

New concept in durability improvement of hip total joint endoprostheses

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Starting from the well-known fact that the rolling movement always has a lower friction compared to sliding friction, the authors have conceived and realized a pivoting movement joint on a “layer of balls” with “compensation space”, placed between the acetabular cup and the femoral head. This technical solution allows free self-directed migration of the balls, depending on the resistance opposed, with successive occupation of the “compensation space”. As a concept, the proposed technical solution excludes the existence of a cage for maintaining the relative positions of the spheres. It can be observed that the smallest values of the force and of the friction coefficient are obtained for the prostheses with balls and self-directed movement (approximately 5 times smaller than the values obtained for a classical prosthesis). For all the couples tested, the friction force grows with the growth of the normal load and of the oscillation speed. Changing the contact mechanism for the artificial hip joint from one sliding contact between two large surfaces, to a multitude of rolling contacts, could lead to some problems regarding functionality and durability of the active prosthesis elements. The key to an accurate evaluation of damaging mechanisms acting on THP with self directed rolling balls is a clear and complete picture of the load transfer mechanism.

Key words: total hip prostheses with rolling bodies, MOM prostheses, self-directed movement

1. Introduction

Theoretical and experimental research over the last 30 years have tried to contribute to the improvement of orthopaedic endoprostheses durability, through constructive changes and even through changing their functional principle.

Total hip endoprostheses with wheels represent one of the first attempts to decrease wear, by replacing the sliding movement with the rolling movement for one degree of freedom of the joint. This solution, suggested by a staff from the Imperial College of Science, Technology and Medicine (IC) in London [1] consists in the constructive modification of the modular hip prosthesis, by introducing a rolling bearing with conical

wheels between the femoral stem neck and the femoral head. It has been considered that a rolling bearing with conical wheels, that can support significant radial and axial loads, is most adequate for reaching this goal. But this requires a small diameter of the interior ring, imposed by the necessity of a reasonable diameter of the femoral head. Ensuring a satisfactory resistance for the bearing to challenge by fatigue is also necessary. Ensuring changeability of the femoral head is also imposed. Regarding these constraints, a cylindrical wheel (needles) bearing has been considered. One must notice that rolling bearings with needles present a great durability to fatigue.

Other attempts regarding changing the constructive solution of total hip prosthesis took into consideration the fundamental change in the type of relative

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Received: January 1st, 2013

Accepted for publication: July 30th, 2013

movement between the components of the total hip prosthesis. Whereas, generally, the present technical solutions are based on the natural revolutive movement of the femoral head in the acetabular cup, Katsutashi Bekki and Kiyoshi Shinjo [2] imagine a different design, the total hip prosthesis with “balls train”. This mainly consists of a dual joint construction.

The French idea of the “Supertête” prosthesis consists in placing the friction contact inside a bearing. The solution belongs to “*Fondation de l’Avenir*” in collaboration with “*La Direction Générale de l’Armement (Ministère de la Défense, Mission Innovation)*” [3]. In the opinion of French researchers, this technical solution can reduce the wear of the prosthesis with almost 99%. In order to achieve this result, a small spherical bearing of an “absolutely new” type, as the authors claimed, lubricated with synovial fluid, the natural lubricant of any prosthesis, was integrated in the femoral head. Designed and built in accordance with aeronautics industry standards, the femoral head is claimed to have reduced wear, being designed to carry 25,000 N, while the hip joint maximal forces do not overpass 5,000 N. At this moment, the “Supertête” prosthesis is a French Patent, an International Patent being under examination.

Several prototypes, in different laboratory testing phases were made in order to establish the prosthesis’ functioning period. The authors estimate that this artificial joint is able to function more than 30 years for a frequency of loading of approximately 1 million of cycles/year.

Another kind of total hip prosthesis with balls is proposed by the Institute of Solid Mechanics, of the Romanian Academy, in collaboration with the University of Medicine, and the University Hospital of Bucharest [4], making the object of a Romanian Patent.

