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Correlation between joint kinematics and poliethylene wear using finite elements method for total knee replacement

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ABSTRACT

Survival time of total knee replacement represent today a great concern for orthopedic surgeons and prosthesis designers too. Loosening of the component, and especially of the tibial one, is the most important cause of total knee replacement failure. During the gait cycle, forces developed in the knee have a cyclic pattern and a value between 10 and 40 Mpa (megapascal), so the components of the artificial joint are subject to intensive stress and secondary for major wear. At the level of total knee replacement, the mechanism responsible for this is delaminating, scratching, pitting and abrasion. Our study tries to find, using the finite element method, the correlation between total knee replacement kinematics and stress concentration at the level of polyethylene during the gait cycle, related to position of tibial component in the frontal plane. The results showed that position of 15° of flexion, corresponding to middle phase of unipodal weight bearing (mid stance), is the most important mechanical demanding for tibial polyethylene, and the position of these component in the frontal plane has a critical importance.

Key words: total knee arthroplasty; finite element method; stress concentration; gait cycle; polyethylene wear

OBJECTIVES

Total knee prostheses have continuously evolved in the last 20 years, but the process of knee implants improvement is still far away from its final point. At this moment does not exist a perfect prosthesis to provide joint stability and mobility close to normal and to the most reduced wear of its constitutive materials. The building shapes used until now lead to partial restore of articular movement and cinematic models are in the most cases different by those of a normal knee joint.

Thus, it is mandatory to know joint bio-mechanics: the pressure and location of the contact before and after joint replacement, distribution of forces and the extreme values for tensions developed in ligaments, joint stability as well as its kinematics recovery. This

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phenomenon can not be assessed with computational simulation assistance without an accurate establishment of kinematics and kinetic joint parameters (relative speed, trajectories, forces, reaction and moments) by various methods. At the moment, one of the non-invasive, high precision methods is the so-called *finite elements method*. This technique can accurately establish by numerical calculus the mechanical answer of a body with simple geometry (cube) when a force is applied upon it. The same analysis can be done in case of a complex geometric body by decomposing it in a multitude of simple geometric elements – cubes – and then combine the every single body equations. Every single element influences in the same time the answer of neighboring elements.

Our study tries to establish using finite element methods, stress values and distribution at the level of tibial component polyethylene using the kinematics data obtained experimentally by video imaging analysis. ❑

MATERIAL AND METHODS

The steps of this study consist in three-dimensional reconstruction of knee joint before and after replacement, and computation of replaced knee kinematics, forces and moments appeared at this level. In the last step, the simulation of joint contact using finite elements method will provide the stress pattern at the contact surfaces. We have performed this algorithm for two patients who sustained a total knee replacement for knee arthritis (genu varum), stage III according to Alback classification.

1. Three-dimensional joint reconstruction

Three-dimensional joint reconstruction has been achieved by serial slices obtained from computed tomography of the patient and also by anterior-posterior and latero-lateral radiographs of the joint after knee replacement. Images have been achieved using MRIco software in DICOM format, after a JPEG format conversion.

The import of images inside of parallel surfaces of A_{img} dimension at d_{img} distances has been made using an advanced software Pro/Engineer (1) for three-dimensional geometric modeling. On the every image have been identified interest zones and established points on their most precise contour shape (2). Next stage includes surfaces outlining and solid bodies modeling by spline curves obtained at previous stage. Therefore, an assembly composed by 2 solid bodies will result: femur and tibia, which represents computational the knee joint morphology. The assembly has been modeled using Pro/Engineer and is remarkable for its precise geometry (maximal errors beside scanned images after spline curves interpolation are below 0.5 mm) (3).

2. Knee joint kinematics and kinetics computation.

The kinematics of geometric model made at first stage is based on data resulted from video analysis of images obtained from the patient, for normal walking, before and after joint replacement. The position of markers used in this analysis has been established according VAKHUM protocol (4,5).

The experiments for "in vivo" determination of joint kinematics have been made using the system for images acquisition and analysis, SIMI Motion (SIMI Reality Motion Systems GmbH), to obtaining an accurate cinematic of a replaced joint. In the last stage of image processing, the cinematic curves have been outlined.

