PRELIMINARY STUDIES REGARDING LOAD TRANSFER MECHANISM IN TOTAL HIP PROSTHESES WITH ROLLING BALLS

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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 serious problems regarding functionality and durability of the active prosthesis elements. The key to an accurate evaluation of damaging mechanisms acting on THP with rolling balls is a clear and complete picture of load transfer mechanism. The present paper summarize preliminary results regarding dynamics of some original design proposed by authors in [4], combining general nonlinear FE analyses of entire joint with analytical evaluations of local contacts.

1. INTRODUCTION

Nowadays, the design solutions for Total Hip Prostheses are diverse encompassing for improving the materials used for prostheses elements and reshaping geometrically and/or tribologically the load transfer path. In such context, Total Hip Prostheses with rolling balls have been found as a possible viable alternative design to current industrial products, based on low friction of rolling contact, against sliding one (now used in most industrial designs). Different designs of Total Hip Prostheses with rolling bodies have been developed in order to improve the tribological performances of the artificial joint. We could mention here the design with ball train, proposed by Katsutoshi and Kiyoshi [1], the French "Supertête" prosthesis [2], or the design with conical rolling elements proposed by Imperial College of Science, Technology and Medicine of London [3].

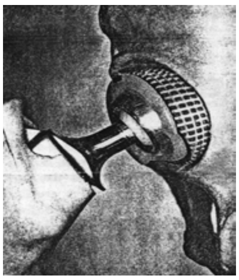

Fig. 1 – „Supertête" prosthesis.

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If the French design (see Fig. 1), obtained by “Fondation de l’Avenir” in collaboration with “Ministère de la Défense, Mission Innovation”, propose the insertion of a frictional contact inside a bearing, the design suggested by Imperial College of Science, Technology and Medicine of London (see Fig. 2) consists in a major modification of a modular hip prosthesis by introducing a rolling bearing with conical elements between the femoral part stem neck and the femoral artificial head. The bearing rotation axis corresponds with the axis of femoral stem neck, the rolling elements being guided by both the external surface of stem neck and the internal surface of the ball replacing the femoral head.

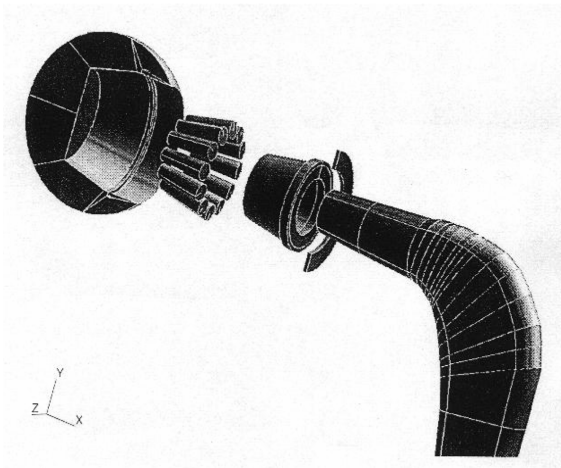


Fig. 2 – Total Hip Prosthesis with conical rolling elements proposed by Imperial College of Science, Technology and Medicine of London.

But changing the contact mechanism from sliding to rolling in a hip prosthesis is not an easy task due to difficulties encountered in establishing the load transfer path, a critical characteristic of tribological behavior of joint with large influence in functionality and durability of prosthesis active elements. Basically, the sliding contact between large surfaces of femoral head and acetabular cup was replaced by a multitude of rolling contacts with a different pattern of stress distribution influenced by rolling elements position at some instant during relative movement between femoral and acetabular parts.

In the present paper, the authors focus on the original design proposed by them in [4], *i.e.* a Total Hip Prosthesis with rolling balls (see Fig. 3). A characteristic of this design solution is the fact that the artificial joint will work similar to a spherical bearing, having what is called a “compensation space”, *i.e.* enough free space between the femoral and acetabular parts of the prosthesis to allow the movement of the balls.

