SERBIATRIB`07
10th International Conference on Tribology
and
WORKSHOP`07
Sustainable Development in Industry by Apply Tribology Knowledge

THE KNEE PROSTHESIS SIMULATOR CONTROL

Lucian CAPITANU, Luige VLADAREANU, Justin ONISORU, Aron IAROVICI
Institute of Solid Mechanics of Romanian Academy, Bucharest, Romania

Abstract

This paper is a thorough analysis on the phenomenon of wear of the total knee prosthesis (TKP) due to biomechanical cyclic stress on the tibial insert of ultra-high molecular weight polyethylene. The focus is on the evolution of the phenomenon, from adhesive wear pits followed by delaminating and even breaking the insert. The paper presents a control system for a knee prosthesis simulator (KPS) with 5 degrees of freedom which maintains a constant force of vertical pressure on the tibial component. Some theoretical considerations, the mathematical modelling of the non–conform contact between the femoral condyle and the tibial tray , the experimental results, as well as a possibility to predict the fatigue wear of the insert of ultra-high molecular weight polyethylene (UHMWPE) based on FEM simulations of common activities are presented here.

Keywords: *knee prosthesis, fatigue wear, knee prosthesis simulator, motion control system,FEM*

1. INTRODUCTION

Recent clinical studies (Blum et al. [1], Wasielievski et al. [2]) on massive wear of the tibial polyethylene insert caused by non-conforming contact for the artificial knee joint, have shown that this is the main cause for the knee prosthesis replacement (TKR). In [3], Knight et al. reports that in all of the 18 worn prosthesis (from 209 studied cases of primary TKR) one could observe the wear pits on the surface of the tibial tray (specific to the adhesive wear) as well as delaminating. Prosthesis life was about 80 months, close to that time reported in [4] by Heck et al. (i.e. 72 months). Other studies focuses on the massive delaminating of the polyethylene that could occur earlier (Engh et al. [5], Jones et al. [6], Kilgus et al. [7], Mintz et al. [8]). One case study published by Ries et al. [9], shows also, based on the analyses on the tibial insert of the TKP, that is a correlation between polyethylene's massive wear and delaminating and the progress of crystallization in a plan concurrent with the failure plan, noticing at the same time an oxidation peak below the contact area of the UHMWPE inserts.

Although disputed, that idea that the wear of the polyethylene insert can be reduced by increasing of its thickness could be rather false. Most recent studies ([3], [4]) consider that the main cause of this phenomenon of joint wear is represented by the high level of the superficial pressure caused by incongruent contact areas ([3], [4]), and we base our study on this idea.

2. THEORETICAL AND EXPERIMENTAL STUDY OF ARTIFICIAL JOINT WEAR

The TKP must do flex-extension movement (FE), antero-posterior translation (APT) and internal-external rotation (IOR) during a cyclic loading. The first step to studying the TKP wear was to analyze, from a theoretical and experimental point of view, the ball/plan type frictional couple under above mentioned movements, considering the load having a constant amplitude.

The experimental adopted method is based on a control system for 5 degrees of freedom of the knee prosthesis simulator (KPS), which maintains a constant compressive force on the tibial component (see Fig.1 for schematic representation of the KPS and Fig. 2 for the control system). The frictional couple is composed from a Co-Cr alloy ball representing the condylar part of the femoral component of a TKP and a 5 or 10 mm thick polyethylene plane disk of ultra-high molecular weight (UHMWPE) mounted on a Co-Cr alloy plate, placed right under it, representing the tibial component of the same prosthesis.

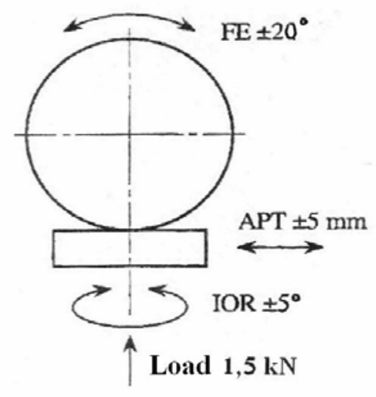

Fig.1.Kinematics of friction couple

The effective movements and the loading are based on biomechanical studies. As we stated before, the movement was mainly triaxial consisting of flexion-extension movement (FE), anterior-posterior translation (ATP) and internal-external rotation (IOR). The flexion-extension movement has been applied to the ball, but the APT and IOR movements have been applied to the disk (see Fig.1). All movements were made by intermediate of a crank gear. The variation of the movements in time was almost sinusoidal, the period being 1 *s*. T testing device resembles the one used at Helsinki University Technology by V. Saikko, T. Ahlroos and O. Calonius [10].

