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FEM and Experimental Analysis of a Total Knee Prosthesis

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Abstract: In this study, a comparison between two different approaches used to study a total knee prosthesis is presented. In particular, the contact area of the components of knee prosthesis has been evaluated using both a numerical and an experimental approach. The numerical analysis has been performed by FEM Models, whereas the experimental study has been conducted using an ultrasonic-based method. To setup the FEM simulations, CAD Models of the components of the prosthesis have been reconstructed using a classic reverse engineering approach. Obtained results has allowed evaluating the contact area of the components of the prosthesis and demonstrated a very good level of correlation between numerical and experimental data.

Key words: FEM, ultrasonic methods, reverse engineering analysis, CAD Model, knee prosthesis, contact area

INTRODUCTION

The human knee joint is a complex structure that must meet two apparently contrasting needs: to allow adequate mobility to permit the normal motion and to possess the necessary stability to give a correct support to motor tasks to be performed. Due to injuries and pathologies, its functionality can be compromised, so much as to make necessary to treat surgically by partial or total reconstruction of the joint itself using a knee prosthesis. The useful life of a prosthesis is difficult to calculate but thanks to continuous technological advances, patients can count on increasing duration of prosthetic implants. In this regard, in this work has been studied one of the main problems that lead to failure of the prosthesis: the wear of the polyethylene insert. The contact stress observed experimentally on the surfaces of the polyethylene insert is inversely proportional to the extent of the surface of congruency between the articular heads juxtaposed (Morrison, 1970).

The techniques used for the evaluation of the contact area can be both numerical and experimental (Cerniglia *et al*., 2012; Ingrassia and Mancuso, 2013; Ingrassia *et al*., 2014). The literature reports some results on the use of experimental techniques such as ink techniques, joint-casting, stereophotogrammetry, pressure sensitive films (Harris *et al*., 1999; Liau *et al*., 2001), ultrasonic techniques. In general, however, the experimental techniques that interpose a means of abutment between the contact surfaces may vary the state of contact between the interfaces, distorting the results obtained in an indirect way. The application of ultrasonic methods in the study of contact problems is essentially based on the known pulse-echo technique, widely used in non-destructive inspections in industry (Krautkramer and Krautkramer, 1983; Arone *et al*., 2006; Cerniglia *et al*., 2008).

The aim of this research is to characterize the contact between the contact surfaces of a prosthetic implant through two different approaches, numerical and experimental and compare the results. The numerical tests have been performed by finite element analysis and the experimental investigation has been developed using the ultrasound technique. The tests were carried out for two different load levels associated with two different angles of inclination.

MATERIALS AND METHODS

The main prosthetic knee replacement surgery can be classified into two main types:

- Total-provides for to intervene on both articular components, femoral and tibial
- Monocompartmental when osteoarthritis affects only the outside or inside of the knee

The total knee prosthesis consists of several elements that are functionally replace the physiological articulation. The tibial component is constituted by a metal plate of support and an insert of polyethylene; the femoral component is made of metal and reproduces the anatomical shape of the condyles. In this study a total knee prosthesis, the Multigen Plus by Lima-Lto has

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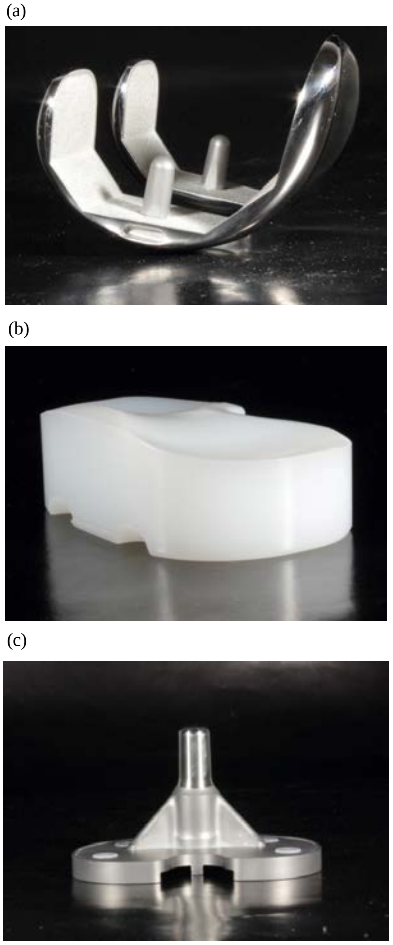