Analyzing some hip prostheses retrieved by revision, the appearance of some forms of polishing of the femoral head was observed, as well as significant plastic deformations followed by local hardening. At the same time, obvious traces of wearing through fretting of the acetabular cup of UHMWPE, which in some studies are confounded or assimilated with the adhesive wear. Starting with the well-known fact that the rolling movement always has a lower friction compared to sliding friction, the authors have conceived and realized a pivoting movement joint on a “layer of balls” with “compensation space”, placed between the acetabular cup and the femoral head [5]. This technical solution allows free self-directed migration of the balls, depending on the resistance opposed, with successive occupation of the “compensation space” (Fig. 1).

As a concept, the proposed technical solution excludes the existence of a cage for maintaining the relative positions of the spheres. This study targeted

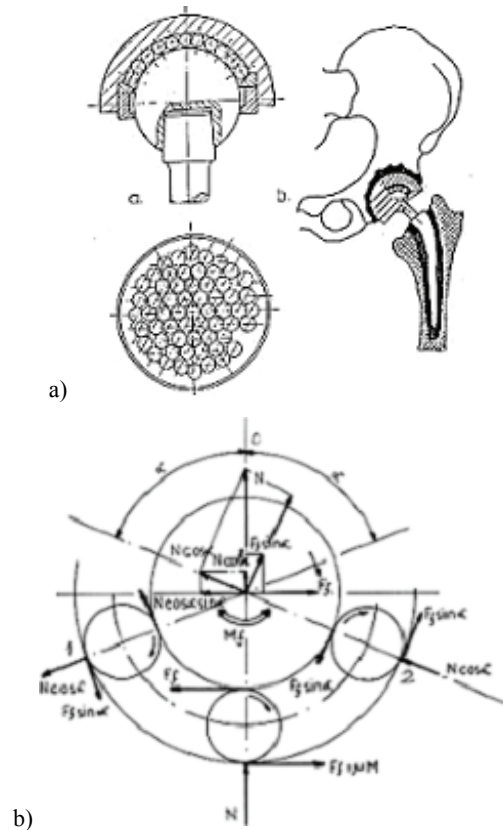


Fig. 1. (a) Self-directed rolling balls scheme and (b) one of the methods of fixation into the acetabulum, and the forces in the transversal plane of the proposed hip joint prosthesis [5]

contact mechanism including friction and wear phenomena accounting. The usual type of hip prostheses has high-density polyethylene cups (UHMWPE), ASTM-F648 (ISO 5834-2), and the femoral head from Stelit 21, ASTM-F 799 (ISO 5832-12). Based on the idea of reconsidering the potential of completely metallic type McKee-Farrar prosthesis, suggested in recent literature, a total hip prosthesis having the acetabular cup made from Ti6Al4V – ELI, ASTM-F 136 (ISO 5832-3/1990) alloy, with a density of 4.5 g/cm³, and the femoral head made from a Co-Cr-Mo alloy, with the density of 8.8 g/cm³, ASTM-F 799 (ISO 5832-12), was tested. The proposed hip prosthesis, with self-directed rolling balls, was made using a femoral head from Stelit 21, the acetabular metallic cup from Ti6Al4V-ELI alloy and the balls from stainless steel. All the prostheses have the femoral head of 28 mm in diameter. Practical realization of the joint described has proved that the free compensating space must be bigger than the volume of the ball in order to avoid the blockage. Studies have been carried out in order to determine the possible positions and the maximum number of balls, with a given radius, that could be distributed in the rolling space.

Based on the studies shown, a self-directed rolling balls prosthesis was constructed, having a femoral head diameter of 28 mm and 199 balls with a 2.5 mm diameter each. During the research we have made a comparative measurement of the friction coefficient for three types of prosthesis, at $\pm 30^\circ$ oscillations, in the presence – or in the absence – of physiological serum used as lubricant. For the experimental trials two comparison frequencies were used, namely 60 oscillations/min and 120 oscillations/min, corresponding to a normal and an accelerated step frequency.