The amplitude of the flexion-extension movement was 40°. If the FE movement would have been the only movement occurred during the process, the sliding distance between the extremities would have been around 20 *mm* for a ball diameter of 54 *mm*. Anyway, synchronizing the APT movement (having 10 *mm* amplitude) with the FE movement, in a way that the maximum flexion would coincide with the maximum anterior translation of the disk while the maximum extension would coincide with the maximum posterior translation, the friction distance between prosthetic parts was reduced.

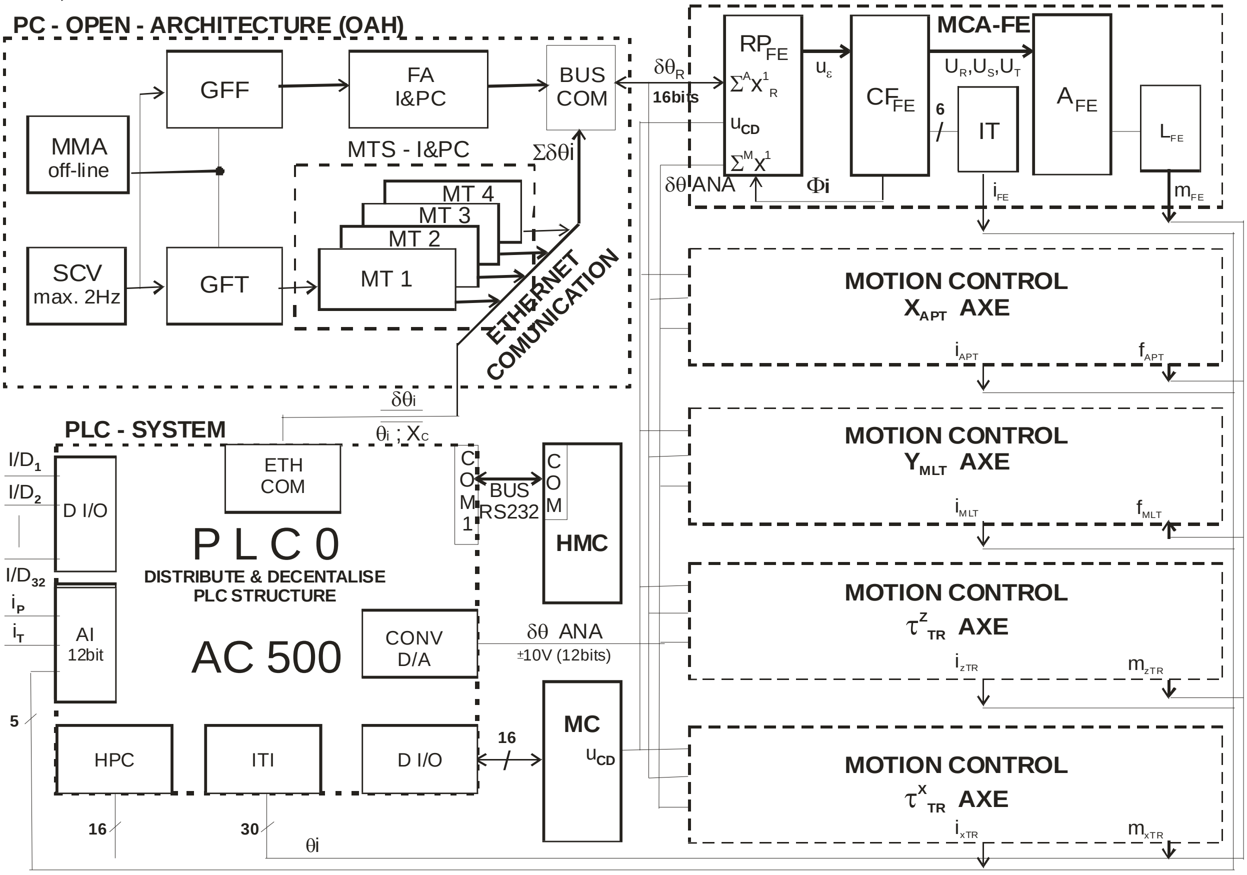

Fig. 2. Control system for the knee prosthesis simulator (KPS)

The crank mechanism has been designed that way that the difference in phase of the IOR and APT sinusoidal waves should be $\pi/2$. Consequently, the contact trace on the UHMWPE disk represents a symmetrical eight-form narrow figure, having 9.42 *mm* length and 0.22 *mm* width. The length of the locus of the point of application of the force was about 18.84 *mm*. This value served in the calculation of the wear factor for one cycle friction distance.

