Numerical Analysis of the Effect of Material and Dimensions on the Mechanical Behaviour of Total Hip Prosthesis

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Received: 02-10-2023 **Accepted:** 13-12-2023 **Published:** 20-01-2024

Abstract

The objective of this work is to analyze by numerical simulation based on the finite element method, the in-vitro mechanical behavior of a total hip prosthesisfor four different femoral head diameters: 22.2; 28.0; 32.0 and 36.0 mm, with a constant thickness of 50.0 mm of acetabular cup and for three different pairs of biomaterials (head-cup): 316L/UHMWPE; 316L/PP virgin and 316L/PP extruded. In this context, the extruded polypropylene acetabularcupsare machined from a solid-state extruded polypropylene (PP) block using the Equal Channel Angular Extrusion(ECAE) process.Thus, this analysis will determine the stresses generated by the body to choose a mechanical behavior of prosthesis and a couple of materials that offer better bio-functionality. It will also highlight the effects of the internal diameter of the cup and the nature of the biomaterials used for the functioning and reliability of the prosthesis studied.The obtained results allowed us to evaluate the distribution of stresses and deformations by comparing the amplitude and location of the hot spot of the analyzed cases. These results demonstrate that the couple material 316L/UHMWPE, for the 36.0 mmfemoral head, indicates a better stress-strain distribution at the acetabularcup in comparison to those presented by the other two pairs of materials and extruded for the other three diameters. This can be attributed to the fact of the increase in the ductility of the material and in internal diameter that will tend to increase the surface contact and consequently decrease the pressures exerted between the head and the cup, thus it delays the appearance of wear and increasing the life of the acetabularcup.

Keywords: Total hip prosthesis, Cup, Femoral head, ECAE, Polypropylene PP, UHMWPE, FEM.

Tob Regul Sci. ™ 2024 ;10(1): 383-396
DOI : doi.org/10.18001/TRS10.1.26

1. Introduction

Numerical simulation has become an essential tool in biomechanics for the analysis and determination of the mechanical behaviour of the articular parts of the human body. It is currently a real alternative to the in-vitro experimental tests. Numerous studies in the biomedical field have also shown a major interest in the use of numerical simulation, especially for the development of total hip prosthesis, and mainly its two main elements are; the head and the cup, which establish the functionality of the joint [1,2].The evolution of biomechanics in the field of total hip prosthesis is ensured by the introduction of a material in contact with organic matter (bone, muscle, etc.); this material must have properties of compatibility with the physiological environment.

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In general, a total prosthesis is constituted of two interlocking parts designed to replace the diseased hip joint. One of the parts replaces the articular part of the pelvis (acetabulum), and the other part replaces the neck and the head of the femur. In other words, the artificial implant consists of a "stem" implanted in the femur and a ball-shaped head attached to the neck of the stem and articulated with the acetabulum(Figure 1).

The replacement of the joint is ensured by the friction couple, which is the sensitive point of the total hip prosthesis because it is a place of wear and stress concentration that induces respectively the generation of particles more or less tolerated by the human body and the internal deformation. For total hip prosthesis, the limit of effectiveness depends on several features, including the type of loading applied, the material used and their geometries [3].

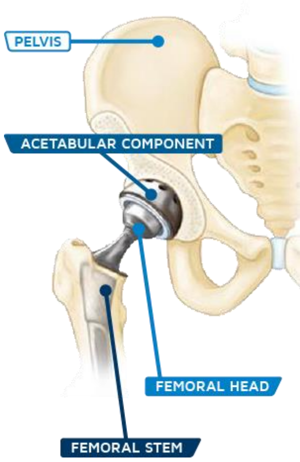


Figure 1.Total hip prosthesis

Several studies have been conducted to analyze the in-vitro mechanical behaviour of a total hip prosthesis [3,4]. Hu et al. [5] have tried to evaluate the stresses borne by the femoral head and the cup of a total hip prosthesis. Liu et al. [6] were particularly interested in the study of the biomaterials used and their degradation by impact, as well as the phenomenon of wear and deformation of the total hip prosthesis cup. It has been demonstrated that the main factor conditioning long-term arthroplasties is the presence of wear and cracking. Furthermore, numerous studies in biomechanics indicate that the main cause of failure of a total hip prosthesis is the wear of its component. The use of the finite element method and numerical models makes it possible to simulate these different wear modes to evaluate the internal variables (forces, stress field, displacement field...) that are difficult to analyze using experimental methods [7-10].

The analysis of the in-vitro behaviour requires the localization of the hot spot and the evaluation of the amplitude of the stress and deformation at the level of the cup. Generally, stress is responsible for the failure and sometimes for the rupture of the cup in service.

2. Materials and methods

Four different materials were used in this finite element simulation. Polyethylene (UHMWPE) and polypropylene (virgin and extruded PP) for the acetabularcup, and austenitic stainless steel (316L) for the hip prosthesis femoral heads. The mechanical properties of these materials are presented in the Table 1.

Table 1.Mechanical characteristics of the used materials

Materials	E (MPa)	(υ)	σe (Mpa)
316L	200 000	0.3	284
UHMWPE	1400	0.3	10.58
Virgin PP	1100	0.4	22
Extruded PP (V=0.45 mm/mn)	700	0.4	14

where: E, υ,and σe are respectively the Elastic Young Modulus, Poisson Ratio and the Yield Strengthof the considered materiel.

