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Prediction of Crack Propagation Direction in the Cemented Total Hip Prosthesis

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The major inconvenient of the Poly methyl methacrylate *(PMMA)* is the crack formation; this phenomenon takes place during the polymerization process which is the result of an exothermic chemical reaction. In this context, this study aims to predict the behavior of macros cracks situated in the most heavily loaded sites in newly used bone cement. In fact, the prediction of crack propagation directions in bone cement during exercising the most practiced activity by patients allows determination of the most favorable cracking directions and subsequently provides orientations for the studies aiming to fight against this phenomenon.

Keywords: surgical cement, biomechanics, stress intensity factor, dynamic loading, Finite Elements, crack propagation direction.

1. Introduction

Until now, the prediction of crack propagation direction in fragile materials was very slightly investigated, even less when it's about complex structures. But today, thanks to computation technology and advanced software, it becomes possible to determine with high accuracy the nature and magnitude of stresses induced in all types of materials and even for complex structures.

The fracture mechanics has obtained considerable importance in these recent years, in order to study and control crack behavior under static loading and mechanical fatigue. The majority of research works in the fracture mechanics domain were performed for plastic behavior materials, actually, these research works aims the development of crack growth criterion to be applied within the biaxial factor. But, using elastic behavior material has become vital in lot of domains that are chara-

cterized by the high amplitude of induced constraints and the presence of mechanical shocks, indeed, the PMMA used in total hip prosthesis for example must ensure efficiency in all conditions previously mentioned to ensure a lifetime exceeding 10 years.
The cracks behavior in mixed mode has attracted very slight attention, but in fact, it is more realistic and more dangerous than the first mode (mode-I), the crack growth in mixed mode happens with every static or dynamic crack propagation and even during a low or high cycle mechanical fatigue, especially when cracks are positioned beside default or making an angle with the axis of loading.
This study was established to determine the angle of cracks initiation that are situated in most loaded locations of total hip prosthesis cement which is a hyper fragile material, and to predict propagation direction of a rectilinear geometry cracks located in six different positions and under real body loading conditions.

2. The objective

The hip joint is the strongest joint in the human body and the most mobile of the lower limb, it finds its mobility due to the most powerful muscles of the human body, and it is held in place by a multitude of strong ligaments. This anatomical specificity induces very important stresses in femoral bone and for patients carrying a total hip prosthesis the stresses are directly affecting the bone cement. In fact, the PMMA is the weakest link in force transfer chain of THP, however, cracking is the main mode of PMMA damage.
The mechanical behavior of total hip prosthesis is, until now, under investigations. This study comes within this context as objective of a three-dimensional prediction of crack propagation direction during the patient's most exercised activity that is related to the THP (slow walking activity). Until today, this complex behavior prediction cannot be performed without using finite elements method, this behavior depends on the interaction of four components of the prosthesis. In this work the simulated THP is exposed to a very realistic loading conditions and boundary conditions, based on measurements of the *in vivo* hip joint contact forces and different muscular efforts.

3. Materials and methods

The prediction of crack propagation in the bone cement layer requires a determination of precise amplitude cartography of both normal and tangential stresses along the structure during all the cycle period, to do this, it is important to determinate also the variation of muscular forces acting on the hip-femur system, and the resultant forces applied on the femoral head, during one cycle activity.
As it's indicated in Fig. 5, the cement is actually interacting with the femoral implant and the spongious bone, where it's supposed to insure three fundamental functions: the biocompetance, the biompatibility and the antibiotics transfer from cement into the femoral bone to avoid infection complications. In this work, we will simulate the most unfavorable crack propagation cases, by creating six deferent cracks in the highest stress regions.