The APT movement was realised by allowing the tibial part to have a linear horizontal guided translation (with low friction) and using the signal of a loading cell to determinate the friction force between the Co-Cr ball and the UHMWPE disk. Considering a Coulombian friction, the authors were able to calculate the friction coefficient μ (even that due to viscoelastic properties of the polyethylene, a more adequate term to use was the coefficient of the total kinetic resistance, due to a substantial indent between the ball and disk [10]).

The mathematical model from which the trajectories for femoral and tibial movement are generated, is extensively described in previous studies (see [11], [12]). The trajectory of the tibial movement is real-time controlled by the KPS control system and is composed of 4 movement functions corresponding to the 4 degrees of freedom: anterior/posterior translation X_{APT}, medial/lateral translation X_{MLT}, tibial rotation τ_{TR}^{X} around the vertical axis respectively tibial rotation τ_{TR}^{Z} around the anterior/posterior axis. The femoral flexion/extension, which represents the 5th degree of freedom, synchronized with the tibial movement trajectory through the trajectory control, accordingly to the mathematical model (evaluated off-line) and the chosen law of movement.

The control system (see Fig. 2) could manage 4 knee prosthesis simulator stations, each of them allowing, individually or jointly with the others, that the loadings (F_x, F_y, F_z, M_x, M_y, and M_z in a Cartesian coordinate system) to be monitored continuously or at periodical intervals by intermediate of some load cells. Supplementary, temperatures control for 8 measurement points is available. A reference position interpolation for all 4 tibial axis is provided by intermediate of a multi-tasking system. Monitoring parameters are available for evaluating the prosthesis materials behaviour, implant wear, change of the friction rate, tribological behaviour of frictional couple, etc. The simulator allows uninterrupted work 24h/day, respectively 0.086 millions cycles per day (at a frequency of 1 *Hz*).

The first experiments made using FE and APT biaxial movements lead to inferior wear rate. Adding IOR movements (around a vertical axis of the UHMWPE disk, with an amplitude of 10°) the wear rate increased. This paper refers only to the output of the application of FE and APT movements, when the wear indentation is linear. Adding up IOR movements give a more complex wear phenomenon.

Five 40 mm diameter GUR 1050 disks (with different thickness , irradiated or not, aged or not - for complete description see results section) having a were tested for lubricated friction under a compressive cyclic load of 1.5 *kN* (for 5 millions cycles). Each test took eight weeks and occurred at a 1 *Hz* frequency. Tests had been stopped at 0.5 millions cycles intervals in order to change the lubricant. While pausing the tests, the specimens and the plates were water-flushed. At the end of the test, the disk was dehydrated in a vacuum for 30 minutes. The full contact pressure values were calculated starting from the presumption that the contact diameter was equal with the width of the worn side while the distribution of the contact pressure was elliptical.

The lubricant used is normal saline sterilized solution in three parts filtered 0.1 μm, with a low level of proteins and endotoxines, diluted 1:1 and free from additives. The quantity of lubricant in the acrylic testing basin was of 200 *ml*. The basin was deliberately big and open, in order to prevent overheating that might affect the wear simulation. Tests were undertaken at the room temperature. Daily was checked the temperature near the basin as well as the lubricant's temperature. During the tests the value of the friction force was also registered.

3. PREDICTION ON FATIGUE WEAR ON THE KNEE PROSTHESIS COMPONENTS

The methodology for predicting the fatigue wear phenomena combines FE analyses of active loading cycles of relevant routine activities with a summation technique that is based on computation of a cumulative estimator of damage.

A FE model of the artificial joint contact was used (see Fig. 3a) for all analyses. The model includes one femoral condyle and one half (the medial one) of the polyethylene insert, and of the metallic tibial tray. For deformable parts (the tibial parts) solid brick elements with 8 nodes and 3 DOF's per node (all three translations) are used. The femoral condyle having a thoroidal shape with a radius of 22 mm in the sagital plane (the flexion plane), and a radius of 30 mm in the transversal plane was considered rigid.