2.1 Process of Equal Channel Angular Extrusion (ECAE)

The extrusion is a recent technique which allows large plastic deformations to be introduced into the extruded material without changing the geometry of the sample [11]. Extruded polypropylene (PP) reprocessed into a solid state block is obtained from the experimental setup developed by members of the LMA/USTHB Advanced Mechanics Laboratory, in collaboration with the Mechanics Laboratory of Lille (France) [11-13], for the design and modelling of a new total hip prosthesis cup.This equal channel angular extrusion (ECAE) process was first used by Segal in the early eighties (1980)[11-14]. The principle use is to extrude a material in a matrix consisting of two channels at equal sections making an angle ϕ generally between 90° and 135°; and a second angle ψ, characterizing the angle at the elbow of the matrix. This sets the circular shape of the connection of the two channels (Figure 2).

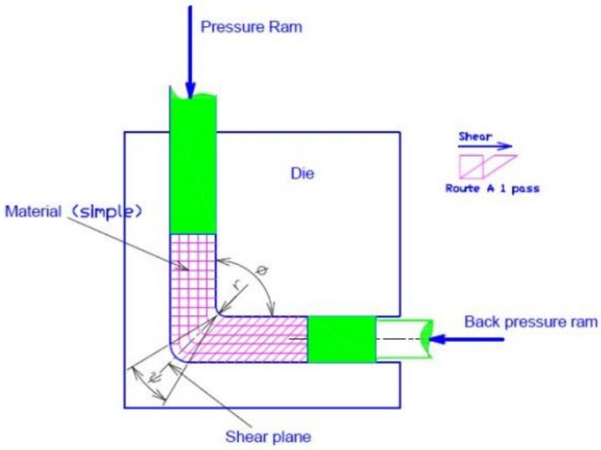


Figure 2.Schematic illustration of the ECAE processes[11, 12]

One of the advantages of this process is that the extruded sample geometry is not changed and the section after extrusion is preserved. In order to achieve important deformations, the extrusion in several passes was remarked [11-14]. The polypropylene (PP), treated by the method of the ECEA process is used for the design and modelling of a new cup of the total prosthesis of hip.This method allows us to determine the mechanical characteristics of the used materials presented on Table 1.

2.2 Numerical simulation and boundary conditions

Using a numerical simulation based on the finite element method, we will carry out a study of the diameter effect of the femoral head for couples for different materials on the in-vitro mechanical behaviour of PTH. Also, we have chosen the Charnley model which is the most used on the market [3], and applied external loading forces have been selected at the limit of boundary conditions of the acetabularcup (Figure 3).

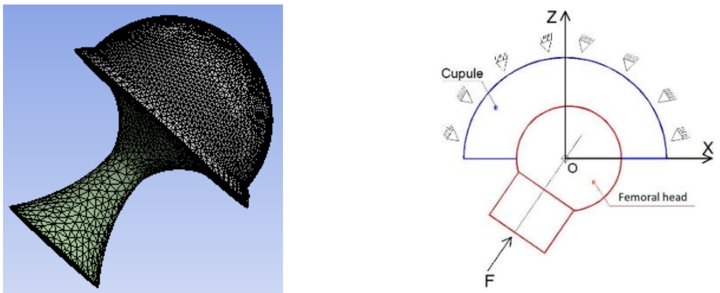


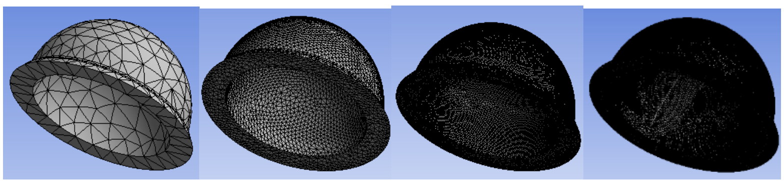
Figure 3.Modelling and boundary conditions of the cup-femoral head couple: (a) Finite element modelling and(b) Boundary conditions

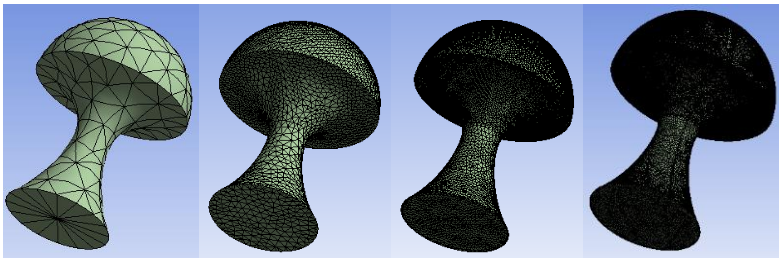
In order to be as close as possible to the real model, we applied a force of 3000N to the femoral head center[15,16] and the value of 3000N corresponding to the support a phase of the walking subject of 75 Kg, according to the theory of the balance of Pauwels[3]. These loading conditions are considered as an extreme case of the prosthesis effort that can withstand; and it represents the force that a man can exert on a single support when climbing stairs. Also, the acetabularcup can be inclined at 45°, in the frontal plane and recessed on its outer edge [7-10].It is noted that our calculations were developed using ANSYS code program (Workbench) and the mesh elements was chosen of the ten-node tetrahedral type one which is known as the "isoparametric finite elements".

The natural hip joint functions not only because of the ogival shape of the architecture and the elasticity of the cartilage but also due to a virtually zero coefficient of friction of the joint that cannot be reproduced artificially (PTH) [3].The basic assumption for hippest prosthesis designs is thatfriction is considered to be negligible initially [4]. The friction between the head and cup of a total hip prosthesis is responsible for damage to the rubbing surfaces and the formation of wear debris. The behaviour laws of the friction materials are of the elastoplastic type; the contact between the head and the cup of total hip prosthesis follows Coulomb's law of friction, and it is assumed to be dry with uniform clearance [3]. The coefficient of friction is taken in the order of $\mu = 0.001$[5].