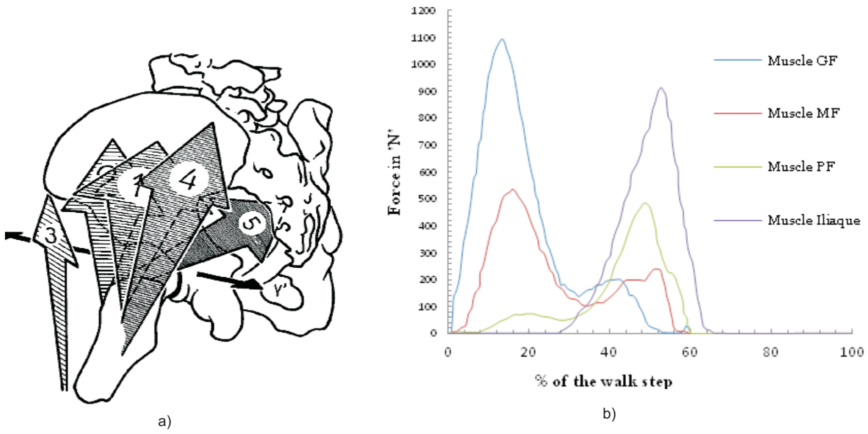


Figure 1 a) Schematic representation of the hip's strongest muscles: Gluteus medius – 1, gluteus maximus – 2, TFL – 3, gluteus minimus – 4, semimembranosus – 5, b) Exerted forces by major muscles during a walk (determine by the instrumented femoral implant): *Gf:* gluteus maximus, *Pf:* gluteus medius, *Mf:* gluteus minimus and the iliac muscle during normal walking

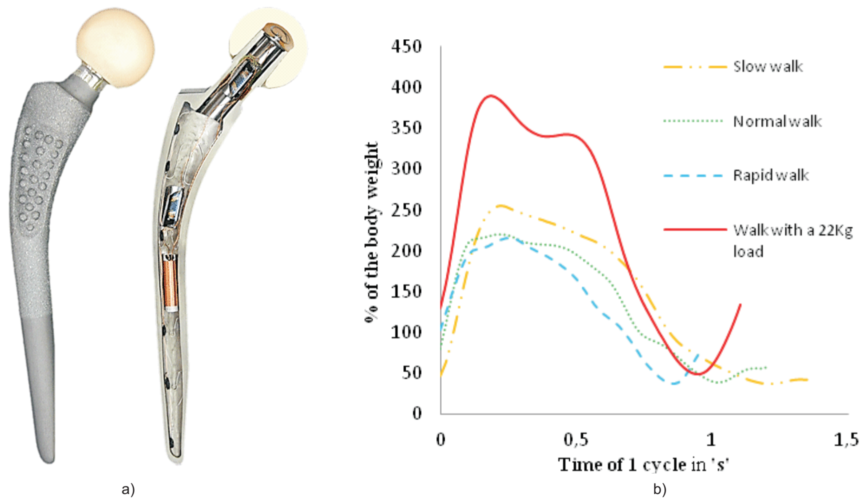


Figure 2 a) Instrumented femoral implant, b) The variation of resulted forces F_{res} in function of body weight during 1 cycle of the walking activities

3.1. *Muscular forces*

The hip muscles are numerous; however, some have a low action on the hip joint articulation, or even negligible. In this work, we have determined the efforts of the strongest muscles (such as the gluteus maximus, the gluteus medius, the small gluteus and the iliacus) (Fig. 1a) [4].

3.2. *Boundary conditions*

The instrumented THP implant with a telemetric data transmission allows the determination of contact forces generated at the hip, which is essential for the definition of total hip prostheses design [1] (Fig. 2a). The processing of data that can be transmitted by a modern instrumented total hip prostheses, allows the determination of:

– the nature of exerted forces on the femoral implant (traction, compression, torsion or shear forces),

– the magnitudes of resulting forces and generated moments around the three axes [2],

– the tridimensional femoral implant deformation,

– the resulting temperature during practiced activities [4].

