# MECHATRONIC SUSPENSION SYSTEM WITH DRY AIR INFLATED NETWORK FOR LOWER LIMB PROSTHESIS

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**Abstract -** The suspension system used for lower limb prosthesis is the most important part of the assembly design, due to its main goal of providing the permanent contact with the stump. The paper has analysed the theoretical aspect of providing the contact force by using the mechatronic system comprising a network of dry air inflated cells. The FEM study computed the Von Misses and the displacement values for the lateral surface of the cell, made of biocompatible material, whose elastic properties have been set as user material. Consequently, the contact force with the stump is depending on the friction coefficient of the material the cell is made of. Meantime, the influence of humidity is analysed too. The experimental set-up has pointed out the values of the contact force measured with the force transducer, as well as the contact distance after deformation.

**Keywords**: Mechatronic suspension system, Lower limb prosthesis, Cells, Elastic properties, Biocompatible material.

## 1. Introduction

The design and experimental research of the lower limb prosthesis is focused on the suspension system, whose main role is to provide the permanent contact between the stump and the socket. The possibility of adjusting the fitting could be a solution for improving the functionality and the patient wellness.

As the suspension could be lost, the patient desire will be to tighten it and whether it is not done correctly it could damage the skin, create an excessive pressure and some other unwanted, severe diseases. If the suspension is enlarged during wearing it, the first consequence will be the loss of mobility and dynamic balance, gait stability, causing some troubles for the spine and other specific clinical problems. Moreover, the contact loosing could be objectively caused by the limb volume variation during the daily activities, so that the intermittently adjustment is recommended before some troubles will occur. So, we may conclude that if the suspension system is not working properly, the patient progress through a normal life is hindered by the constant management of the volume limb variations.

Another aspect is referring to the magnitude of the clearance between the stump and the socket, so we must mention it is very small and at the same time it must be sensed by the patient. The paper [1] mentioned that incremental changes in the socket size, approximatively 0.33% socket volume, were enough for feeling a change in suspension system fitting causing negative influences. The purpose of the study was to investigate the volume limb variation during the period the socket size was controlled adjusted. The authors have analyzed the dependence upon the volume limb variation and the socket dimensions, as well as the possibility of changing the limb position inside, concentrating stresses at different locations.

Consequently, the researchers have found out some solutions for adjusting the socket dimensions and the suspension system by controlling them permanently. The paper [2] described the solution for the incremental changes of socket dimensions by using a cable routed into the connector laminated into the socket that is aligning the cable with the take-up spool of a DC motor. The actuating system is comprising the encoder, the planetary gear and the PID controller too. The PID controller was used because of the stiffness and damping variations of the socket panels during wearing as well as for obtaining an independent movement regardless of external torque disturbances. The Android application was created to exchange data with the wireless module and the information exchange between the micro-controller and the mobile phone was implemented via UART serial communication. The motor-driven cabled socket provided cable length changes smaller than 5 mm.

The paper [3] proposed a solution for improving the adjustable socket volume during walking with intermittently enlargements and reductions. The solution consists of three-panel adjustable socket, motor-driven and with inductive sensors embedded providing real-time information about sensed distance. The real-time socket adjustment was done by a mobile phone application that is communicating wirelessly with the motor system. The inductive sensors have 32 mm diameter and 0.15 mm thickness and are placed inside the socket being into direct contact with the tissue. The system affords changes with 4.75 mm of cable length as increment, so the radial distance of the socket panel could be changed with 0.4 to 0.5 mm.

A new electromagnetic suspension system that is comfortable and easy to be controlled is presented in [4], because of the property of properly transmitting force acting onto the body. The electromagnets are embedded in the socket, and they are controlled by the microprocessor according to the pressure force as sensor signal output. The reference pressure is defined to maintain the force of 88.9 N. The pressure sensors were attached to the liner made of strong nylon. The electromagnets were mounted in the molded socket. The control system processed the measured pressure and sent proportionally signal to the corresponding electromagnet via Arduino microcontroller. The experiment was done by pressurizing an inflatable bladder within the sleeve and socket over 13 s.

The literature shows the peak pressures in the sockets are in the range 0.77 – 1.1 bar relative pressure.

The paper [5] presents the vacuum-assisted socket which create lower positive-pressure impulse and peak relative pressure of 0.83 bar during the stance phase and negative relative pressure -0.36 bar during swing phase.

There is some information regarding the mean peak stump/socket interface pressure [6]: the maximal was up to 2.158 bar relative pressure over the patellar tendon during walking upstairs and the maximum relative pressure over the popliteal area was 1.906 bar while walking down slope.

The paper aims to reveal the characteristics and the advantages of using a new suspension system consisting of dry air inflated network working as a mechatronic system used for monitoring permanently the contact with the stump by controlling the pressure force level. Meantime, the system affords a genuine solution for the inside volume ventilation whether the humidity sensor provides the values outside the acceptable range.