Fig. 1: Total knee prosthesis; a) Femoral component; b) UHMWPE insert and c) Tibial component

been used. It is a total prosthesis that consists of three coupled components: the femoral, the tibial and a polyethylene insert positioned between them (Fig. 1).

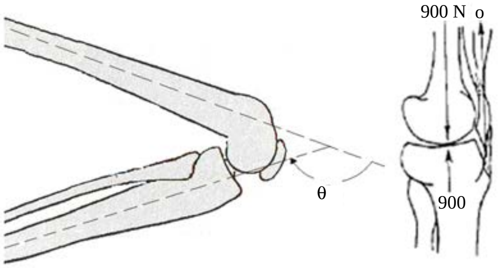

Fig. 2: Angle of flexion-extension θ (on the left) and b) θ = 0° configuration (on the right)

Table 1: Rotation range during usual activities and values of force on the knee (P = Body weight)

Activity	Rotation range (°)	Forces on the knee (P)
Walk	0-67	3.02
Go up the stairs	0-83	4.25
Go down the stairs	0-90	3.83

The femoral component is made of a CoCrMo alloy and internally coated with porous titanium. The tibial plate is made of fixed Ti 6Al 4V cemented by a special coating which increases the stiffness of the system and improves the stability in order to reduce the wear in the load zone. The insert is in High Molecular Weight Polyethylene (UHMWPE), a biocompatible material that is used for over thirty years in the manufacture of prosthetic implants due to its advantageous features: low friction coefficient, high wear resistance (maximum between polymers), high impact resistance and high chemical stability. The main factors of degradation are the sensitivity to oxidation which leads to a decrease in the molecular weight and stress cracking (creation within microvoids); the combination of these two processes also reduces the fatigue strength, creating the possibility of brittle fracture. In the case of hip prosthesis and knee prosthesis occur wear phenomena of UHMWPE with a speed of 0.1-0.6 mm/year. Histological studies of periprosthetic tissues show the presence of debris and polyethylene particles released by wear phenomena (Chiesa *et al*., 2000). The size of these particles is widely variable and may cause an inflammatory reaction which in extreme cases, may be responsible for bone necrosis. The minimization of wear is necessary for the proper functioning of the prosthetic implant.

As regards the loads acting in the joint during normal use conditions is to be highlighted as these depend on the particular activity and body weight. In the condition of angle of flexion-extension θ = 0° in which it is not necessary muscle activity and traction to the tendon is nothing, the maximum force that the femur and tibia are exchanging is equal to body weight P (Fig. 2).

In the case where the angle of flexion-extension varies which is realized even during the normal walking, the value of the force acting on the knee depends on it. This can be effectively estimated considering a coefficient with respect to body weight P (Table 1).

In particular, in this research have been considered two different load conditions for the prosthesis. In the first one has been studied an angle of flexion-extension equal to 0°, in the second equal to 30°. In both cases, it has been considered an individual body weight equal to 900 N during a walk. The loads used were of 900 N for the angle equal to 0° and 2700 N (about 3P) in the condition of 30° flexion.

The numerical approach for the evaluation of the contact area between the femoral component and the polyethylene insert has been developed into three distinct phases: acquisition, through reverse engineering

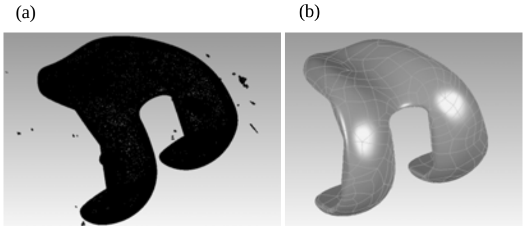

Fig. 3: Femoral component: a) The point cloud and b) The NURBS Model

technique, the shapes of the components of the prosthesis, modelling and assembly of CAD Models, development of finite element simulations.