2.3. Mesh sensitivity

In order to evaluate the mesh sensitivity of the obtained results, additional calculations on a refined progressive mesh were performed. The four meshes tested are shown on Figure 4 and their element sizes are given as: (mesh 1: 0.005m; mesh 2: 0.001m; mesh 3: 0.0005m and mesh 4: 0.0003m). The comparison between the mesh results obtained with a coarse, thin and dense grid is presented in Table 2, and it can be see that the convergence of the solution has been achieved and the solution becomes independent of the mesh sizes on mesh 3 which will give the most convergent and acceptableresults.





Mesh 1 Mesh 2 Mesh 3 Mesh 4

Figure 4.Mesh distribution

Table 2. Mesh sensitivity study for 316L/UHMWPE of diameter: 36.0 mm

Meshes		Mesh 1	Mesh 2	Mesh 3	Mesh 4
Nodes		4 143	84 442	443 284	1 290 009
Elements		8 446	49 384	274 830	806 261
Directional displacement (m)	Min	$-1.4\ 10^{-3}$	$-1.5\ 10^{-3}$	$-1.5\ 10^{-3}$	$-1.54\ 10^{-3}$
	Max	$1.4\ 10^{-3}$	$1.5\ 10^{-3}$	$1.54\ 10^{-3}$	$1.54\ 10^{-3}$
Equivalent elastic strain (%)	Min	$12.0\ 10^{-6}$	$5.6\ 10^{-6}$	$6.6\ 10^{-6}$	$6.6\ 10^{-6}$
	Max	$1.5\ 10^{-3}$	$2.33\ 10^{-3}$	$2.87\ 10^{-3}$	$3.28\ 10^{-3}$
Maximal main elastic strain (%)	Min	$2.0\ 10^{-6}$	$0.1\ 10^{-6}$	$0.03\ 10^{-6}$	$0.011\ 10^{-6}$
	Max	$0.90\ 10^{-3}$	$0.92\ 10^{-3}$	$0.93\ 10^{-3}$	$1.12\ 10^{-3}$
Equivalent stress (Von-Mises) (MPa)	Min	0.027	0.071	0.075	0.083
	Max	59.86	61.99	61.75	61.59
Maximal principal stress (MPa)	Min	-5.44	-6.53	-6.62	-6.62
	Max	15.80	16.18	16.95	17.86

3. Results and discussion

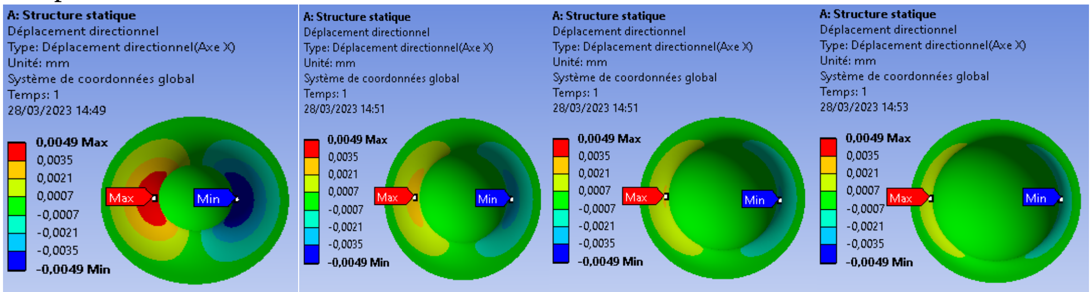
In order to highlight the real conditions of the total hip prosthesis cup, the effects of its diameter and the nature of material couples on the functioning and reliability of the total hip are taken into consideration. That is, the outer diameter of the cup is fixed (d_{ext}=50 mm) while the internal diameter d_{int} are varied from 22.2 mm to 36.0 mm; under the same loading conditions. The maximum and minimal displacements stain and stresses are determined for different friction couple (316L/UHMWPE, 316L/PP virgin, and 316L/ PP extruded).

3.1 Geometry effect onthe total hip prosthesis cup (THP)

In fact, the external diameter represents the real diameter of the femoral head which plays a significant role in the mechanical behaviour of the total hip prosthesis having a diameter of 50mm.In our case, the effects of the internal diameter of the cup and its evolution on the displacements are considered, strain deformations andthe stresses on the cup for different femoral head diameters: 22.2; 28.0; 32.0 and 36.0 mm. The finite element results are obtained using the mesh 3.

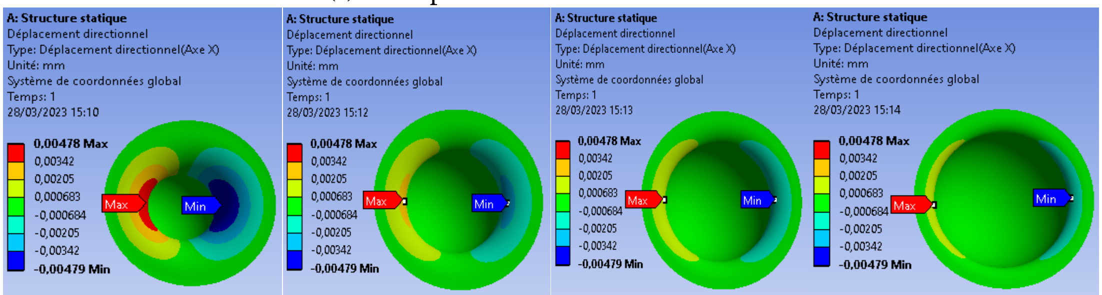
3.1.1 Directional displacement as a function of cup diameter

Our computations focus on a comparative study of directional displacement for a prosthesis with respect to the different internal diameters (22.2; 28.0; 32.0 and 36.0 mm). The Figures.5 and 6illustrate the directional displacement along with the cup for the 4 thicknesses used. After overloading, the displacement reaches a maximum value of 4.910^{-3} mm in the case of a 22.2 mm diameter cup, and a minimum value of 2.110^{-3} in the case of a 36.0 mm diameter cup.



