluid volume, while nine lost. The main conclusion was that the fluid volume loss is during stand than during walk, and the volume losses appeared during stand than during rest.

As we may infer from the papers presented above, the real-time area of contact with the stump is critically affected mainly during standing, but in this paper, we aim to add some other external factors acting as perturbations, so that the suspension system could be improved. We must pay attention to the volume accommodation, which should be matched to the activities and to the particularities of each subject. Typically, the volume of residual limb can be changed from -11% to 7% per day [4].

The paper [5] studied the balance process affecting the standing of the lower limb amputees, while some external perturbations are acting. The main problem is the way the patient will control this process and what strategies he will apply depending on the magnitude of external forces which are acting, so that the position of the body's center of mass (CoM) is changing. In this study there were mentioned the following strategies: ankle and / or hip one, the load or unload one, or the stepping one. The main conclusion was the balance control strategies were shown to depend on the direction of perturbation and they involve the movement of the limb in a new position that will increase the pressure force acting on the contact surface between the skin and the socket. The paper [6] proposed a solution for the socket to actively compensates the limb volume changing especially on long term. This new device was tested only on gait simulator using a closed loop algorithm.

This paper presents a new solution of lower limb prosthesis that affords the real time control of the contact surface between the socket and the skin, even though this contact is influenced by some external factors, such as limb volume.

2. THE SOLUTION FOR THE LOWER LIMB PROSTHESIS

The proposed solution for improving the contact between the limb and the patient skin was designed as a network dry air inflated cell, covering the internal active surface of the liner. The system is supplied with very well controlled pressure by using a closed loop system based on force sensors, so that a real time variable pressure force will be generated, and the contact will be firmly assured. The pressure supplier is the dry air pump actuated with a DC motor controlled with Arduino Uno. As we may see from the Fig. 1 the main components of the proposed system solution are: 1 – the dry air inflated cell with thin walls and made of elastic material; 2 – the pipe; 3 – the three ways valve; 4 – the dry air pump actuated by DC motor; 5 – Arduino Uno microcontroller; 6 – set of relays.

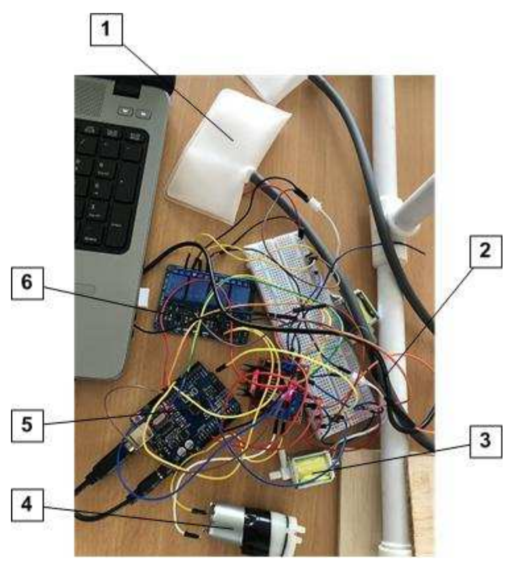

Fig. 1. The main components of the network inflated cell system.