Reverse engineering and CAD modelling of the prosthesis: The 3D shape of the prosthesis has been acquired by 3D scanning system COMET 5 which consists of a 11 mega-pixel camera, a laser source, a workstation and software, the COMETPlus which manages the data from the scanning phase until export to a CAD Model or point cloud acquired. The procedure for acquisition of the individual components of the prosthesis was as follows. Initially, the surfaces to be acquired have been opacified with a spray white detector to limit the noise produced by any reflections or excessive absorption of the projected light. Subsequently has been projected, by means of the laser light source, a regular pattern of fringes on surfaces; the fringe pattern resultant was then processed in accordance with the principles of the optical Moire technique (Chen *et al*., 2000). The point cloud models captured using this technique are usually subject to noise (Fig. 3a) and for this reason, it is necessary to filter the data before we can have data correct and consistent. To this aim has been used the software Geomagic Studio, thanks to which the acquired point cloud has been filtered, suitably finished, interpolated in NURBS surfaces (Fig. 3b) and converted into solid CAD Models. The CAD Models have been assembled in two different configurations: 0 and 30° (Fig. 4).

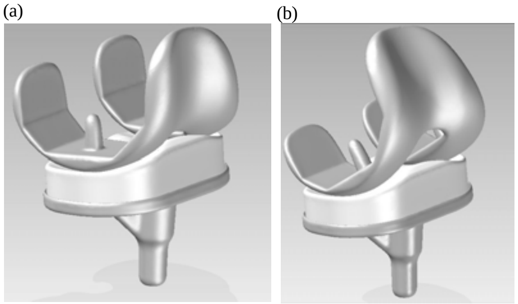

Fig. 4: CAD Models of the prosthesis: a) Configuration at 0° and b) The configuration at 30°

FEM analysis: The assembled models have been imported into ANSYS Workbench and have been meshed with solid elements with eight nodes (Fig. 5).

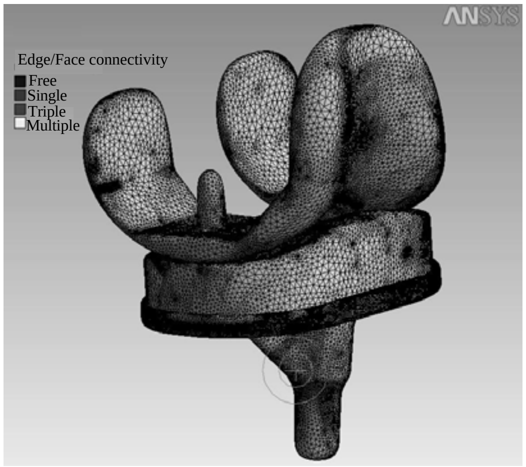

Fig. 5: Mesh of the FEM Model of the prosthesis for the configuration at 0°

Subsequently, the characteristics of different materials have been defined and have been set the conditions of contact between the various prosthetic components. In particular, it has been used the method augmented Lagrangian (Simo and Laursen, 1992) and have been used two different types of contact type surface-to-surface: bonded and frictional. In particular, it has been chosen a friction coefficient of 0.01, a value consistent with those reported in the literature (Godest *et al*., 2002) for such a combination of materials. This choice, although, arbitrary not affect the validity of the results because as shown by Godest *et al*. (2002), the value of the friction coefficient has a negligible influence on the evaluation of the pressure to the contact.