After having determined the muscular forces and the applied forces on the femoral implant of each activity, we projected all acquired forces (magnitudes and directions) on the adopted coordinate system (Fig. 3a): the exerted force on the femoral head is simulated by the decomposition of resulting forces in the three main axes, the muscular forces are also decomposed according to the main axes but their application surface is on the bone and it is similar to their real application sites *in vivo*, while the knee is considered as a joint with two degrees of freedom, one displacement along the Y axis and one rotation on the X axis (Fig 3b).

Then we proceed to simulate the mechanical behavior of the total hip prosthesis subjected to accurate body forces (dynamic loading). According to studies and to doctors, the slow walk activity is recommended for the patients, and indeed, it is the most exercised activity by THP carriers, that's why it has been selected for this work.

3.3. *The analyzed structure*

The numerical model of the analyzed total hip prosthesis is illustrated on Fig. 4. This model is composed of an implant (shaft and implant's head) (Fig. 4a), of a surgical cement (Fig. 4b) and the femoral bone (cortical bone and spongious bone) (Fig. 4c–d). The femoral implant and the femoral bone are attached together with the surgical cement as shown in Figure 5. The interactions between these components (implant – cement – bone) determines the lifetime of the cemented hip prostheses.

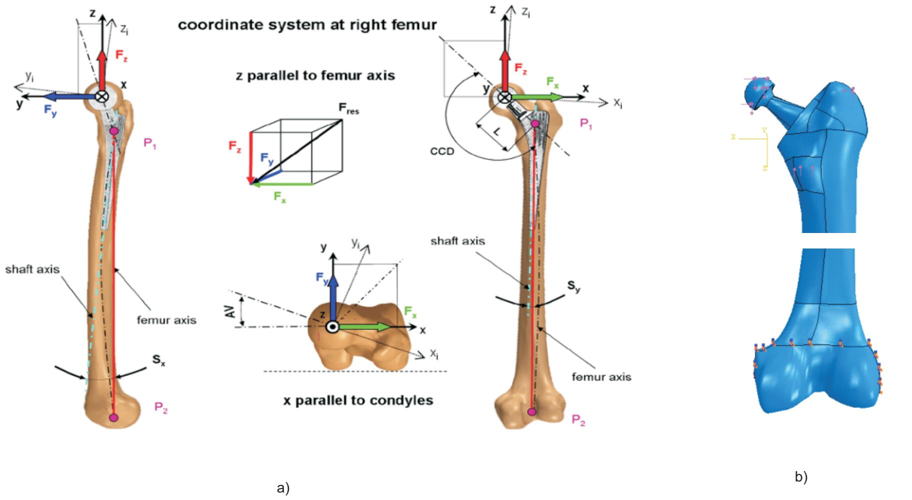


Figure 3 a) Theadopted coordinate system: Fx, Fy, Fz are the component of the resulted force applied on the femoral head, the point $P_1$is the center of the femoral head, and P_2 is the center of the femur's inferior extremity, the connection between $P_1$and $P_2$is the 'Z' axis, (O, X_i, Y_i, Z_i) is the implant system which is actually use by the computer to calculate Fx, Fy, Fz and the resulting force F_{res}, b) Illustration of boundary conditions: the applied forces (body weight and muscular forces) on the top and the forced displacements and rotations (displacements according to X and Z axis = 0, rotation around Y and Z axis = 0) on the bottom