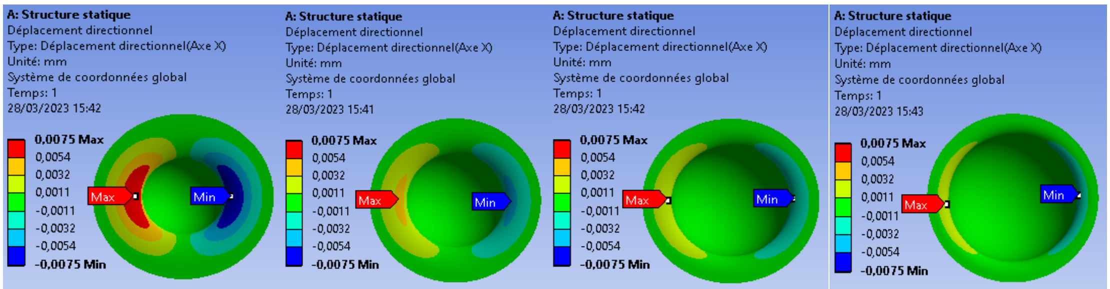
Ø 22.2 mm Ø 28 mm Ø 32 mm Ø 36 mm

(a) Couple of 316L/UHMWPE



Ø 22.2 mm Ø 28 mm Ø 32 mm Ø 36 mm

(b) Couple of 316L/Virgin PP



Ø 22.2 mm Ø 28 mm Ø 32 mm Ø 36 mm

(c) Couple of 316L/PP extruded

Figure.5.Visualization of the directional displacementalong x directionof the cups with different diameters

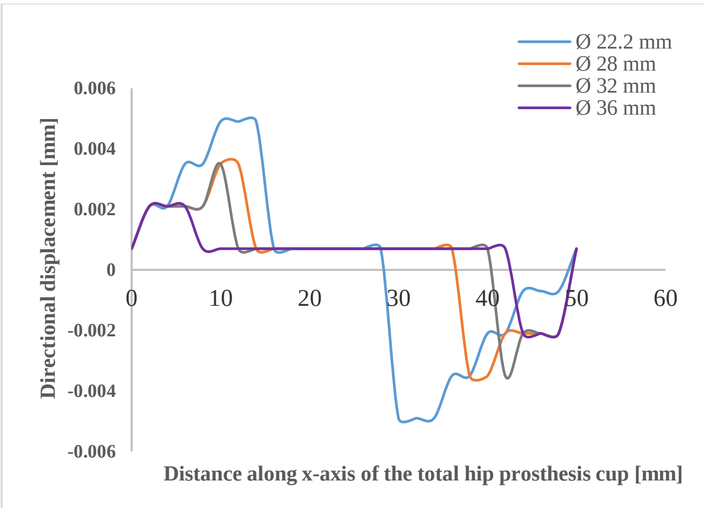
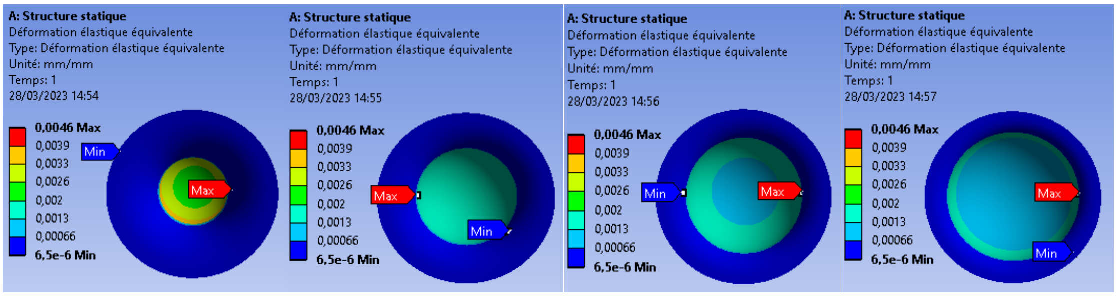


Figure6.Evolution of the directional displacement along the x-axis direction of the cup for different diameters (case of 316L/UHMWPE)

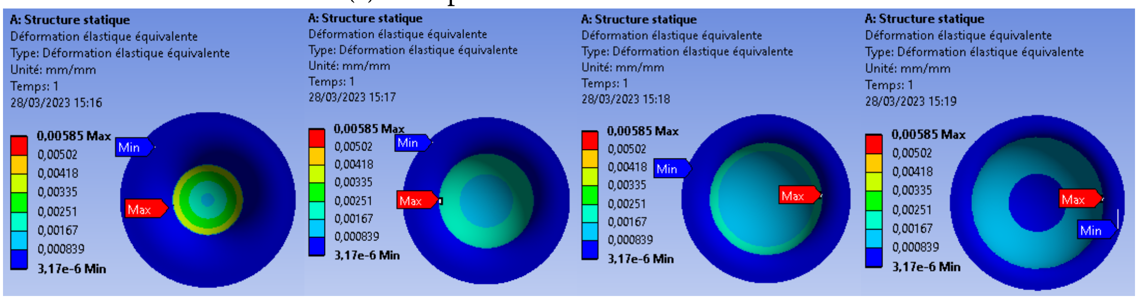
3.1.2 Equivalent elastic strain

Figures 7 and 8 illustrate the equivalent elastic strain distribution in the acetabular component. After overloading, the deformations generated at the 22.2 mm inner diameter cup are greater than those generated at the other 28.0, 32.0, and 36.0 mm inner cups diameter. The deformation reaches a maximum value of 0.0039 in the case of a 22.2 mm cups diameter and it is almost four times the value found in the case of a 36.0 mm cups diameter, which is a minimum value of 0.0013.