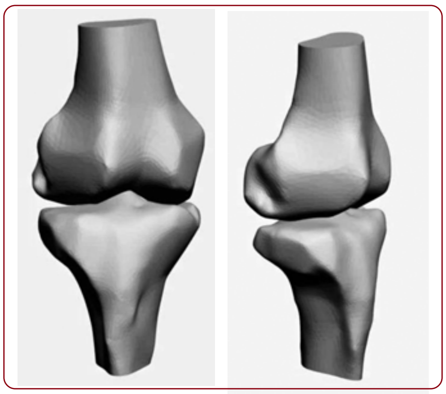

FIGURE 1. Three-dimensional reconstruction of the knee joint

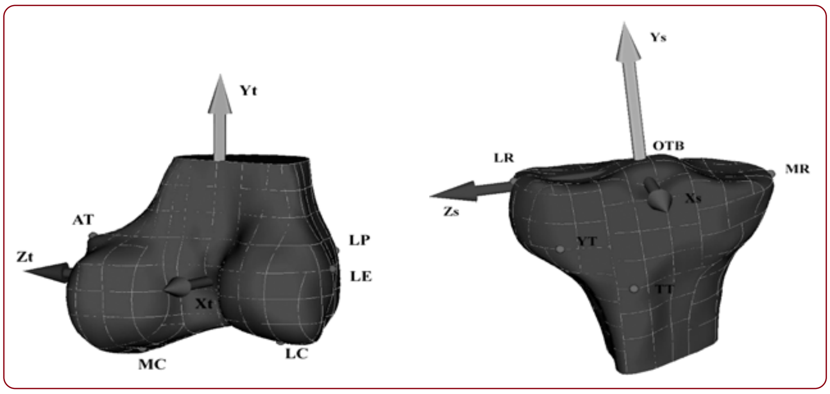

FIGURE 2. The original geometry of femur and tibia with the anatomical markers and axis.

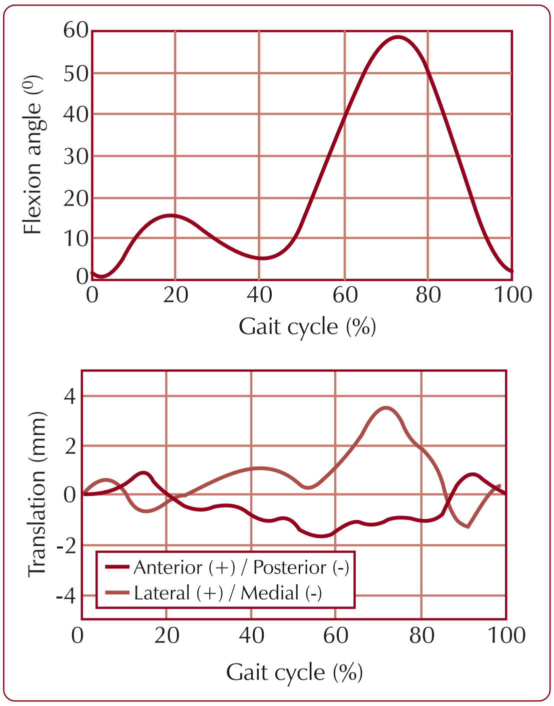

FIGURE 3. Cinematic parameters of the patient before TKR (normal walking)

The 4 elements of inferior limbs are interconnected by 26 main muscles. They are spatially represented by functional lines obtained by connecting the origin with insertion points; broad muscles are represented by 2 lines (6,7).

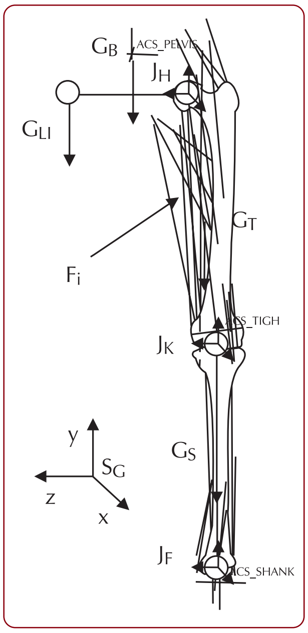

FIGURE 4. Loading diagram of the lower extremity

The mathematic model of human musculo-skeletal and ligamental structure consists in a number of equilibrium equations lower than the number of unknown variables, which are: muscular forces, joint reaction forces and intra-ligamental forces (8-10). In the present case, the acquisition of values has been made for maximal bearing moment, considered the moment when the whole body mass leans on a single foot in walking (6,11). Whole calculation has been made using an original Matlab computational program.