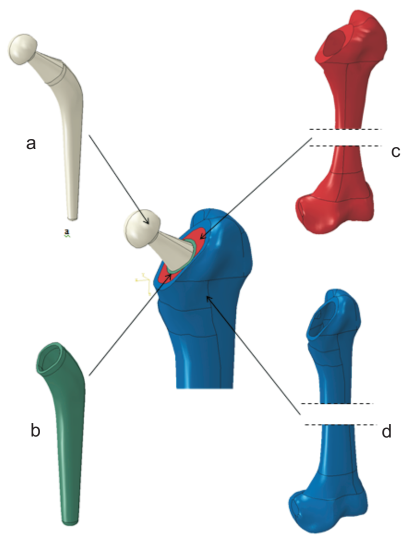


Figure 4 The simulated model: the femur bone with cemented THP type CMK3

This 3D bone model was realized directly from radiology images of the femur, in fact the CT-scan images allowed us to see the cross-section of the femur and according to the luminous intensity of tomographic images, two regions were distinguished: cortical bone and spongious bone, then we imported these images by a 3D modeling software (solidworks) where we numerically built the two femoral component separately then with the assembly interface of ABAQUS software we arranged these two components in their precise positions and finely we cut the femoral neck and we created a housing in the femur's upper extremity (proximal area) in which, the surgical cement and the femoral bone were inserted (the patient weight is 980 N and his tall is 190 cm).

3.4. *Meshing technics and material proprieties*

For a better representation of the artificial hip joint components, the numerical models have been meshed separately using tetrahedral elements (Fig. 5). Because of the geometrical complexity of each component, we have reduced the element size by refining the mesh until having stable results (constant results even with smaller element's size). The mechanical properties of bone and prosthesis's components used in this simulation were defined according to [5] as follows:

Table 1 Mechanical properties of the femoral bone and the total hip prosthesis components

	Young's modulus E [MPa]	Poisson's ratio ν
The cortical bone	20000	0.3
The spongious bone	132	0.3
The femoral implant	210000	0.3
The surgical cement	2000	0.3

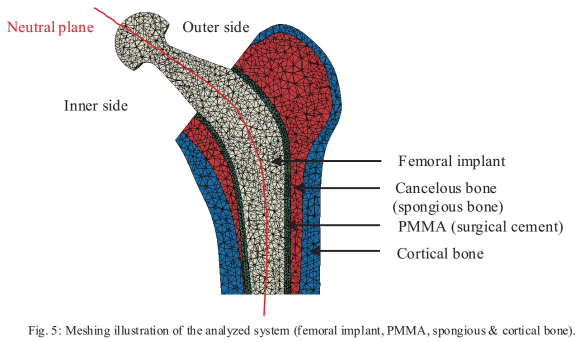


Figure 5 Meshing illustration of the analyzed system (femoral implant, PMMA, spongious and cortical bone)

3.5. *Cracks propagation direction*

Until this hour, it is not technically possible to study the bone cement cracking process without using the numerical simulation and the finite elements method. In this work we will focus our studies on the crack's propagation direction inside the bone cement, those cracks are installed in six different positions, in this study the boundary conditions are almost identical to those applied *in vivo*.

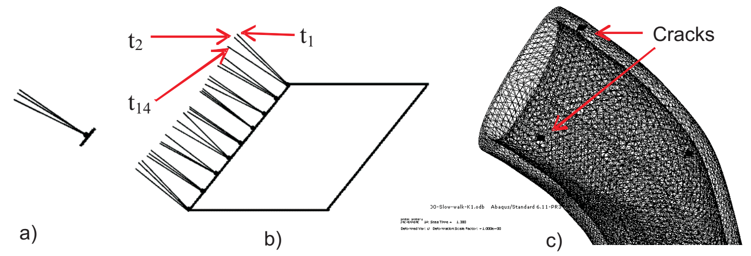


Figure 6 a) Crack propagation direction of node N° 3, b) Crack propagation direction in the first contour at t_1, t_2 et t_{14}, c) Positioning of the crack in the in the upper side of the PMMA

The digital simulation software ABAQUS allows us to determine the stress distribution with high accuracy at the crack front. However, the stress intensity factor is the first parameter responsible of crack propagations, the software package used allows us also to compute, and during each increment' i ', the three modes of stress intensity factor 'K_1' , 'K_2'and 'K_3' corresponding respectively of three modes of crack opening 'mode-I ', ' mode-II 'and' mode-III '.