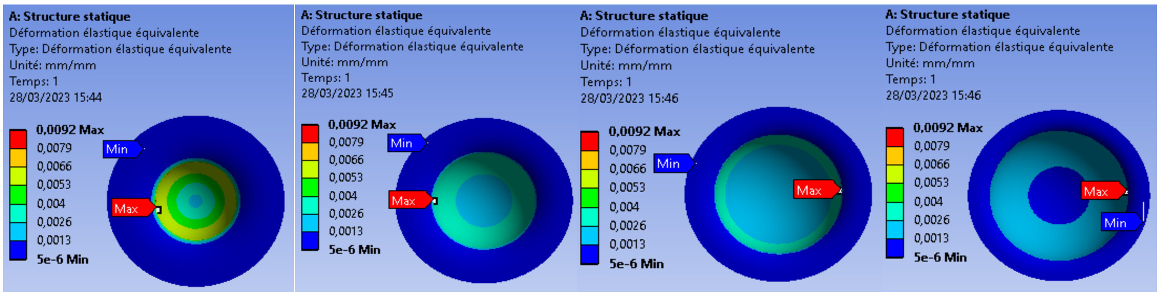
Ø 22.2 mm Ø 28 mm Ø 32 mm Ø 36 mm

(a) Couple of 316L/UHMWPE



Ø 22.2 mm Ø 28 mm Ø 32 mm Ø 36 mm

(b) Couple of 316L/Virgin PP



Ø 22.2 mm Ø 28 mm Ø 32 mm Ø 36 mm

(c) Couple of 316L/PP extruded

Figure 7. Visualization of the equivalent elastic strain along x directionof the cups with different diameters

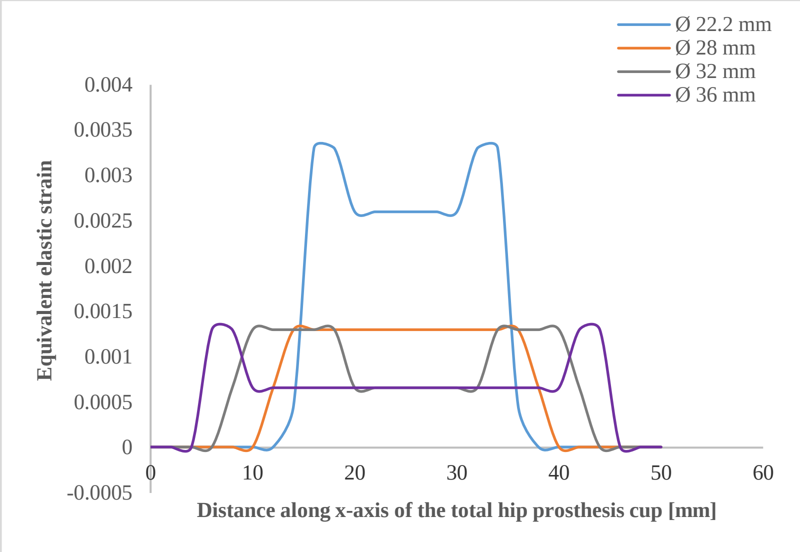
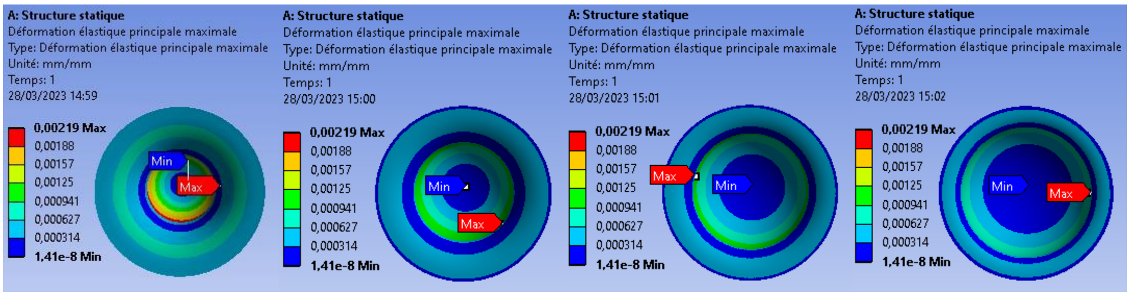


Figure 8. Evolution of the equivalent elastic strain along the x-axis direction of the cup with different diameters(Case of 316L/ virgin PP)

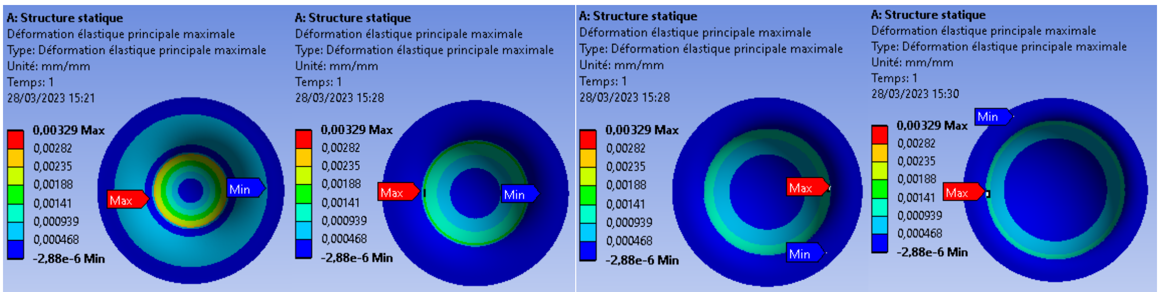
3.1.3 Maximal principal elastic strain

Figures. 9 and 10 demonstratethe distribution of the maximal principal elastic strains in the cup. However, after the overload the deformations generated at the level of the cup with an internal diameter of 22.2 mm are greater than those generated at the level of the other cup with internal diameters of 28.0; 32.0 and 36.0 mm. The deformation reaches a maximum value of 0.00219 in the case of a 22.2 mm diameter cup, and it is almost two times the value found in the case of a 36.0 mm diameter cup, which is a minimum value of 0.000627.