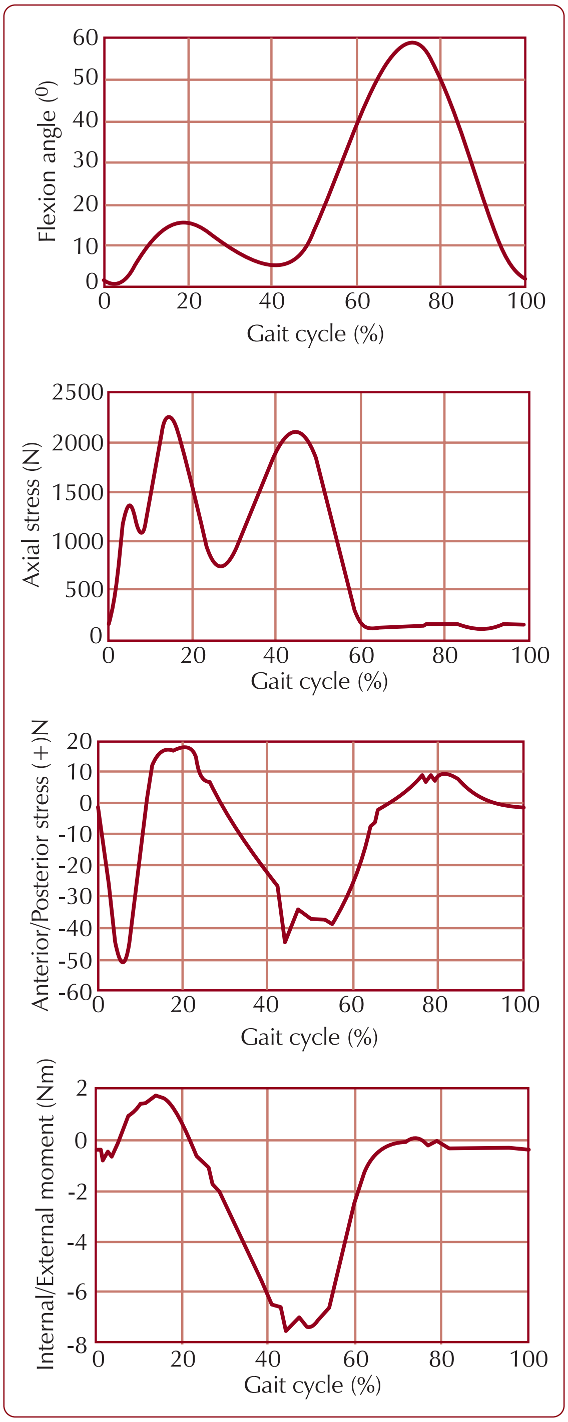

FIGURE 5. Kinetic values obtained after video analysis of the walking and calculus using Matlab

3. The simulation of contact on implant surface in total knee replacement.

The finite elements model of total knee prosthesis surfaces has been developed using a commercial software (LS-DYNA) on previous described three-dimensional model (12,13). To facilitate the analysis, the computational cost has been lowered by separating from the model only the femoral implant and polyethylene tibial element. The initial conditions are computed for a step made in 0.5 seconds (13).

Because the femoral implant is built of CoCr, it is considered rigid, so the elements from its mesh are considered coupled to the mass center. An important reduction of global numeric model is achieved, the freedom ranges of rigid elements nodes being replaced by 6 freedom ranges of mass center (14).

The contact/impact conditions are modeled basing on supposition that at the contact moment, the two surfaces take over the same distortion speed on impact direction. Thus, the moment of impact is separated from the rest of dynamic analysis and the serial impulse equations developed allowing propagating the values (solutions) over this moment, introducing initial conditions from which the analysis can be continued. The polyethylene erosion phenomenon may be quantified introducing the results obtained for a movement cycle in mathematic formulas which calculate the quantity of material removed by friction depending on contact pressure.

The results are considered for position of 15° of flexion in walking, for which the axial efforts are the highest, according to calculation.

Thus, we can notice from *figure a* the values and positions of the highest contact pressure