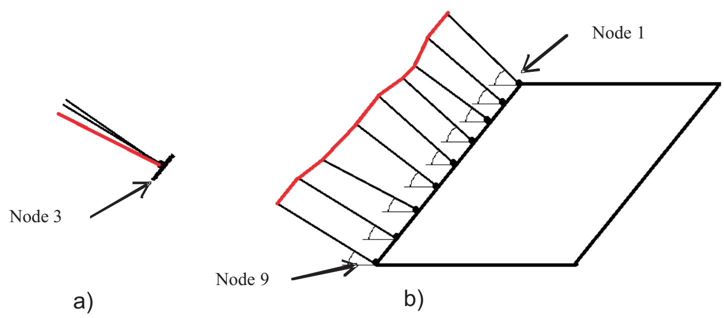


Figure 7 a) The selection of the most likely propagation direction for nodeN°3, b) Representation of the new crack front in the first contour for t = t_3

The SIF or the stress intensity factor is the first parameter responsible of crack propagations process. In this work the SIF of each crack has been computed at

every increment 'i' all along the slow walking activity cycle, in fact every material has its own K_c which is the critical value of SIF from which the material cannot resist the crack propagation anymore. Once the SIF/Time curve is establish, we will select the timing corresponding to a maximal SIF value during one cycle, and then we will select also direction of propagation computed for this increment.
By doing this for the first contour we can define the crack propagation direction if the SIF obtained is higher than critical SIF (K_{1c} or K_{2c} or even the K_{3c}), or predict the crack propagation direction if the SIF obtained is lower than critical SIF (Fig. 7a–b), after doing this for all contours we can predict the three dimensional crack propagation for every single position of our structure as its mentioned in Fig. 7a–b.

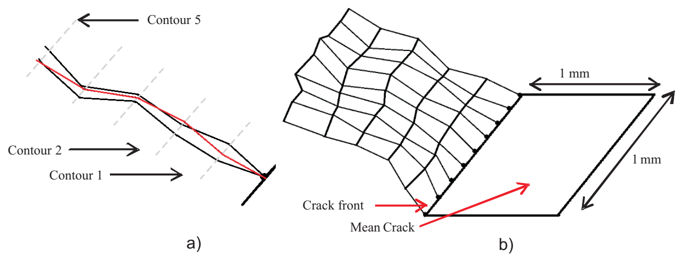


Figure 8 a) Propagation directions of a node at t_1, t_2 and t_n in the first five contours, b) Prediction final propagation direction

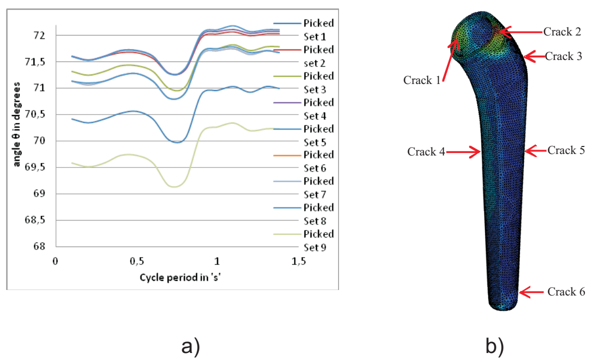


Figure 9 a) Directions of crack propagation in each node forming crack's front, b) Crack positions in the bone cement layer

4. Results and discussions

4.1. *Determination of cracks propagation direction*

The crack propagation direction of the six cracks is illustrated in Figs. 10–11, these cracks were positioned in the most heavily loaded region of the bone cement in order to simulate the crack behavior under extreme conditions.

In Fig. 10 the nodes are called “picked set” (they are called so in the software), we note that each node has its own propagation direction, indeed each node is surrounded by a different stress cartography, the resulting stress intensity factor in each node is also different and this can explains the difference of resulting propagation directions in each node of the crack front.
We notice also that the difference between propagation directions of neighboring nodes is generally less than 0.2° this small difference can be explained by the fact thatthe neighboring nodes are so close to each other (approximately 100μm) that the difference between generated stresses in each node is so small and by consequence the crack propagation conditions in each node is almost similar to the neighbor node. And the maximum deference reached between extremity's nodes (1 and 9) equals to 2° degrees for the crack No. 1 and 7° degrees for the crack No. 6 for example.