Finally, boundary conditions relating to loads and restraints have been imposed, trying to reproduce faithfully the experimental setup used for the tests. As mentioned previously, have been analysed two configurations to vary the angle between the femur and tibia. It has been considered a first configuration with angle of 0° and a second angle of 30° (intermediate value that reaches the joint during the walk). For both configurations analysed the tibial plate has been blocked (perfect fit) while on the femoral component has been imposed an increasing displacement along the tibial axis direction. In particular, the vertical displacement agent on the femoral component has been increased over time until

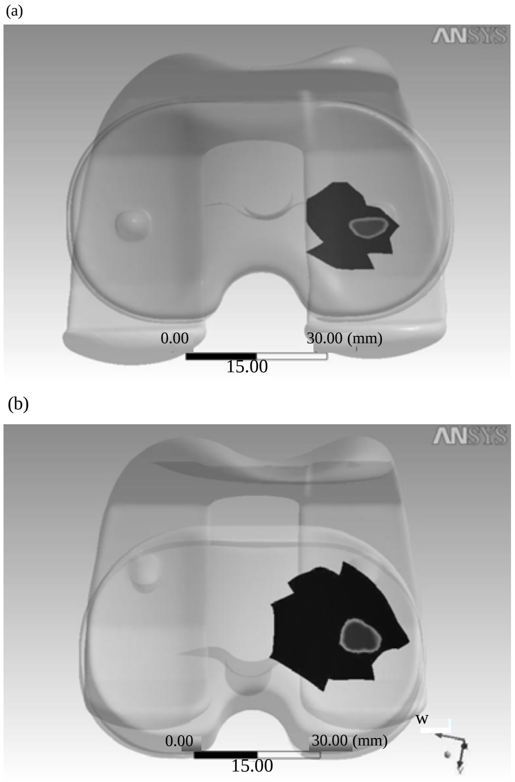

Fig. 6: a) Contact area at 0° and b) 30°

the value of the reaction force constrain along the tibial axis was equal to 900 and 2700 N, respectively for the configuration at 0 and 30°.

Figure 6 show the contact areas and the location of the maximum pressure at the interface between the condyles of the femoral component and the polyethylene insert.

In the case of the configuration at 0° (Fig. 6a), the contact area, slightly elliptical has a mean diameter of about 3.2 mm while in the condition of angle equal to 30° (Fig. 6b), the area of contact pseudo-circular shape with a radius of 3.7 mm. In both cases, any small irregularities of the contact areas can be traced to the inevitable errors and noise generated during the phase of acquisition and reconstruction of the shape. In the cases analysed, however, the errors are of negligible magnitude. The calculated maximum pressures are equal to 27 and 30 MPa, respectively for the conditions of 0 and 30° and these values are below the breaking point of the material.

Experimental evaluation of the contact area: As regards the ultrasonic method, the reflection coefficient at the interface between two media of separation perfectly adherent and characterized by a certain value of the acoustic impedance Z_1 and Z_2 is expressed by the relation $R = (Z_2\text{-}Z_1)/(Z_2+Z_1)$. An increase of the contact pressure results in an increase in the area of real contact and therefore a minor portion of the ultrasonic waves will be reflected. The observation of a decrease in the amplitude of the reflected signal denotes a state of the most intimate contact.

These concepts have been applied to analyse several case studies of contact as the interaction between wheel and rail station, human joints, bolted joints. In all these cases, the ultrasonic method has shown its value in providing useful information over the nominal area of contact, the real area of contact and the contact pressure. Expressing the reflection coefficient R as the ratio between the amplitude of the incident wave (H_0) in the absence of load and the amplitude of the reflected wave for a given applied load (H_i), R assumes two extreme values. It has a unit value when no portion of ultrasonic energy is transmitted through the interface (no external load), null value when all the energy is transmitted through the interface which implies that each point of the two surfaces is in perfect contact (ideal situation). In practice, an interface stressed will be characterized by an intermediate value of the reflection coefficient, value dependent on the conditions of the contact. So, the quantitative analysis of ultrasonic reflection can be used to define the boundaries of the contact region through the graphics processing of data on the reflection which allows the construction of chromatic maps outlining the extent and the degree of coupling as a function hue associated. The devices used to perform the tests consist of a material testing machine, a sensor, a trigger, a signal receiver and an oscilloscope. The sensor used is a piezoelectric immersion with nominal frequency of 4 MHz and a diameter of 10 mm. During the tests, it has been necessary to reduce by 50% the diameter of the active area of the crystal by means of a special reducer, to increase the resolution of the acquisitions.