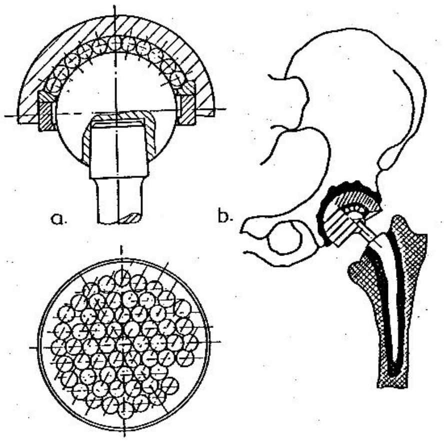


Fig. 3 – Hip prosthesis with rolling bodies

Previous research studies performed by the authors focused on the determination of the initial position of rolling balls due to geometrical restraints of the assembly and on the estimation of the overall friction coefficients in dry and lubricated motion. 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 he authors (see [4], [5] and [6]) 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.

The present study will use 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).

2. METHODOLOGY

As we previously stated, a general study of the proposed design will target the following mechanical aspects:

– characterization of load transfer mechanism through the joint elements (statics of enveloping loads and/or dynamics studies of natural, physiological movements);

– evaluation of tribological behavior 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 active elements of the joint) and determination of influencing factors for all these unwanted phenomena.

Lessons learned from previous attempts (structural overall analysis performed in [7]) lead to decoupling the statics and dynamics of the joint (FE analyses) from the tribological behavior (separate analytical evaluation) in order to save computational effort and assuming simplifications.

The characteristics of the prosthesis under evaluation are as follows:

– type: Total Hip Prosthesis (THP) with 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°;

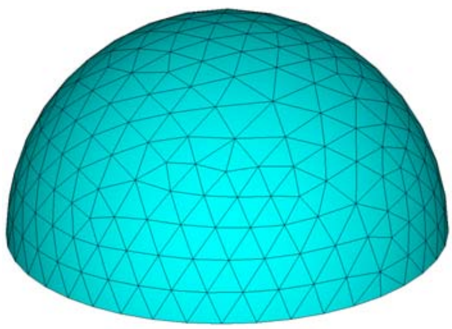
– material used for components (see physical properties shown in Table 1): femoral head – Stellite 21; acetabular cup – Ti6Al4V; rolling balls – CoCrMo alloy.

Table 1

Material properties of components of THP with rolling balls

Property	Stellite 21®	Ti6Al4V (ASTM F136)	CoCrMo alloy (ASTM F75)
Density [g/cm^3]	8.31	4.5	8.31
Young 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

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 resulted configuration of artificial joint was used in order to build the numerical model for load transfer path through the balls bed. The 3D numerical model (see Fig. 4) is a large one – 58784 elements and 73,100 nodes, with numerous surfaces in contact, requiring high computational resources and significant time for simulation.



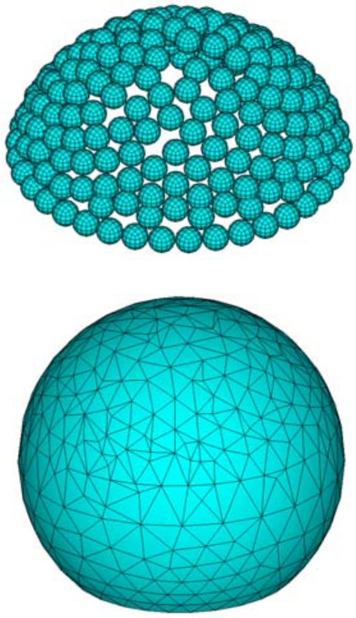


Fig. 4 – 3D model of the artificial joint.

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

1. Femoral head and balls have been considered rigid (their stiffness is much higher than acetabular cup stiffness).
2. The compressive force and flexion drive moment have been maintained constant.
3. Linear elastic behavior 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 cup, respectively between the ball and femoral head with the center of each ball.

The train of balls was not actually modeled as it is; instead of 3D representation of the balls (Fig. 5), unidimensional contact elements have been considered between the center of each ball and the active surfaces of femoral and acetabular prosthetic elements.

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 with 4 times the diameter of one rolling ball).