## 2. The Friction Coefficient for the Proposed Solution of the Suspension System

The proposed suspension system was designed following the goal of maintaining permanently the contact with the stump and reaching all the imposed conditions as it has been mentioned above. At the beginning we must choose the dimensions of the dry air inflated cell that will be the elementary part of the network. It has been done the three-dimensional model of the thin wall cell by using Catia V5 R17 (figure 1) and it has the following dimensions: length 124 mm; width 65 mm; wall thickness along Y axis 1 mm; height 2 mm.

Based on the three-dimensional model, it has been applied the FEM static analysis considering the dry air relative pressure 1.1 bar and the material properties set for the nitrile rubber as new material file for the software. This material is a biocompatible one and it is part of the device used for determining the cardiovascular tension. As it may be observed there are deformations for the lateral wall whether the two frontal walls are blocked by clamps.

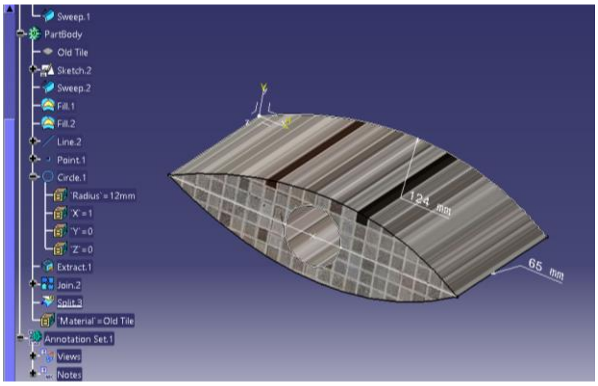


*Figure 1: The thin wall cell with its dimensions.*

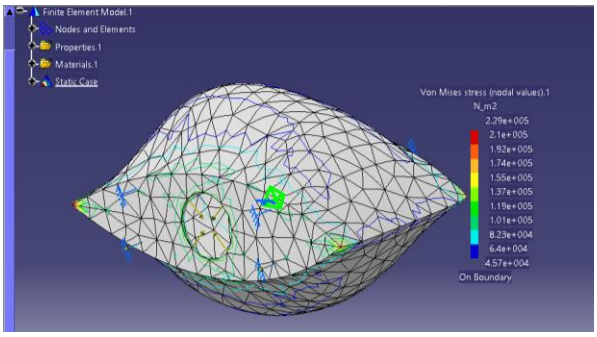


*Figure 2: The FEM analysis of the thin wall cell.*

The pneumatic circuit used for providing the controlled air pressure is presented in the figure 3, where we have the following components: 1- compressor actuated with DC motor; 2- air filter; 3- pressure regulator; 4-system used for controlling the air properties; 5-electro-valve controlled with electromagnet; 6-thin wall cell; 7- sensor system (pressure force sensor, humidity sensor and temperature sensor). The entire pneumatic circuit is controlled with Arduino due to the importance requirement of maintaining a working pressure value lower than the maximum value imposed by clinical conditions.

An advantage of using this solution for the suspension system is the opportunity of controlling the humidity level inside the volume existing due to the radial clearance. The total number of inflated cells was divided in two categories even and uneven. When the working pressure on one side, even or uneven, is exceeding the maximum imposed value for pressure force or humidity, the electro-valve affords the circuit opening and the dry air is released inside for a short period of time.

According to [7] the skin has the Young's modulus of 20 kPa and the Poisson ratio of 0.5, so whether we aim to evaluate the adhesion test to the skin, we have to consider the Hertz model for computing the stress and the area of contact, which will be theoretically a sphere with plane section a circle of radius 12 mm when normal force 7N is acting on. The friction force is directly depending on the normal force by the friction coefficient μ and we should mention the variation of value for this coefficient. Generally, all the materials suitable for prothesis suspension have the friction coefficient (COF) higher than 1.5. The paper [7] analyzes three types of materials too: gel of block copolymer E= 0.13 MPa; silicone gel E=0.75 MPa; silicone elastomer E=0.17 MPa and the friction coefficient for all of them considering some contact area of limbs, so from this experimental study we found out the minimum COF is 1.32±0.13 and the maximum value 3.42±0.8. The need of permanent friction is a condition to continue attachment of the socket to the stump and it depends on two mechanism: the adhesion component and the deformation, so the latter is involving the elastic response named bulk modulus.

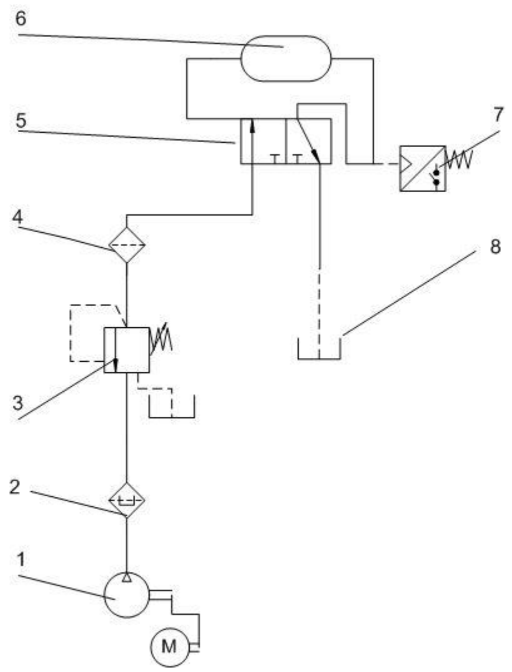

*Figure 3: The schematic of pneumatic circuit*

There are some differences in skin hydration and temperature from one patient to another as well as differences between male and female. Typically, dry skin has a COF of 0.2 – 0.5 and the moist or wet tissue exhibits friction coefficient greater than 1. Moreover, all these values are influenced by the skin properties.