To ensure the application of the exact load among the components constituting the prosthesis in question, it has been necessary to arrange the specimen to be able to interface with the material testing machine INSTRON which allows precise adjustment of the load imposed. This has been done by means of the interposition of anchoring devices, designed to allow both the relative inclination that the correct alignment with the moving crosshead of the machine. Furthermore, in the femoral component has been created a containment enclosure for the water when the analyses were carried out by immersion (Fig. 7).

The UHMWPE visco-elasticity is such as to provide a change in the level of load imposed due to an increase in deformation. This decrease in load induces an incorrect

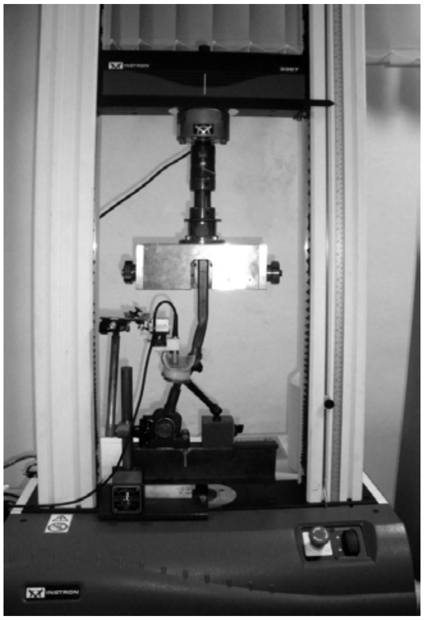

Fig. 7: Prosthesis mounted on the testing machine

evaluation of the results. To clean the analysis by this spurious effect has been conducted a preliminary load test in displacement control for evaluating the performance of the load as a function of time. After a first phase in which the decrease is of exponential type, the slope is less marked and such as to ensure the correct evaluation of the load applied to less of variations equal to 10%; deemed immaterial to the analysis. From this stems the need to perform all acquisitions after an initial stabilization period of 300 sec. The experimental tests have been preceded by a preliminary study aimed to determine the level of attenuation of the ultrasonic waves, due to the diffusion caused by the particular surface (porous titanium) of the femoral component. The amount of energy diffused depends on the conditions of roughness of the surface on which the acoustic waves affect from the value of the wavelength and angle of incidence. Normally, a surface is considered to be specular (absence of diffusion) when the relative roughness R_t is <10% of the wavelength (λ). Roughness to further the phenomenon of diffusion is not negligible and increases with the increase of roughness R_t attributed to the prosthesis during the production process can be considered in the order of 60 m (Bellemans, 1999). Therefore, the wavelength of the longitudinal wave must be greater than 0.6 mm to obtain the absence of diffusion. Given that the longitudinal wave velocity (v_L) in CoCrMo is 5.88 mm/μsec just use a probe with a frequency of less than 9 MHz ($vL = \lambda \cdot f$). With the used probe (4 MHz), the wavelength is equal to 1.47 mm (respecting the relation R_t <0.1 λ) and the signal does not undergo substantial attenuation in the area with a roughness (equal to 6.7% compared to an area specular).