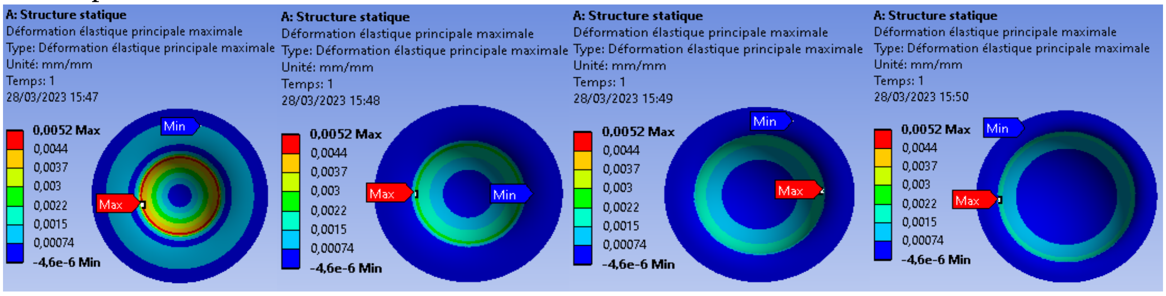
Ø 22.2 mm Ø 28 mm Ø 32 mm Ø 36 mm

(a) Couple of 316L/UHMWPE



Ø 22.2 mm Ø 28 mm Ø 32 mm Ø 36 mm

(b)Couple of 316L/Virgin PP



Ø 22.2 mm Ø 28 mm Ø 32 mm Ø 36 mm

(c) Couple of 316L/PP extruded

Figure 9.Visualization of the Maximal principal elastic strain along x direction of the cups with different diameters

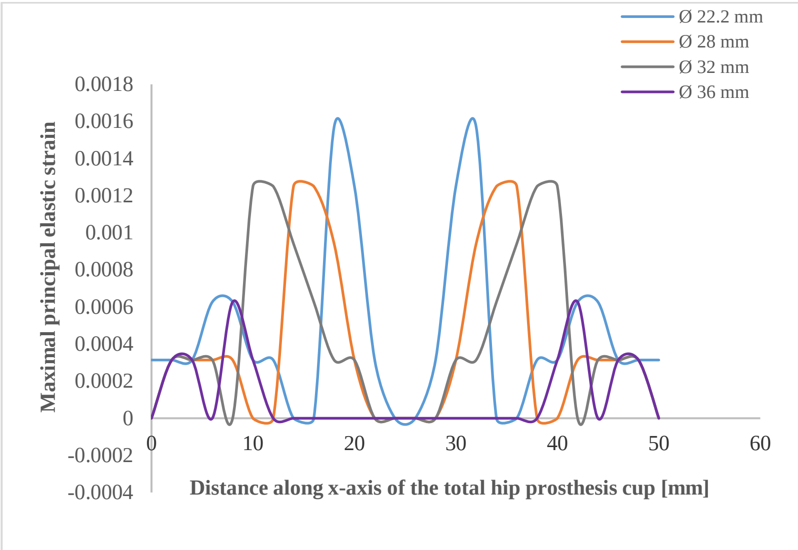
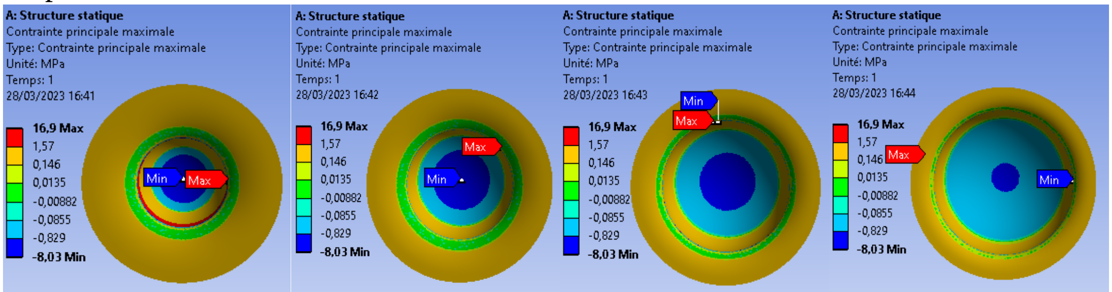


Figure 10.Evolution of the maximal principal elastic strain along the x-axis direction of the cup with different diameters (Case of 316L/UHMWPE)

3.1.4 Maximal principal stresses

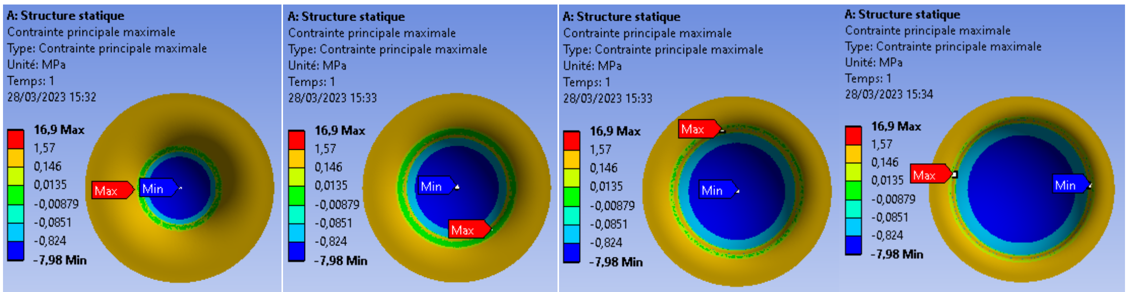
Figures 11 and 12 illustrate the distribution of the maximal principal stresses in the cup room in the same previous loading conditions and along the (x) axis. The tensile and compressive stresses are represented by the principal stresses, which are simply the eigenvalues of the stress tensor.