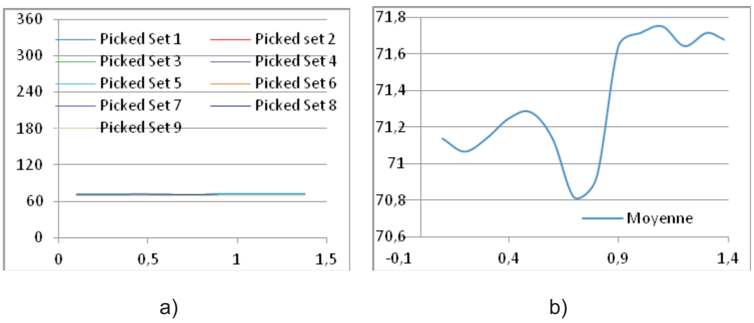
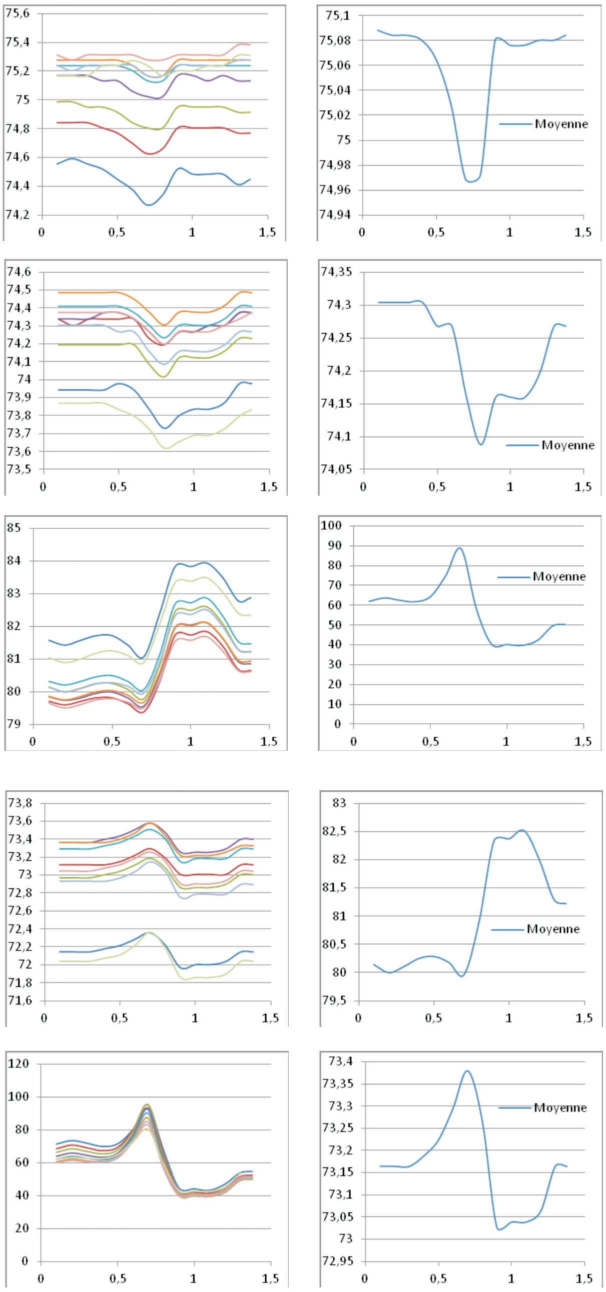


Figure 10 a) Directions of crack propagation in each node forming crack's front in a scale from 0° to 360°, b) The average propagation direction of the nine nodes forming crack's front