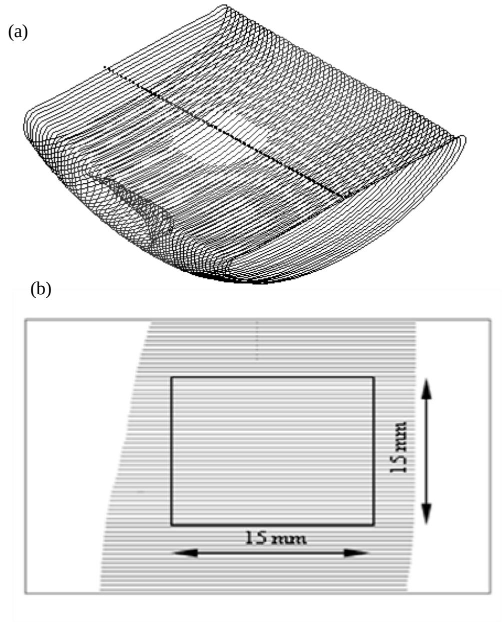

Fig. 8: Sections made to define the geometric characteristics of the area of interest

The experimental evaluation of the contact surface affects the interface between the femoral component and the tibial insert the prosthesis. The loads have been adopted as in the case of numerical tests of 900 N for a tilt angle between the femoral component and the tibial equal to 0° and 2700 N corresponding to an angle of 30°.

The acquisition method adopted for the tests is the C-scan which provides the two-dimensional representation of the extension of the contact area. The path of the sensor during the analysis has been driven by a pattern matrix, through the adoption of a guide that allows controlling the movement along two perpendicular directions (Fig. 8). The area inspected has a size of 15×15 mm, with acquisitions made with pitch 0.5×0.5 mm thereby resulting in a 31×31 matrix elements.

Figure 9 shows the maps that provide a clear definition of the extension of contact for both levels of load. For loading of 900 N and angle $\theta = 0°$, the average radius is 3.1 mm; for the load of 2700 N and angle $\theta = 30°$ is the average radius of 3.5 mm.

From the comparison of the maps as observed also numerically, it is possible to note that an increase of the load corresponds to an area of contact and greater to vary the angle θ, contact moves according to the movement of roto-translation to which the prosthesis is subject during normal flexion-extension of the joint (Fig. 10).