The results obtained indicate that the maximum stress level (tensile and compressive) generated at the peripheral zone of the inner surface, in the case of the 22.2 mm inner diameter cup, is greater than that generated at the other 28.0, 32.0 and 36.0 mm inner diameter cups. The compressive and tensile stresses reach a maximum value in the case of a 22.2 mm diameter cup, and a minimum value in the case of a 36.0 mm diameter cup. Thus, the head is globally subjected to compressive stresses, while the cup is subjected to tensile stresses, mainly centered on the surface.



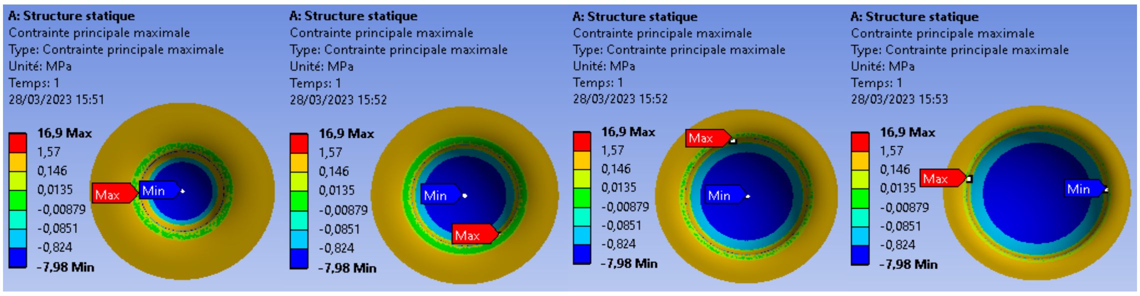
Ø 22.2 mm Ø 28 mm Ø 32 mm Ø 36 mm

(a) Couple of 316L/UHMWPE



Ø 22.2 mm Ø 28 mm Ø 32 mm Ø 36 mm

(b) Couple of 316L/Virgin PP



Ø 22.2 mm Ø 28 mm Ø 32 mm Ø 36 mm

(c) Couple of 316L/PP extruded

Figure 11. Maximal principal stress of cups in service with different diameters

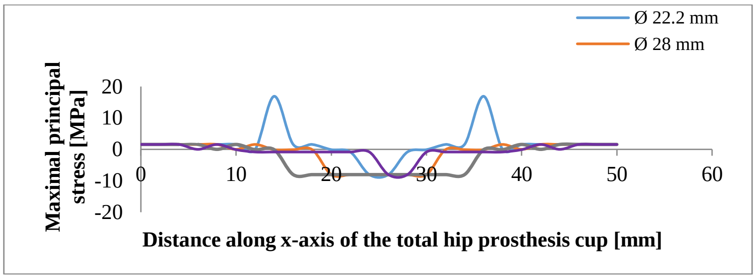
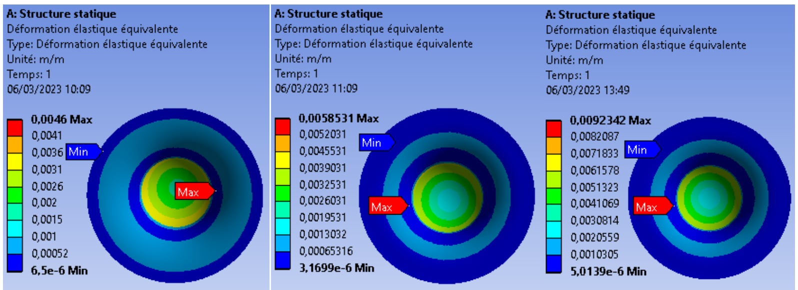


Figure 12.Evolution of the maximal principal stress along the x axis direction of the cup with different diameters (Case of 316L/UHMWPE)

3.2 Effect of couple of material

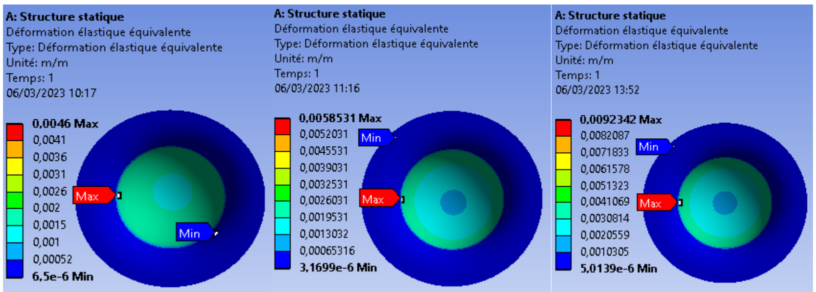
3.2.1 Equivalent elastic strain

Figures 13 and 14 illustrate the equivalent elastic strain distribution in the cup for the three material couples, using the 36.0 mm femoral head diameter that gave a good stress and strain distribution. It is noted that the deformations generated in the extruded PP cup reach a maximum value of 0.0026, which is higher than those generated in the other PP virgin and UHMWPE cups, which are 0.00195 and 0.001 respectively.