After the loads on each ball have been determined (being categorized based on balls regions rather than each ball itself) a local analysis was performed for establishing the extreme Hertzian contact parameters based on the following methodology [8]:

– maximum pressure, given by $p_0 = \sqrt[3]{\dfrac{6PE^{*2}}{\pi^3 R^2}}$, (1)

– radius of contact spot, given by $a = \sqrt[3]{\dfrac{3PR}{4E^*}}$, (2)

– mutual approach between bodies in contact, given by $\delta = \sqrt[3]{\dfrac{9P^2}{16RE^{*2}}}$, (3)

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

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}, \tag{4}$$

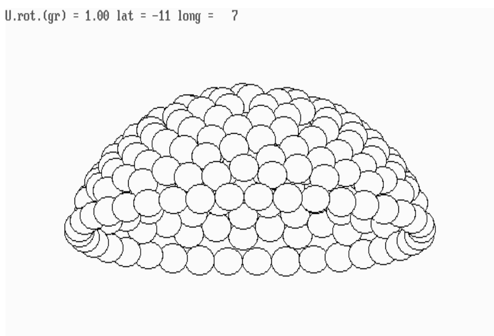
with R_1, R_2 – curvature of surfaces in contact; E^* – relative plane-strain modulus

$$\frac{1}{E^*} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}. \tag{5}$$

3. RESULTS

After performing the geometrical assessment, based on the methodology presented in [4], it results that the maximum number of balls needed for the spherical joint is 199, distributed on 12 consecutive rows as follows:

$n_0 = 37$; $n_1 = 19$; $n_2 = 19$; $n_3 = 19$; $n_4 = 19$; $n_5 = 19$;
$n_6 = 19$; $n_7 = 19$; $n_8 = 14$; $n_9 = 9$; $n_{10} = 5$; $n_{11} = 1$.



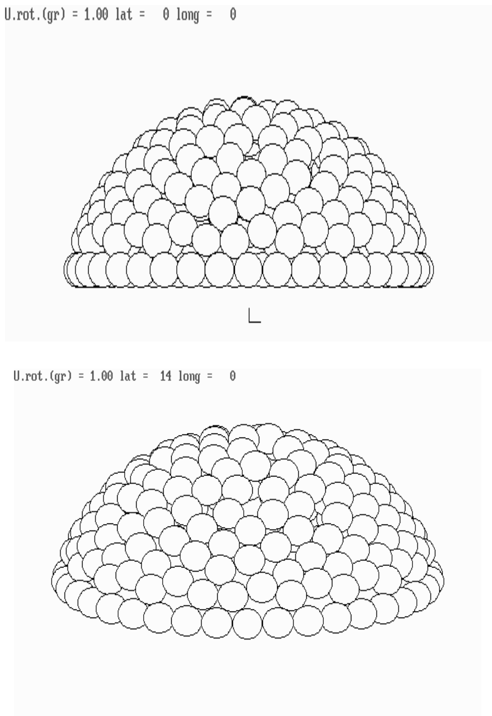


Fig. 5 – Arrangement of rolling balls for study case
(up – lateral 15° view; middle – frontal view; down – lateral –15° view).

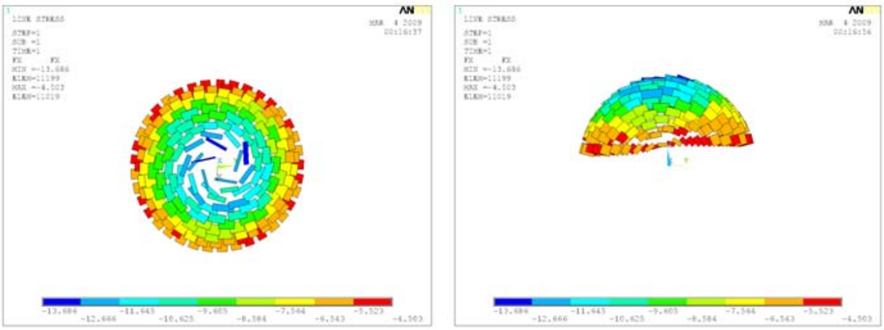
Images of the rolling balls positions for $\varphi = 0$ and $\beta = 0° \pm 15°$ (where φ and β are the azimuth and zenith angular coordinates in the spherical coordinate system associated with the femoral head), are shown in Figs. 5 above. One could notice from the results of the mathematical analysis that the arrangement of the balls in the rolling space is asymmetrical and will not be uniquely determined.