Elastic linear constitutive laws are considered for metallic as for the plastic parts. The materials properties are listed in Table 1.

The routine activities considered relevant for this study are the active cycles of the normal walking, stair descending, and stair ascending activities. The kinematics of all three movements are illustrated in Fig. 3 where the segmental movement of the lower member are sketched (Bergmann et al. [13] - see Fig. 3c and Fig. 3d). The compressive force of contact is also plotted comparative for all activities (Taylor and Walker, [14] - see Fig. 3b).

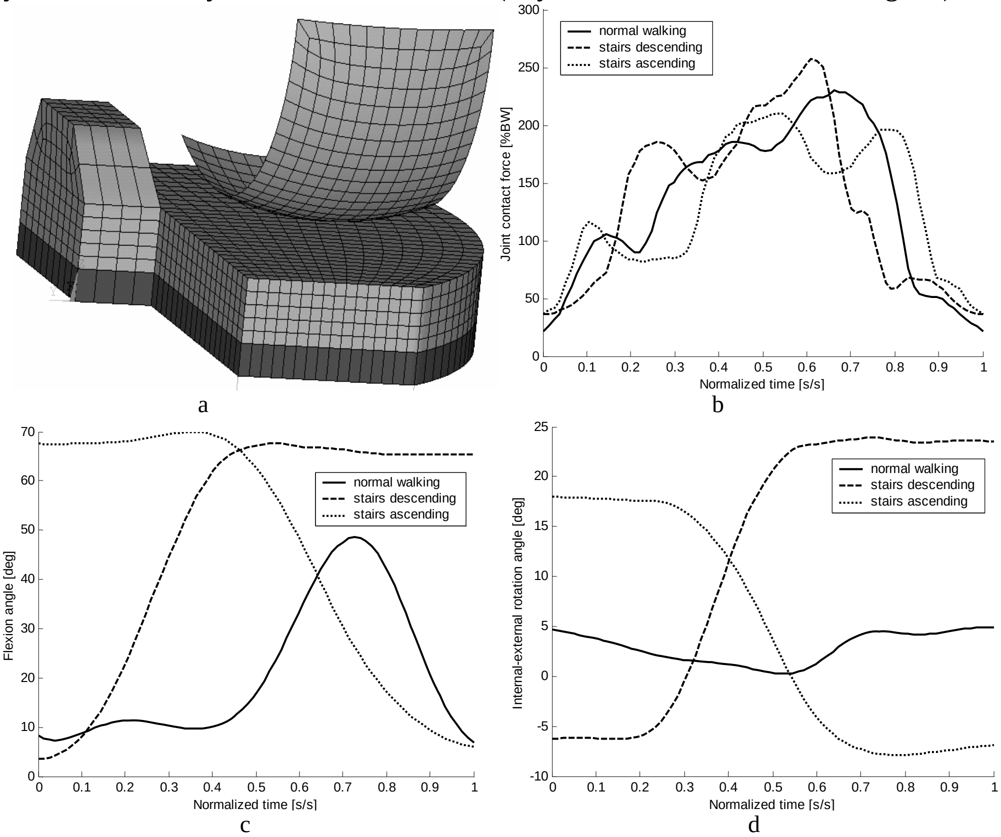

Fig. 3. FE model (a), loadings (b) and kinematics (c) and (d) used in analyses

The compressive force is applied to the tibial tray (as distributed pressure on the lower basis of it). The two rotations (flexion and internal-external rotation) are dynamically constraining the femoral part. We considered that for the actual level of flexion (not higher than 70 degrees) does not induce an antero-posterior translation (usually appearing when the ligaments are overstrained, as for extended flexions.

The contact mechanism includes rolling and sliding of the two joint surfaces – the femoral condyliar thoroidal surface and the planar surface of tibial insert; the friction obeys the Coulomb law with a constant friction coefficient of 0.06 which is an upper bound of values determined by tests (see Table 2).