4.2. *Determination of stress intensity factor*

The crack tip opening is mainly controlled by stress intensity factors. In fact, the crack's opening process is governed by variation of the three modes of stress intensity factors ‘K_1’ , ‘K_2‘ and ‘K_3‘, where the combination of those modes define the direction of crack propagation. In Figure 12 is represented the variation SIFs ‘K_1’, ‘K_2‘ and ‘K_3‘ in function of time, where it's clearly illustrated that their variation is totally independent one of the other. We also note that for the slow walking activity the critical stress intensity factor is not reached which means that the cracks will propagate only under fatigue loading.
As it's known, the cracks propagation speed is proportional to stress intensity factors which are induced on the front line of the crack, indeed, more the SIFs absolute value for K2 and K_3 are bigger and more the crack propagation speed is faster, in this case: the signs of K_2 and K_3 indicates the way of crack opening (if it's positive the crack tends to open in a certain way, and if the sign is negative the crack opens in opposite way).



a) b)

Figure 11 Crack propagation directions for cracks N°: 2,3,4,5 &6 from the top to the bottom respectively, where (**a**) column is the variation of crack propagation directions in function of time for each node forming crack's front, (**b**) column is the average propagation direction of the nine nodes forming crack's front

But for the first mode it's quite different: when the K_1 magnitude is positive then the crack tends to open, but when the K_1 is negative the crack tends to close and in this case the crack propagation will not be possible according to the first mode.

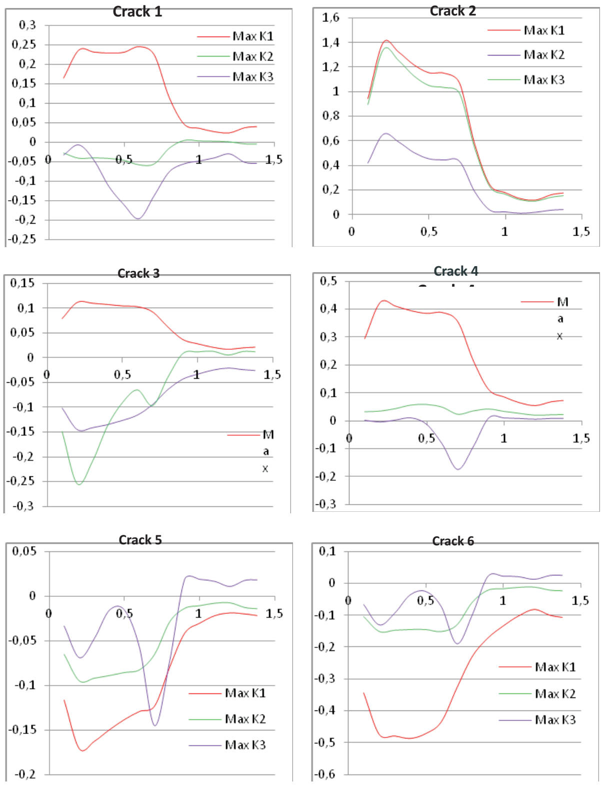


Figure 12 The variation of K_1, K_2 et K_3 during slow walking activity

4.3. *Prediction of cracks propagation direction*

Previously, we have shone the crack propagation directions of each node in all cracks but, those directions can be applied only in the first contour, in fact each contour has its own crack propagation directions and the most probable direction of propagation is determined by the highest SIF magnitude. Bellow the crack propagation direction is predicted according to this methodology.

The crack propagation is computed for each single node starting from the crack's front, in fact, each node has its own propagation direction which is slightly different from the neighborhood's one. The 2 dimensional crack propagation direction of each node is plotted in Fig. 13, and the intersection of contour lines with those directions is marked by a point.