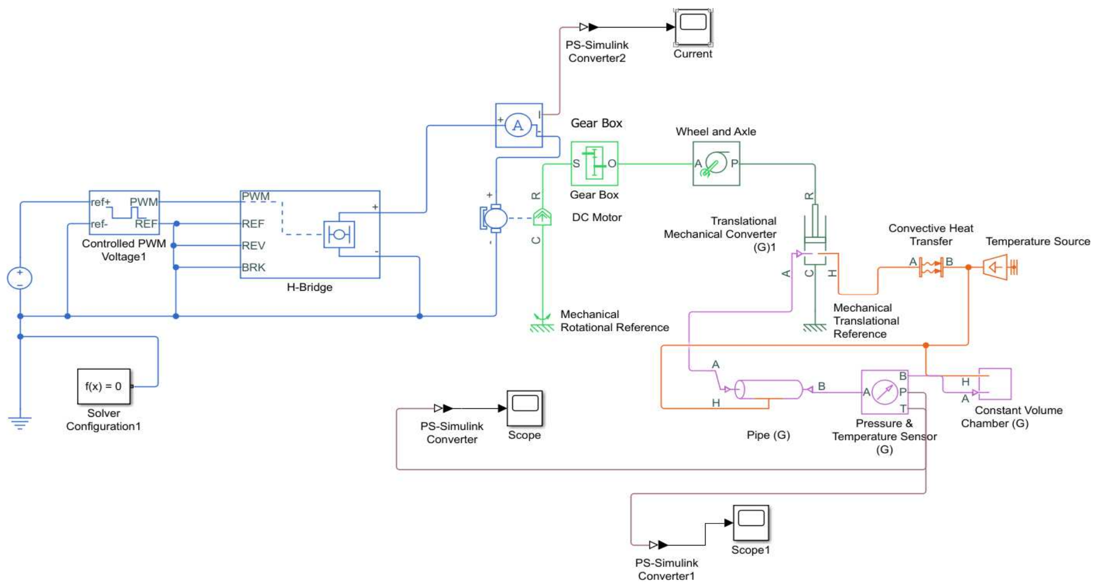

Fig. 2. The schematic of the Simscape model.

The pump with small dimensions is actuated by the DC motor controlled with the driver L298N and Arduino microcontroller, so it has a PWM variable speed. The pressure supplied in the system is passing through the three ways valve and if the pressure in the cell is higher than the working limit value it is discharged in the atmosphere. The force sensor placed on the surface contact between the cell and the skin may measure the working pressure force and it sends the signal to the Arduino analog port.

When this force exceeds the maximum limit, the three-way valve starts to discharge the pressure, so the real time control system is working in a closed loop. The air pump and the three-way valve were chosen from catalogue for medical equipment, so they satisfied special working conditions from safety reasons.

3. THE MATHEMATICAL MODEL OF THE SYSTEM

The mathematical model of the system was solved by using the Simscape module.

The schematic is presented in the Fig. 2. The electrical voltage is controlled with PWM technique. The H-Bridge and the speed control PWM technique were used for the rotational movement of the DC motor shaft whose rotor inertia is 0.01gcm^2. The gear box with the ratio 5 and the Wheel and Axle with radius 50 mm were used. The translational mechanical converter has a cross-sectional area 0.001 m^2 and the dead volume 1e-05 m^3. It has the role of pneumatic cylinder providing the required pressure values. Finally, in the constant volume chamber we have studied the pressure and temperature variation during the actuation time of 0.02 s by using the pressure and temperature sensor.

The heat transfer was modelled by the convective heat transfer block. The computed results for pressure and temperature variation are presented in the Fig. 3.

In the Fig. 4 and Fig. 5 there are presented the evolution of DC parameters, electrical current and rotational speed, which are following the rule imposed by PWM technique. Regarding the rotational speed variation, we may observe the increasing values during a very short period 0.01s.

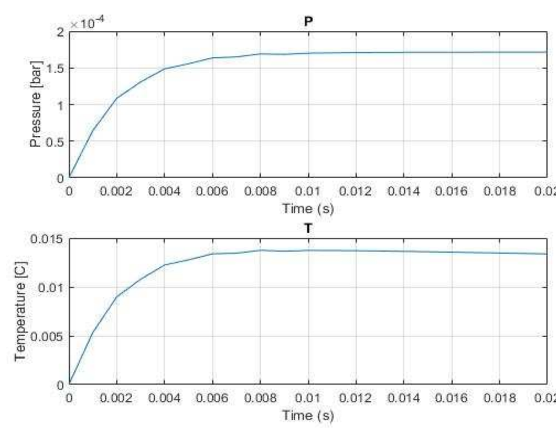

Fig. 3. The pressure and temperature variation inside the inflated cell.