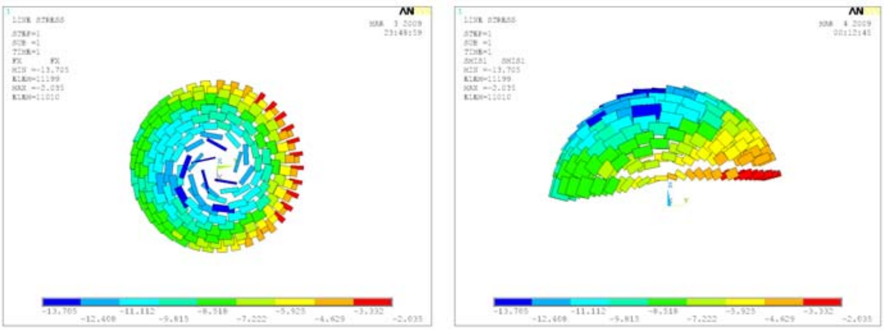
After applying 1 kN compressive load onto the artificial joint having the balls train configured as resulted from the geometrical analysis, the loadings on each rolling ball during the 37.6° flexion were determined by FE analysis of a dynamic nonlinear model of the entire joint. Several instances have been selected for presenting the results in both vertical and normal views to the flexion plane in Figs. 6 (corresponding 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:

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

2. 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 of a rolling ball (from ~1.35% of the total joint compression force – as for flexion angles lower than 18.8°, to ~1.98% of the total joint compression force – as for a flexion of 37.6°).

0

13.686

9.4

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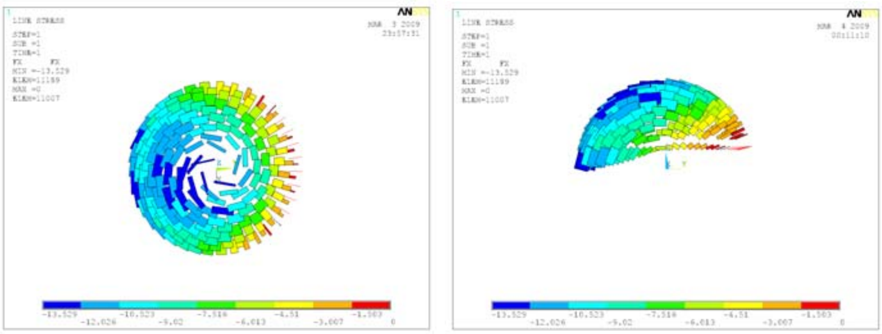
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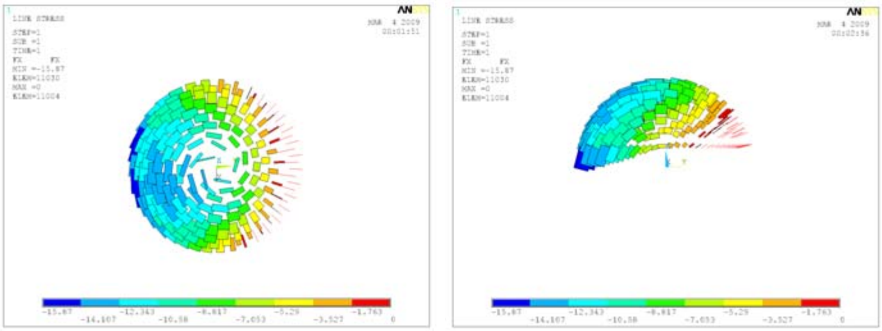
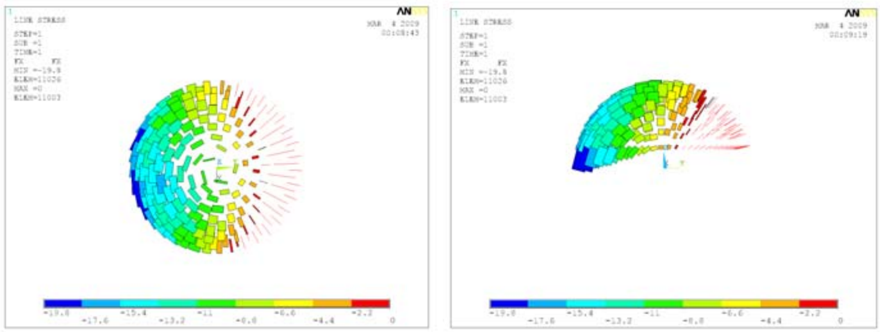