The couples were submitted to normal load demands of 500 N, 1000 N and 1500 N. The values of the friction forces were measured, taking into account the variations of the normal force with the oscillation angle. Only the values of the friction forces in the (0) position of the couples (in the vertical direction) have been taken into consideration. According to this information, for most of the acetabular cups, the wear is between 10° in the lateral and 10° in the median direction. Therefore, the region can be placed around the vertical axis of the acetabular cup, in an anatomical position, where it is located in live recordings. For some joints, the wear speeds can be influenced by abrasive particles turned up due to the deterioration of the finished surface of the femoral head.

It can be observed that the smallest values of the force and of the friction coefficient are obtained for the prostheses with balls and self-directed movement (approximately 5 times smaller than the values obtained for a classical prosthesis). For all the couples tested, the friction force grows with the growth of the normal load and of the oscillation speed. The variation domains of the friction coefficients, in the experimental conditions presented before, are:

- Stelit 21/UHMWPE type couple, dry friction, $\mu = 0.285 \div 0.342$,
- Stelit 21/UHMWPE type couple, lubricated, $\mu = 0.035 \div 0.065$,
- Co-Cr-Mo/Ti6Al4V alloy couple, dry friction, $\mu = 0.300 \div 0.345$,
- Co-Cr-Mo/Ti6Al4V alloy couple, lubricated, $\mu = 0.065 \div 0.141$,
- couple with balls in self-directed movement, dry friction, $\mu = 0.120 \div 0.205$,
- couple with balls in self-directed movement, lubricated, $\mu = 0.006 \div 0.009$.

The tests did not allow a quantitative measurement of the acetabular cups' wear and of the femoral head, due to the lack of some comparative method of measurement that would be adequate for all the couples under study. Still, some very clear qualitative obser-

vations were made, which enabled the following conclusions to be drawn:

- for the couple type Stelit 21 /UHMWPE, the wear is manifested through the uneven polishing of the femoral head and through the appearance of some traces of wear by friction inside the polyethylene acetabular cup;
- Co-Cr-Mo / Ti6Al4V alloy couples, polishing and fine uneven scratches show up, on both elements of the prosthesis, even in the presence of physiological serum;
- the self-directed movement balls prosthesis did not show signs of wear. Under the testing conditions used in the laboratory, there were no traces of abrasion or seizing.

The tribological behaviour of the articulation with balls justifies a deeper analysis of the stresses and displacements under demanding conditions, compared to the classical articulation (Fig. 2).

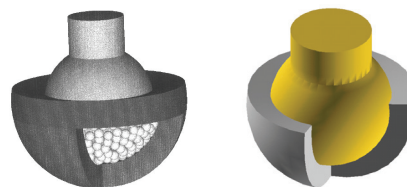


Fig. 2. The three-dimensional simplified models: left – model with self-directed balls, and right – classical model

This model considers the exterior surface of the acetabular cup built-in and the femoral head executes a rotating movement in the diametric plane, under the action of a compression force. Due to the big number of contact points, the analysis was done for a very short duration of the movement (quasi-static analysis), of 0.8×10^{-3} sec. It was established that the compression force and the rotation moment are to be constant throughout the demand period. For the case under study, it results that the most requested balls are not in the movement direction, a fact otherwise predictable. They are found in the maximum resistance space produced in the escaping area (the blocking hoop). The maximum value of the tangential stress, obtained in the last time step, is very small compared to the admissible stress. The maximum normal displacement was 0.033 mm.

The geometrical studies (see [6] and [7]) have shown that generally the balls are located non-symmetrically and that the configuration for a given space and a given number of balls is not unique. Tribological studies performed by the authors (see [4], [6], [7]) have shown very low values of overall friction coefficients (0.12 to 0.2 for dry joint and 0.006

to 0.009 in the presence of lubricants), leading to an enhanced functionality of the prosthesis itself.