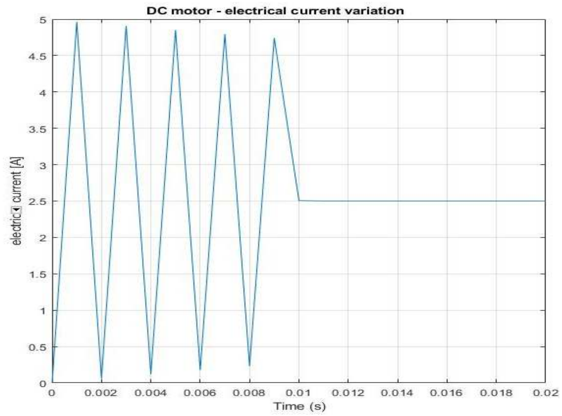

Fig. 4. The DC motor electrical current variation

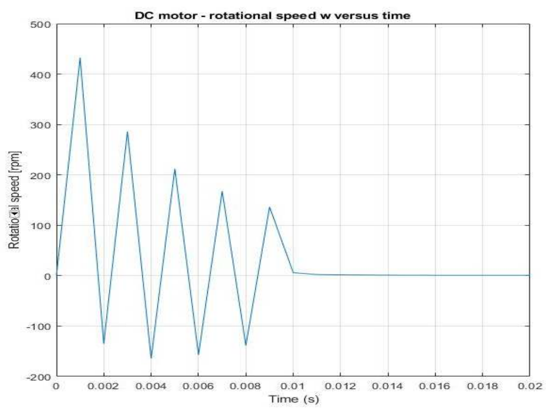

Fig. 5. The DC electrical motor rotational speed variation

4. THE EXPERIMENTAL SET-UP

The experimental set-up based on the system designed before is presented in the Fig. 6 and we may point out the main characteristics: we have used two types of inflated cells denoted “b” and “f” which have different dimensions to apply two values of pressure forces on the patient skin. The pressure force developed on the external shape of the cell “f” is measured with the sensor force denoted “a”. The mechatronic module was put in a compact package with smaller dimensions, so it is more comfortable for the patient. The air pump “d” actuated by the DC motor has the role of supplier through the pipe “e”.

The maximum value for the pressure acting on the patient skin is about p= 0.0683 bar to avoid the circulatory diseases. The effective modulus of stratum corneum in the wet state is about $E_1 = 5 – 10$ MPa depending on the water level and the measurement values are $E_2 = 10 – 40$ kPa [7].

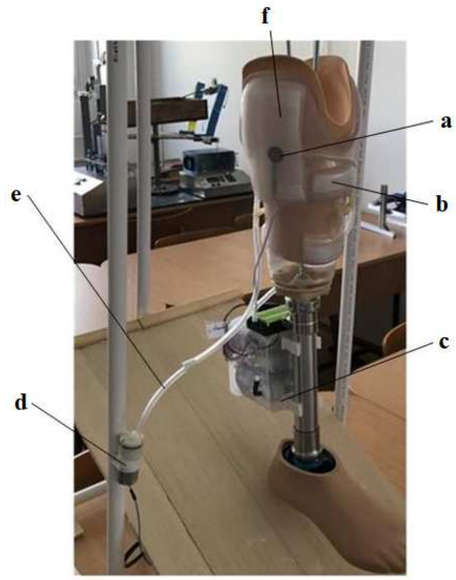

Fig. 6. The experimental set-up of the lower limb prosthesis.

The friction coefficient is increasing depending on the skin morphology and on the state, wet or dry one.

As we may observe from the experimental set-up (Fig. 6) we have used two types of cells with the following dimensions: the bigger contact area “f” has 124 mm length and 65 mm width, and the smaller contact area “b” has the length 58 mm with the width of 30 mm.

For each of them we have considered the Persson contact mechanics theory to analyze the contact between the skin and the cell surface [7].

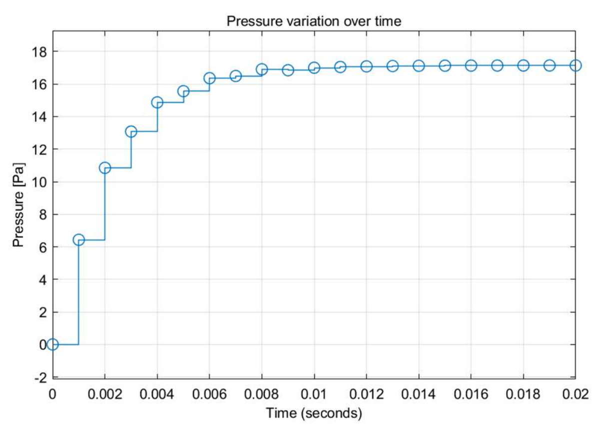

Fig. 7. The pressure variation over time.

From the Fig. 7 we may infer the maximum value for pressure variation p =17 Pa, which was computed in Simscape. If we consider the values of working area for the two cells, we may compute the pressure force acting on the skin for the two dimensions of the cells.

The elastic modulus of the bulk skin is E_3 = 20 kPa and the Poisson ratio is ν_3 = 0.5. For the stratum corneum, which is a layer with 20 μm thickness, we consider the Young's modulus E_4 = 1 GPa and the Poisson ratio ν_4 = 0.5 [7]. If we consider the plastic deformation of the dry skin when this pressure force is acting, the paper [7] assumed the friction coefficient of the dry skin μ_1 = 1.45 for wet skin and μ_2 = 2.2 for the dry skin.