28.2

15.870



37.6

19.800

Fig. 6 – 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 right part of the pictures).

3. 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°…60° from the equatorial plane (the rows located lower have small loads on each balls, and for the rows located higher each ball carries a bigger load but the number of balls is low).

The distribution of rolling balls loading versus the zenith positioning angle of the rolling ball is presented in Fig. 7. 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 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).

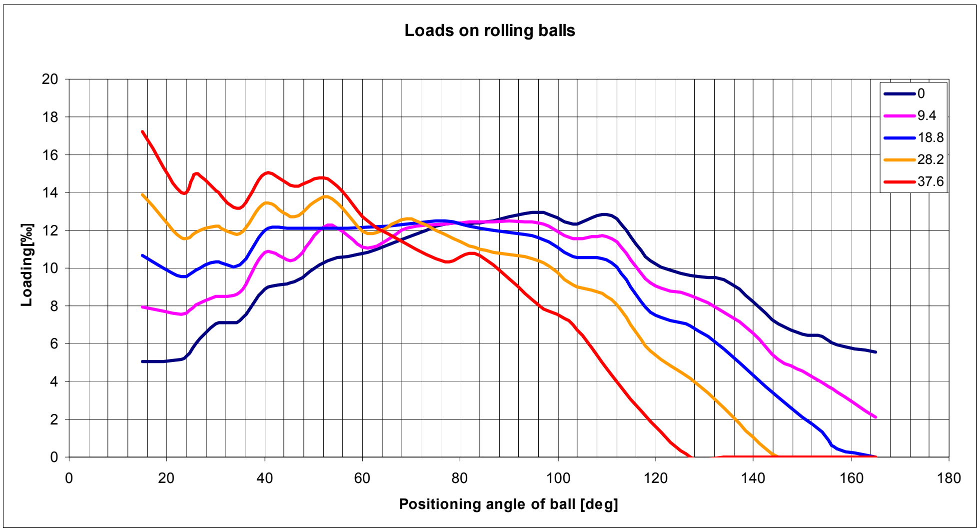


Fig. 7 – The rolling balls loadings versus zenith positioning angle of ball.

Table 2

Computed local tribological parameters for contacting bodies inside the joint

Parameter	**Femoral head – rolling ball contact**		**Rolling ball – acetabular cup contact**	
Curvatures of surfaces in contact R_1, R_2 [mm]	$R_1 = 14$ $R_2 = 1.25$		$R_1 = 1.25$ $R_2 = 16.5$	
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	
	Minimum	Maximum	Minimum	Maximum
Transferred compressive load P [kN]	0.01353	0.0198	0.01353	0.0198
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

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 previous section. The results have been presented in Table 2. Analyzing these results, one could draw the following conclusions:

1. The femoral head is higher loaded than the acteabular cup (the contact pressures are higher) but the affected area is smaller (the contact spots have smaller radius due to higher stiffness of 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 acetabular cup active surface. The compressive load could lead to very small migrations of femoral head toward the acetabular cup (between 4.2 and 5.4 μm), which could be neglected in a detailed mechanical analysis.

4. CONCLUSIONS

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 to 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 (very complex model with large number of surfaces in contact, leading to increased computational time even for low accuracy, see previous study [7]) 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 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 that 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 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 balls train. 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.

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