2. Materials and methods

The present study uses the results of the previous studies in order to determine the load distribution through the balls bed and the compressions generated between the joint elements (femoral head, rolling balls, acetabular cup). As we previously stated, a general study of the proposed design focuses on the following mechanical aspects:

- characterization of load transfer mechanism through the joint elements (statics of enveloping loads and/or dynamic studies of natural, physiological movements);
- evaluation of tribological behaviour of all joint elements (including contact mechanics of all active interfaces – femoral head-ball, ball-ball, ball-acetabular cup);
- estimation of functional threats and damaging mechanisms for the proposed design (i.e., clear definition of criteria for joint locking, fatigue of prosthetic parts, wear of the active elements of the joint) and determination of influencing factors for all these unwanted phenomena.

Lessons learned from the previous attempts (structural overall analysis performed in [8]) lead to decoupling the statics and dynamics of the joint (FE analyses) from the tribological behaviour (separate analytical evaluation) in order to save computational effort and assuming simplifications. The characteristics of the prosthesis under evaluation are as follows [9]:

- type: Total Hip Prosthesis (THP) with self-directed rolling balls;
- geometrical features: outer radius of femoral head – 14 mm; radius of each rolling ball 1.25 mm; internal radius of acetabular cup – 16.5 mm; spherical cap for balls bed (subtended angle) – 160°;
- material used for components (see physical properties shown in Table 1): femoral head – Stel-

lite 21; acetabular cup – Ti6Al4V; rolling balls – CoCrMo alloy.

The methodology used for computing the number of balls needed for assembling the joint and their positions inside the artificial joint is that used in [4].

The resulting configuration of artificial joint was used in order to build the numerical model for the load transfer path through the balls bed. The 3D numerical model (see Fig. 3) is a large one – 58,784 elements and 73,100 nodes, with numerous surfaces in contact, requiring high computational resources and significant time for the simulation.

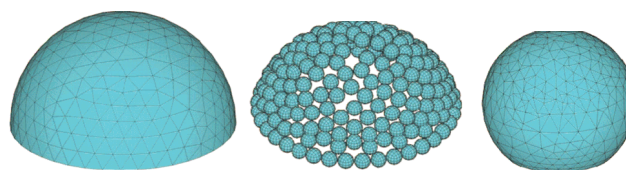


Fig. 3. 3D model of the MOM artificial joint (acetabular cup, self-directed balls, femoral head)

Instead of using a big model with multiple non-linearities, a simplified model was built based on the following hypotheses assumed:

1. Femoral head and balls were considered rigid (their stiffness is much higher than that of acetabular cup).
2. The compressive force and flexion drive moment were maintained constant.
3. Linear elastic behaviour of acetabular cup was assumed.
4. The compressive forces acting at the ball-to-ball contact surfaces are smaller than the compressive forces between balls and femoral head, respectively between balls and acetabular cup. This assumption allows us to use, instead of spherical balls, unidimensional nonlinear elements (compression only) connecting the spots of contacts between the balls and the cup, respectively between the ball and the femoral head with the centre of each ball.

The train of balls was not actually modelled as it is; instead of 3D representation of the balls (Fig. 4), unidimensional contact elements have been considered between the centre of each ball and the active surfaces of femoral and acetabular prosthetic elements.

Table 1. Material properties of components of THP with self directed rolling balls

Property	Stellite 21 [®]	Ti6Al4V (ASTM F136)	CoCrMo alloy (ASTM F75)
Density (g/cm ³)	8.31	4.5	8.31
Young's modulus (Gpa)	248	110	210
Yield strength (MPa)	517	795	450
Tensile strength (MPa)	724	860	655
Intended use	Femoral head	Acetabular cup	Rolling balls

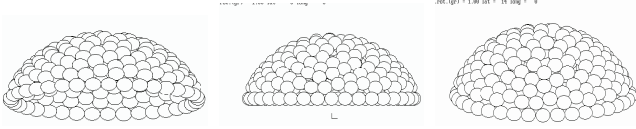


Fig. 4. Arrangement of rolling balls for study case (left – lateral 15° view; middle – frontal view; right – lateral 15° view)

The 3D FE model was loaded by a compressive 1 kN force and a flexion of the joint was considered for ~37.6° (i.e., a relative maximum displacement of circumferential points located on femoral head and acetabular cup equal to 4 times the diameter of one rolling ball).