Finally, we may find out that the maximum friction forces acting on the patient skin, wet and dry, when the two types of cells are inflated are inside the imposed limits whether we must avoid any disease or other injuries. Meantime, the cell material is biocompatible.

The thickness of the socket wall, assumed to be a cylinder, is given by the equation [8,9, 10]:

$$t = \frac{p \cdot R^2 + \frac{q}{2} \cdot \nu \cdot R \cdot L}{E \cdot \Delta R_{max}} \quad (1)$$

where: p – the normal pressure load; R – the radius of the cylinder; q – the transferred shear stress; ν – the Poisson's ratio; L – the cylinder length; E – the Young's modulus; ΔR – the maximum desired radial expansion.

To ensure the safe functioning of the socket, we must verify that the stresses do not exceed the material strength [8]:

$$S_y = q + \frac{p \cdot R}{t} \quad (2)$$

Where S_y is the value for tensile strength of the socket material, SLS Duraform PA.

5. CONCLUSIONS

The paper presented the new solution of the lower limb prosthesis designed as mechatronic system working in a closed loop. The main advantage is the improved suspension system based on permanently controlled contact with the skin, even though there are some volume fluctuations, due to the pneutronic proposed solution. The system is accurate and safe concluding to the patient comfort, so he will enjoy a normal life.

There are many factors influencing the firmly contact between the patient skin and the socket, such as variable volume of the limb during day and night, or during daily activities, circulatory diseases, bony structures, changes in the body weight, so the skin may not be damaged due to excessive pressure. Moreover, the perspiration should be controlled because of the wet skin parameters influence on the pressure force acting on the contact area.

The friction force acting inside the prosthetic socket has two main effects affecting the patient comfort. First it must provide the magnitude needed for the firmly contact with the tissue and the second one it has to be very well controlled, so the distortion of the skin to be avoided.

Moreover, the force magnitude should be imposed in a very tiny interval of values. Whether it is greater than the maximum limit, some trouble could occur – infection, ulcers, tumor, and diabetes. Whether the force is smaller than the minimum limit, the amputee will lose the contact, so the main effect will be the unbalanced body with gait and posture negative influence.

The force distribution should be controlled daily, even thought some external perturbations loads may appear.

In this paper, we aimed to point out the main advantages of the proposed solution for the real time adaptive suspension taking into account a series of factors affecting the functionality. It is a mechatronic system based on pneumotronic components, the pressure of dry air that is inflating a network of cells placed around the internal surface of the socket.

The pump is PWM controlled, and it is actuated by the DC motor. The pneumatic system has a three-way valve affording the functioning in closed loop based on the signal received from the force sensor placed on the contact surface with the skin. When the value measured by the sensor exceeds the limits, the valve will discharge the extra pressure in the atmosphere. The inflated cell material is biocompatible. The entire system is miniaturized, so that the patient may use it without any discomfort.

The functioning time needed for safety and real time adapted contact force providing was computed and experimentally verified conducting to very small amount, 0.02 s.

As future work, our goal is to improve the pneumatic system by using proportional valve, and a powerful air pump with small dimensions.

The elasticity and thickness of the cell material must be more efficient with better functional parameters, so the system response will be better, and the adaptive lower limb will become a smart one.

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SISTEM DE SUSPENSIE ADAPTIV IN TIMP REAL FOLOSIT PENTRU PROTEZELE DE MEMBRU INFERIOR

În lucrare, se prezinta sistemul de suspensie de la protezele de membru inferior care are principalul rol in mentinerea in siguranta si permanenta a contactului cu bontul in timpul activitatilor zilnice, chiar daca sunt unele modificari importante ale volumului sau, boli de circulatie venoasa, alte solicitari mecanice. A fost proiectat sistemul bazat pe componente pneumo-mecatronice care trebuie sa asigure forta de apasare ce actioneaza pe piele. Sistemul de suspensie este format dintr-o retea de celule care se umfla cu aer uscat la o presiune controlata. S-a facut o analiza detaliata astfel incit atunci cind conditiile de functionare influenteaza valoarea acestei forte, presiunea va creste sau va descreste corespunzator. Rezultatele pentru sistemul testat au scos in evidenta timpul foarte scurt pentru reglare si performantele sistemului adaptiv.

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