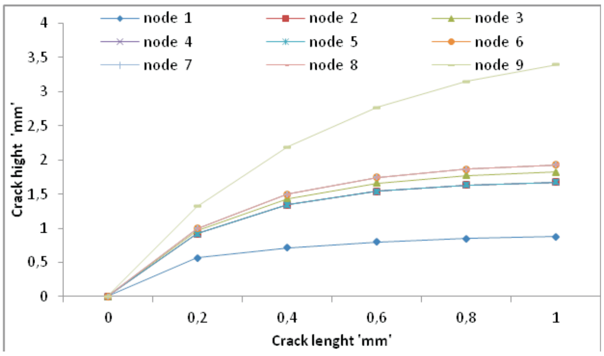


Figure 13 Tow dimensional representation of crack propagation path of each node

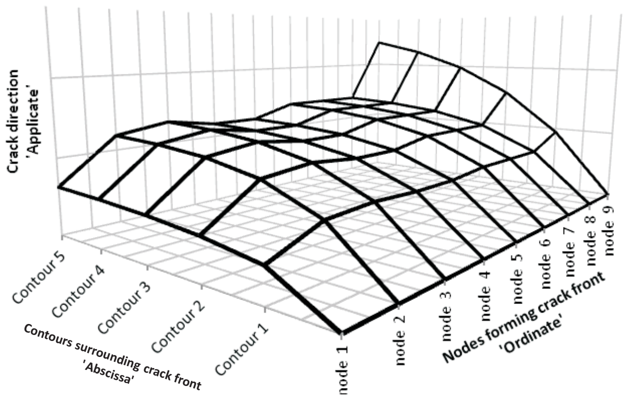


Figure 14 Three dimensional representation of crack propagation area

The prediction of crack propagation is clearly illustrated in Figure 14, in which it's shown that the crack propagation is much stable in the nodes that aren't in contact with non-cracked area, the particular stress cartography of non-cracked area destabilize the directions of crack propagation by affecting the SIF magnitudes, which leads to the appearance of a new propagation directions in the extremities. The final crack propagation direction of crack N° 2 is compiled in the Figure 15, in which we can observe both, the initial crack and the propagated crack. We have chosen the crack N°2 to be illustrated because comparatively to the other cracks it has a very high SIF magnitude. After years of life time, the real crack propagation direction may be a slightly different from the predicted one, because old cements are usually affected by chemical, thermal and mechanical fatigue and may not have the same mechanical properties as new orthopedic cement.

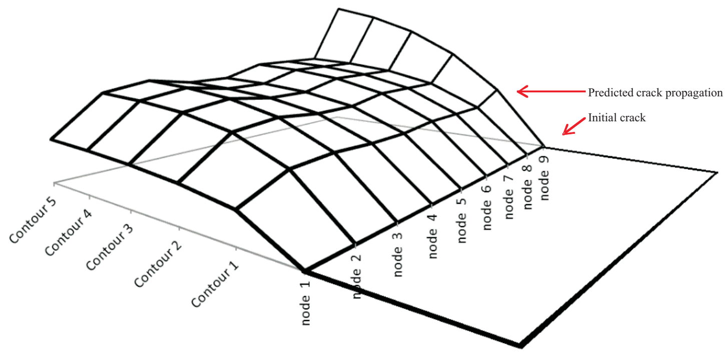


Figure 15 Prediction of crack propagation under fatigue loading

5. Conclusion

This work allowed us to draw a lot of conclusions related to the mechanical behavior under real body loading conditions of orthopedic cement that contains cracks in different positions, among which we mention:

The most dangerously loaded zone in the bone cement layer is the upper frontal region. Comparatively to other regions, this one has the highest stress and SIF magnitudes.

For walking activity, the highest stresses amplitudes were recorded at 0.2s from the beginning of the cycle (at t = 0.2s), and it's also during this moment that the highest SIF magnitudes were observed in all cracks excepts for the crack N°1 where a K_3 peak has been observed at 0.6s, this peak will adds up with the K_1's magnitude to define the 0.6s as the most dangerous moment in the crack N°1.

The lateral sides of predicted propagation are affected by stress nature and repartition on the non-cracked neighbor regions (normal and tangential stress magnitudes), in deed, the extremities nodes (node 1 & 9) show a different crack propagation path than the others nodes which have a relatively more stable propagation.

In a general way, this new technique of crack propagation prediction allows studying crack's behavior in every structure using finite elements method which requires an exact modeling simulation, in fact, more the boundary conditions and material properties of the structure are accurate and more the results are precise.

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