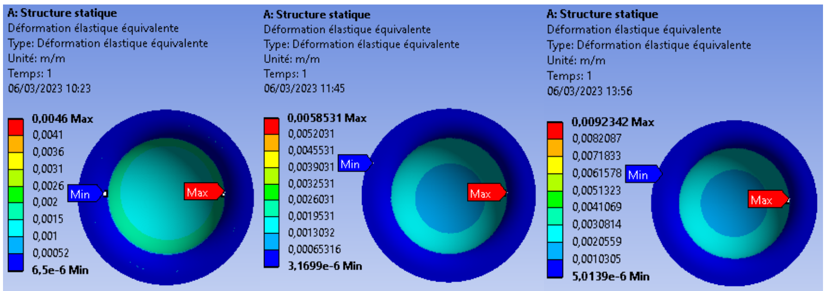
UHMWPE Virgin PP Extruded PP

(a) Cup Ø 22.2 mm



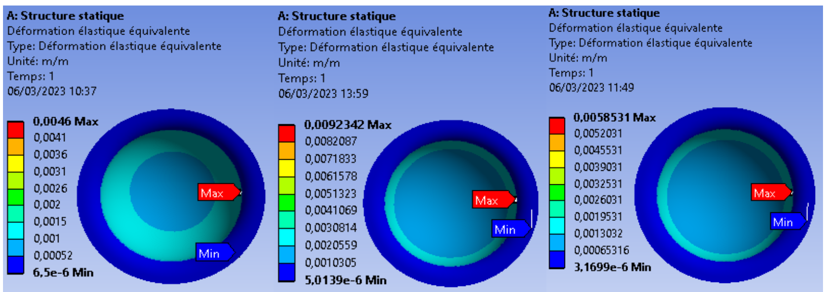
UHMWPE Virgin PP Extruded PP

(b) Cup Ø 28 mm



UHMWPE Virgin PP Extruded PP

(c) Cup Ø 32 mm



UHMWPE Virgin PP Extruded PP

(d) Cup Ø 36 mm

Figure 13. Visualization of theEquivalent elastic strain along x directionas a function with different couples

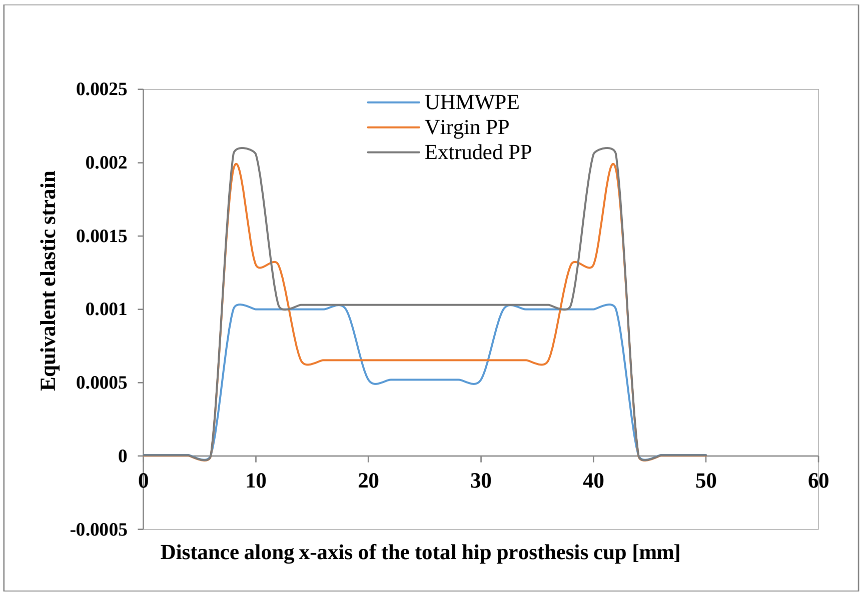


Figure 14. Evolution of the equivalent elastic strain along the x-axis of the cupwith different couples (Case of a Ø 36 mm femoral head)

4. Conclusion

This research work was aimed to determine the in-vitro mechanical behaviour of cup of total hip prosthesis using a numerical simulation based on the finite element method. It was considered different diameters with three pairs of head-cup biomaterials under the effects of stress generated by the body through selecting the pair that offers better bio-functionality. This allowed us to highlight the effects of the internal diameter of the cup and the nature of the biomaterials used on the function and reliability of the prosthesis. The solid-state extruded polypropylene (PP) processed by the Equal Channel Angular Extrusion (ECAE) implies studying the effects of the new mechanical properties of the extruded material on the stresses experienced by the cup of a total hip prosthesis. The objective of this study is to improve the mechanical properties of the new material, such as its ductility, and to reorient the macromolecular chains in order to create guiding privileges for the macromolecular chains.

The analysis of the in-vitro behaviour requires locating the hot spot and assessing the magnitude of stress and strain at the cup. The stress usually is responsible for the failure and sometimes the rupture of the cup.The obtained results permitted us the analysis of the distribution of stresses and strains for the studied cases. The stresses are mainly located on the anterior edge and the lateral side of the cup; the stresses maxima are always located in a band close to the chamfers, at the upper or lower level depending on the location of the head impact. According to the results, it is clear that the couples of material 316L/UHMWPE, for the 36.0mm femoral head diameter, demonstrated a better stress-strain distribution at the cup in comparison to the other two couples of materials and extrusions for the other three diameters, these couples may offer a better compromise for strength and better-optimized bio-functionality of the prosthesis, and may allow for less resulting displacement and deformation at the cup. This can be attributed to the increased ductility of the material and internal diameter that tends to increase the contact area and consequently decrease the pressures exerted and delays the onset of wear.

In fact, the use of UHMWPE material will avoid excessive stress concentration at the cup. Therefore, it gives a better distribution of stressesproduced by the transfer of load from the upper part of the human body to the lower one during walking.

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