The stratum corneum, the layer of about 20 μm thick at the top of the skin, has an elastic modulus

$E \cong 1 \div 3\ GPa$

Similar to rubber in the glassy region, while in the wet state it behaves as rubber in the rubbery region with greater Young's modulus $E \cong 5 \div 10\ MPa$ [8, 9].

## 3. The Experimental Set-up

The goal of the experimental research was to verify whether the pressure force acting on the external shape of the inflated cell has the necessary value to maintain the permanent contact with the tissue. It is very important to determine the first moment when the contact is established and after that to evaluate the magnitude of this force. In order to do this, we have used a force transducer controlled by its own developed software, so we have analyzed the variation of contact force over time. The experimental set-up is presented in fig. 4.

As we may infer from the figure 4, there are six inflated cells, coupled as even and uneven placed on the entire internal lateral surface of the prosthesis cup 4. In the figure 4 it is denoted 5 one cell as part of even set. The pressure circuit is based on mechatronic principles, and it comprises two compressors actuated by DC motors, the compressor 8 for the set of even cell, and the compressor 12 for the set of uneven cells. For the compressor 12 it has been used the electro valve 11 in order to provide the external circuit of ventilation, as we aim to decrease the humidity inside the cup too. The dry air is sent to the cell by a system of tube denoted 7.

When the supply circuit is replaced with the one for decreasing the humidity, the relay 10 has to set the time for doing this, so it opens the circuit for pressure or for ventilation when the command is received.

The software code for Arduino 9 (fig. 4) is written in the file saved on the first personal computer 1. The force transducer 3 sends the signal to the second personal computer 6, so we may record the pressure force variation during the inflation period.

We have considered the working period of 1400 s with three stages: inflation at the beginning, a short period for ventilation – 300 s and inflation again until the compressor is stopped, the pressure has the atmospheric pressure value, and the air is left in the cup. As we may infer from the figure 5, the ventilation period in the middle of the cycle, is characterized by rapid pressure decreasing, during two phases because of the impossibility of plenty air evacuation. The process should be accelerated if the patient has a residual limb with volume fluctuation, so a supplementary force is acting simultaneously.

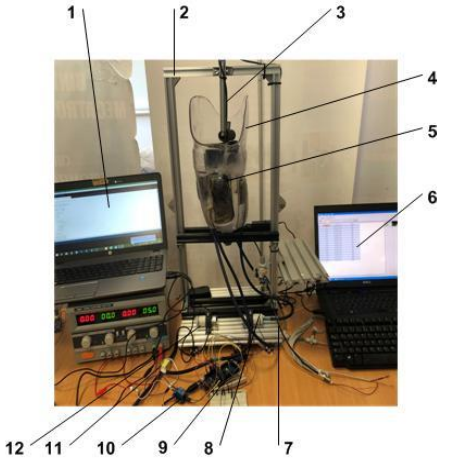


*Figure 4: The experimental set-up.*

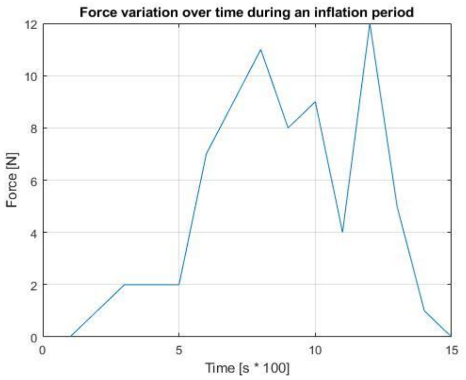


*Figure 5: The pressure force variation on time during the inflation period.*

As future work, we aim to improve the system by using the force sensor placed directly on the cell surface when the patient is wearing the prosthesis daily, is walking or is going on stairs, so the dynamic measurement could reveal better information. Consequently, the mechatronic system could stop the pressure increasing if some accidentally problems occur, so that the clinical negative influences could be avoided in real time.

## 4. Conclusions

The paper has made the theoretical and experimental analysis of contact force provided by the mechatronic suspension used for lower limb prosthesis. The proposed solution is a genuine one and it uses a network of dry air inflated cells. The FEM analysis affords the study of Von Misses and deformation values for the lateral surface of the cells made of biocompatible material. The material properties were defined as user material and were implemented for computation. The pressure values are very well controlled by using the Arduino microcontroller and a force transducer, so we may verify the theoretical results. Moreover, we are able to establish the first moment of contact because of its influence on further measurements.

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