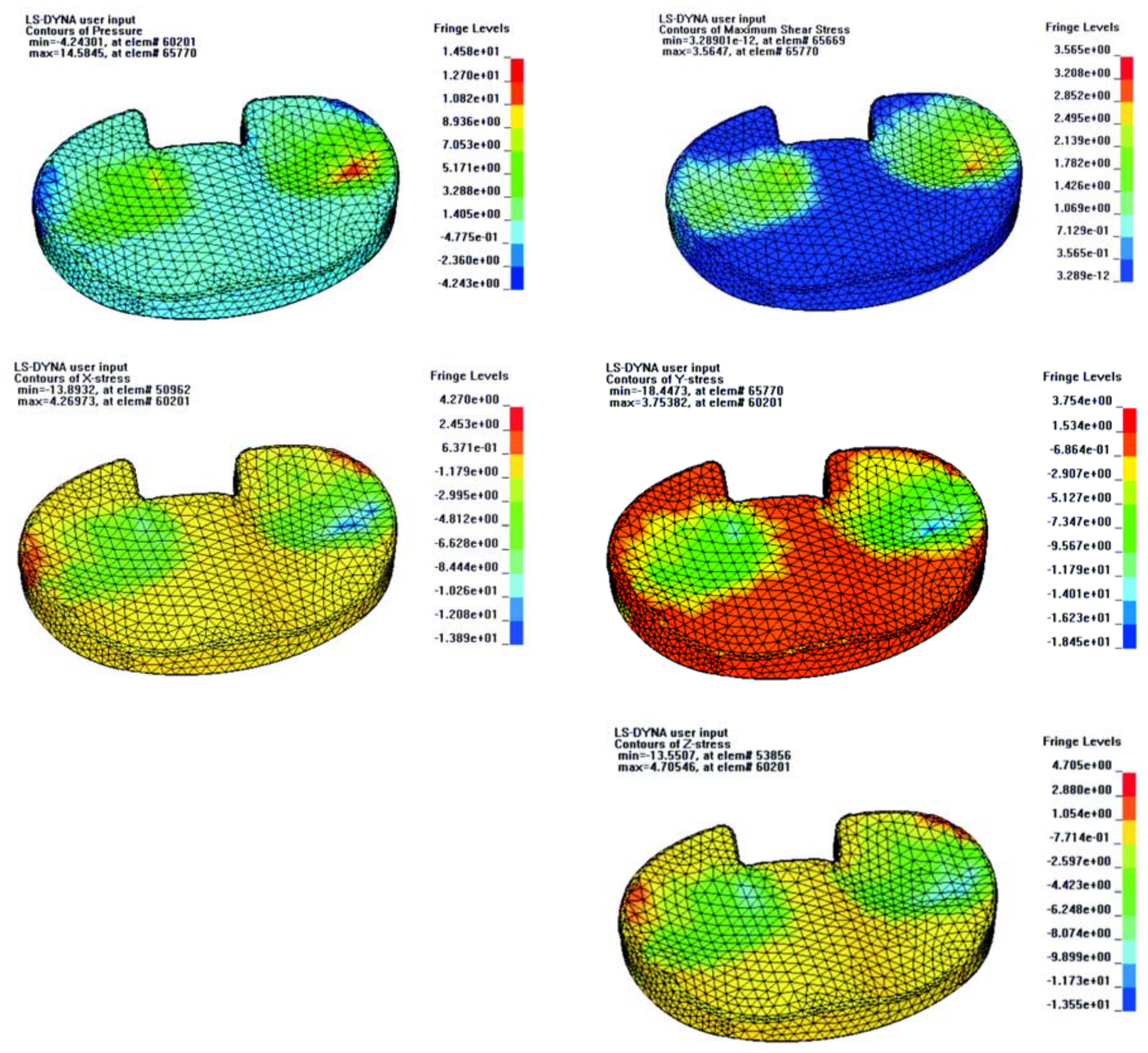

FIGURE 6. Polyethylene contact stress according to finite elements method

areas. An important factor for erosion is the tangent tension presented in *figure b*. In *figures c, d and e* are presented the tension values and distribution by X, Y, Z axes. It's obvious the correlation between the values of loading according to X, Y, Z axes, represented in figure no. 6, where the maximal amount is carried out in 15° of flexion and the tension values estimated dynamically by finite element method.

Therefore, is confirmed the computed analytical result, in which the position of 15° of flexion, corresponding to middle phase of unipodal weight bearing (mid stance) is the most mechanical demanding. Axial compression forces, which are responsible for the wear by abrasion, have an approximate value of 18.5 MPa (megapascal). The tangent forces developed in anterior-posterior direction, responsible for wear by delamination, are around value of 14. MPa (megapascal). ❑

Conclusion

According to these data, those two types of solicitation are the most important for polyethylene wear. This wear is dependent of prosthetic kinematics and also by stress pattern. The lower joint surface congruence, the greater is the value of concentrated forces, but the volumetric wear increase also with joint surfaces congruence. There has to be a balance between these two elements so that total knee prosthesis life time to be extended.

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