After the loads on each ball had been determined (being categorized based on the regions of the balls rather than each ball itself) a local analysis was performed for establishing the extreme Hertzian contact parameters using the following methodology [10]:

- maximum pressure, given by

$$p_0 = \sqrt[3]{\frac{6PE^{*2}}{\pi^3 R^2}}, \quad (1)$$

- radius of contact spot, given by

$$a = \sqrt[3]{\frac{3PR}{4E^*}}, \quad (2)$$

- mutual approach between bodies in contact, given by

$$\delta = \sqrt[3]{\frac{9P^2}{16RE^{*2}}}, \quad (3)$$

where P is the applied compressing load, and R the relative curvature given by

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}. \quad (4)$$

3. Results

After performing the geometrical assessment, based on the methodology presented in [4], it results that the maximum number of balls needed for

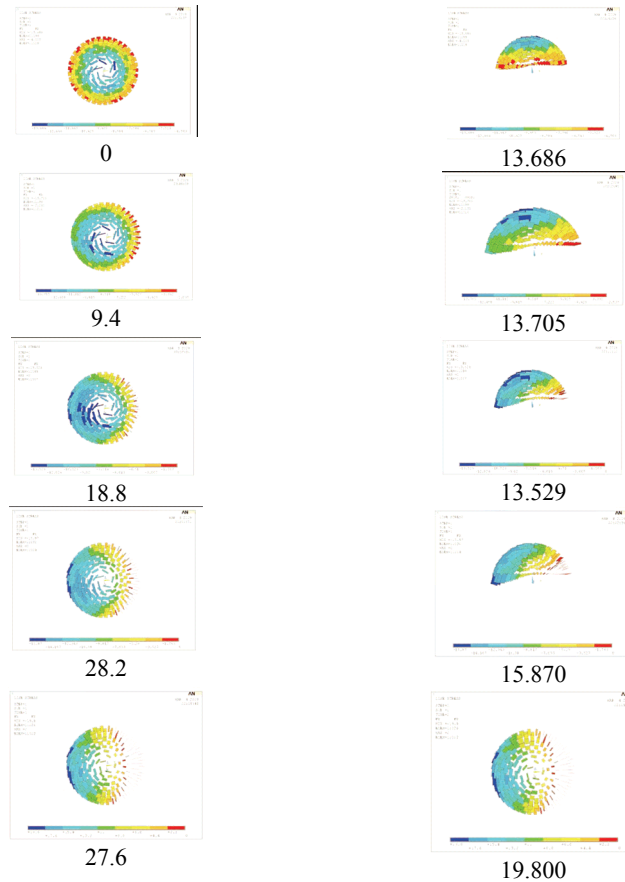


Fig. 5. The compressive loadings transferred from femoral to acetabular parts of the prosthesis for different instances of flexion (between 0° and 37.6°); flexion listed in left, maximum load listed in the right part of the picture)

the spherical joint is 199, distributed in 12 consecutive rows (Fig. 4) as follows

$$n_0 = 37; n_1 = 19; n_2 = 19; n_3 = 19; n_4 = 19; n_5 = 19;$$

$$n_6 = 19; n_7 = 19; n_8 = 14; n_9 = 9; n_{10} = 5; n_{11} = 1.$$

Images of the positions of the rolling balls for $\varphi = 0$ and $\beta = 0^\circ \pm 15^\circ$ (where φ and β are the azimuth and zenith angular coordinates in the spherical coordinate system associated with the femoral head), are shown in Fig. 4. One could notice from the results of the mathematical analysis that the arrangement of the balls in the rolling space is asymmetrical and will not be uniquely determined.