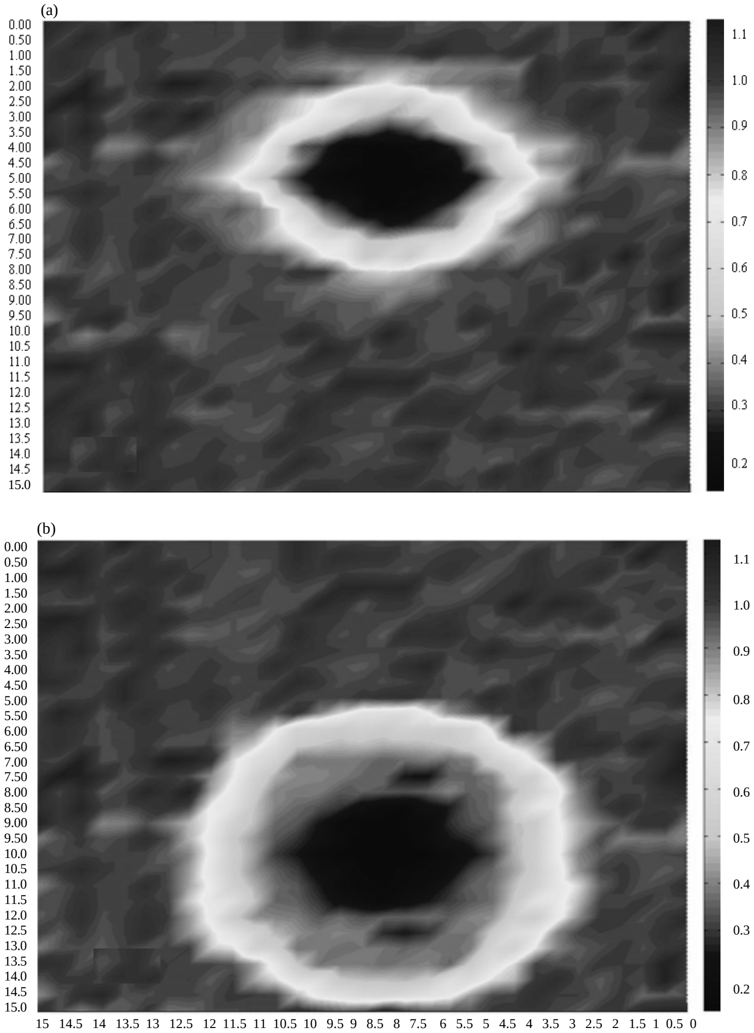

Fig. 9: Maps of the contact area for; a) 900 N and b) 2700 N load

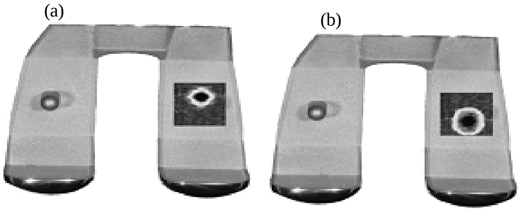

Fig. 10: Position of the contact area for; a) 900 N and b) 2700 N load

RESULTS AND DISCUSSION

As regards the comparison of the results obtained following the two different approaches, it is possible to assert what follows. The data obtained by the two methods are comparable. The experimental results are consistent with those found numerically through FEM analysis.

Table 2: Comparison between numerical and experimental results

Applied force (N)	Angle (°)	Experimental radius (mm)	Numerical radius (mm)	Degree of correlation (%)
900	0	3.1	3.2	97
2700	30	3.5	3.7	94

As summarized in Table 2, the correlation degree between the experimental data and numerical varies from a minimum of 94% for the condition at 30° to a maximum of 97% for the condition at 0°. Consequently, it is possible to say that the procedures used for the determination of the contact area are both effective and can provide very reliable results. The numerical procedure can be used to determine the contact area for different angles and for different loads. It also has the advantage of being able to be used during the design phase in order to optimize the geometries of the surfaces, reducing the pressure to the contact and consequently, increasing the useful life of the prosthesis. The ultrasonic technique, however can be effectively used to validate the numerical data subsequent to the stage of realization of the prototype.

At present, it is not possible to compare the data for the calculation of the maximum pressure at the interface that has been obtained only numerically. The results, however, show a high degree of stress of the polyethylene which is stressed beyond the yield point but below the breaking load.

CONCLUSION

In this research an investigation has been carried out on the contact area between the components of the prosthesis Multigen Plus Lima-Lto. Two different approaches have been used and compared: numerical and experimental. The status of the contact was originally studied by the numerical point of view through the finite element method. The shape of the prosthesis has been acquired by the 3D scanner COMET 5 and later has been made, assembled CAD Models for the two load conditions (0 and 30°) analysed. The boundary conditions imposed during the development of the FEM simulations have been such as to reproduce the experimental setup loads and constraints used for the experimental tests.

The ultrasonic method, based on the pulse-echo has been used to determine the reflection coefficient R, evaluated as the ratio of the two signals acquired at the same point in the presence and in the absence of load.

The results obtained show a high level of correlation between the experimental and the numerical approach. The numerical procedure used in the process of virtual prototyping, allows the study of different solutions in reduced time and cost and can facilitate the search for optimal solutions that improve the performance and useful life of the prosthesis. Ultrasonic method can however, be used to validate the numerical data by performing checks on physical prototypes.

RECOMMENDATIONS

Future developments concern the development and validation of a procedure for the estimation of the pressure to the contact from the experimental data. To do this, it is possible to use a mixed approach theoretical/experimental, making a correlation between the pressures calculated analytically using the Hertz theory and the level of ultrasonic reflection, recorded at the interface of the contact. In this way, it is possible to obtain a calibration curve which is necessary to express the relationship between the reflection coefficient and the nominal pressure of contact, to use as the key to the reading of the chromatic maps, in order to determine the pressure values corresponding to the areas concerned contact.

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