After applying 1 kN compressive load onto the artificial joint having the balls train configured as resulted from the geometrical analysis, the loadings on each rolling ball during the 37.6° flexion were determined by FE analysis of a dynamic nonlinear model of the entire joint. Several instances have been selected for presenting the results in both vertical and normal views to the flexion plane in Fig. 5.

They correspond to 1-diameter, 2-diameter, 3-diameter and 4-diameter relative displacements between the acetabular and femoral parts of the prosthesis. By analyzing the plots, the following conclusions could be drawn:

(a) Even for the initial condition, due to the asymmetrical arrangement of the balls resulting from the geometrical analysis, there is some asymmetry of transferring the load path from the femoral head to the acetabular part.

(b) During the flexion (especially for large angles) a part of the balls will not be loaded anymore, leading to an increase of the maximum force transmitted by intermediate row of rolling balls (from $\sim 1.35\%$ of the total joint compression force – as for flexion angles lower than 18.8° , to $\sim 1.98\%$ of the total joint compression force – as for a flexion of 37.6°), Fig. 5.

(c) By analyzing the loading of each ball row, it has been determined (for the initial position, 0° flexion) that the most loaded rows are those located close to $40^\circ \dots 60^\circ$ from the equatorial plane (the rows located lower have small loads on each ball, and for the rows located higher each ball carries a bigger load but the number of balls is small). The distribution of rolling balls loading versus the zenith positioning angle of the rolling ball is presented in Fig. 6.

Analyzing the graph, the following conclusions could be drawn:

1. As reported before, there is a slight asymmetry of the distribution even for the initial position. This

asymmetry evolves with flexion leading to unloading of some balls located peripherally outside the hemispherical area characterized by the compressive loading pole.

2. The peripheral balls located closer to the compressive loading pole are generally highly loaded, but the highest loaded balls remain those positioned in intermediate rows (between 40° and 60° from the equatorial plane).

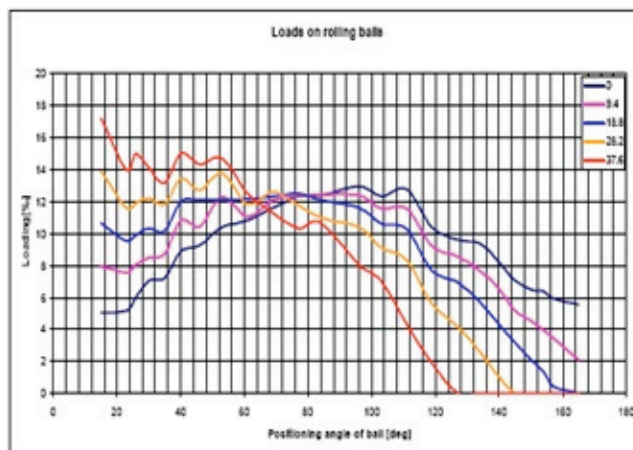


Fig. 6. The rolling ball loadings versus zenith positioning angle of ball

For the extreme maximum loadings of the balls during the analyzed flexion, a preliminary evaluation of tribological parameters of contact between femoral head and rolling balls and between rolling balls and acetabular cup has been performed by using formulae (1)–(3) listed in the previous section. The results are presented in Table 2.

Analyzing these results, one could draw the following conclusions:

1. The femoral head is higher loaded than the acetabular cup (the contact pressures are higher) but the affected area is smaller (the contact spots have smaller radius due to higher stiffness of the femoral head). One could see that the total contact area considering the contact between all rolling balls and the femoral head during flexion is upper bounded by 1.658 mm^2 , but for the contact between the rolling balls and the acetabular cup an approximately 36% larger value (2.258 mm^2) is obtained.

2. The surface more likely to deform will be the active surface of the acetabular cup. The compressive load could lead to very small migrations of femoral head towards the acetabular cup (between 4.2 and $5.4 \mu\text{m}$), which could be neglected in a detailed mechanical analysis.

Table 2. Computed local tribological parameters for contacting bodies inside the joint

Parameter	Femoral head–rolling ball contact		Rolling ball–acetabular cup contact	
	Min.	Max.	Min.	Max.
Curvatures of surfaces in contact R_1, R_2 (mm)	$R_1 = 14.0$ $R_2 = 1.25$		$R_1 = 1.25$ $R_2 = 16.5$	
Young modulus of surfaces in contact E_1, E_2 (GPa)	$E_1 = 248$ $E_2 = 210$		$E_1 = 210$ $E_2 = 110$	
Poisson ratios of surfaces in contact ν_1, ν_2	$\nu_1 = 0.3$ $\nu_2 = 0.3$		$\nu_1 = 0.3$ $\nu_2 = 0.3$	
Relative curvature R (mm)	1.1475		1.1620	
Relative plane-strain modulus E^* (GPa)	124.96		79.33	
	Min.	Max.	Min.	Max.
Transferred compressive load P (kN)	0.01353	0.0198	0.01353	0.0198
Radius of contact spot a (mm)	0.0453	0.0515	0.0530	0.0601
Maximum contact pressure, p_0 (GPa)	3.1429	3.5682	2.3022	2.6138
Radius of contact spot a (mm)	0.0453	0.0515	0.0530	0.0601
Mutual approach between bodies in contact δ (mm)	0.0018	0.0023	0.0024	0.0031

4. Discussion

Nowadays, new and innovative designs try to replace the original artificial hip joint based on sliding movement, by taking into account the advantages of rolling contact between active surfaces, in order to decrease the wear and assure the low friction conditions characteristic of natural joints. Adopting such design could lead to new threats regarding functionality and durability of the prosthetic components. This preliminary study covers the load transfer mechanism in a Total Hip Prosthesis with rolling balls, whose design features were covered in [4]. The geometrical evaluation of the maximum number of balls and their positions inside the cavity formed between the femoral head and the acetabular cup follows the methodology covered in a previous study [4]. The difficulties encountered in the evaluation of both dynamical aspects and tribological ones on the same model (a very complex model with large number of surfaces in contact, leading to an increased computational time even for low accuracy, see previous study [8]) lead to an evaluation methodology based on decoupling the loading transfer mechanism problem from the local problem of contact assessment (between each rolling ball and femoral head and between each rolling ball and acetabular cup).

Based on the results of FE analysis of the artificial joint with self-directed rolling balls flexion under compressive loads, one could conclude that the load

transfer mechanism is asymmetrical due to the asymmetric position of rolling balls either initially and during the flexion. Even though the most dynamically loaded balls during the flexion are preferentially located onto the peripheral rows close to the loading pole, the intermediary rows of balls (located between 40° to 60° zenith angle from equatorial plane) assure the required quantity of balls needed to get most of the compression. Also, at large flexion angles the balls located peripherally outside the hemisphere having the polar axis coincident with the direction of loading will remain unloaded.

Local analytical evaluations of contact parameters lead to the conclusion that the femoral head will be higher loaded than the acetabular cup (contact pressures will be higher) but the affected areas (interference area between the rolling balls and femoral head) will be smaller. The acetabular cup active surface is more likely to deform and the migration of the femoral head to acetabular cup due to deformations resulted under compressive loading could be neglected.

Due to the preliminary status of the study, several directions for development could be foreseen. First, the influence of the contacts established between the rolling balls in the dynamics of the joint must be considered and the load transfer model could account for the initial straining of the train of balls. Also, a complete dynamics of the balls during the relative movement between the femoral head and acetabular cup could be determined using a multi-body rigid

analysis. Natural characteristic movements of the joint could be reproduced and functionality of the artificial joint could be evaluated. Enhanced local tribological analyses could be performed to account for permanent deformations and local yielding at the contact between rolling balls and femoral and acetabular components, and to evaluate the potential damaging mechanisms.

Acknowledgements

The authors would like to thank the Romanian Academy for its material and technical support offered in order to conduct this research.

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