For every activity a damage estimator could be computed from the variation of the shear maximum principal stress in every element (Sathasivam and Walker, [15]):

$$D_f^k = \sum_{i=1}^{n} \frac{1}{2} \left|\tau_{i+1} - \tau_i\right| \cdot \left(\left|\tau_{i+1}\right| + \left|\tau_i\right|\right) \qquad (1)$$

where:

D_f^k - damage function for activity k;

τ_i - shear maximum stress on elements for time t_i

The effect of all activities could be cumulated by evaluating a weighted sum:

$$D_f^{tot} = \sum w_k D_f^k \qquad (2)$$

where the weights are depending on the frequency of the activity.

Table 1. Mechanic properties of materials used in analyses

Material	Longitudinal elasticity module [*GPa*]	Poisson ratio	Remarks
Co-Cr	200	0.3	ISO 5832-4
GUR1050	1.06	0.36	Lewis [12]

4. RESULTS

The results obtained from the experimental tests, performed with a compressive force of 1500 N, and having an FE of ± 20^0 and an APT of ± 5 mm, are listed in Table 2.

The tests 1 and 2 were performed on polyethylene disks having a 5 *mm* width, and tests 3, 4 and 5 on disks having 10 *mm* width. The theoretical length of the frictional distance covered by the contact spot, on each movement cycle, was 10 *mm*. The measurements carried out with the microscope have shown an effective increase of these values, probably caused by the shear stresses occurred on the edges of the contact area. For tests 2 and 3, the polyethylene samples were sterilized through γ irradiation and aged through air convection. Tests 1 and 4 were carried out on samples that were not irradiated and test 5 on samples that were irradiated but not aged.

The wear factor k was determined based on Archard's relation [16]:

$$V_u = F \cdot k \cdot v \cdot t \qquad (3)$$

where:

V_u – volume of material removed through wear (cm^3);

F – working load (*daN*);

v – relative sliding velocity (*cm/s*);

t – test duration (*hours*);

Relation (3) expresses a general law for the dependency of the wear as function of the compressive force between the bodies in contact and the space covered by friction.

Therefore we can write:

$$k = V_u / (F \cdot v \cdot t) = V_u / (F \cdot L_f) \qquad (4)$$

where $L_f = v\ t$ is the length of frictional path.

Table 2 also shows the medium values of the friction coefficient, determined based on the measurements carried out by intermediate of the force transducer coupled on the bearing with low linear friction, part of the generator of the APT movement.

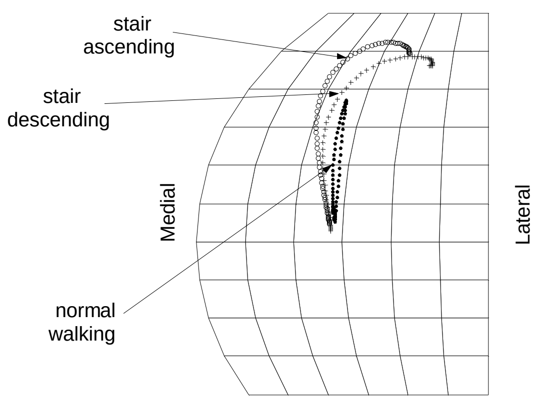

Fig. 4. The contact paths for all three cases considered

Performing the dynamic analyses of the contact between the femoral metallic condyles and the polyethylene tibial insert (in the conditions described above) one could determinate the characteristics of the contact mechanism in the artificial knee. For example, the trajectories of the contact spot for all three activities are plotted on a sketch of the medial part of the polyethylene insert (see Fig. 4).

Table 2. Wear of polyethylene disks and average coefficient of friction

Test	Wear (10^{-3} mm^3)	Wear factor (10^{-11} mm^3/Nm)	Wear pit dimensions			μ
			Length (*mm*)	Width (*mm*)	Depth (10^{-3} *mm*)	
1	72,258	0,935	10,3	1,32	0,6	0,036
2	128,559	1,697	10,1	1,61	1,3	0,053
3	71,311	0,914	10,4	1,31	0,5	0,035
4	120,399	1,514	10,6	1,55	0,9	0,034
5	112,475	1,428	10,5	1,52	1,0	0,047

Examining the sketch one could see that all activities does not involve extension of the knee – it means that only the median and posterior parts of insert are used. For normal walking the trajectory is a closed curve (like a hysteretic loop). The stair ascending and stair descending trajectories are quite similar (even opposite as direction), both of them having a large internal-external rotation (for stair ascending loading at the beginning of the cycle, for stair descending at the end of it). One could see that the normal walking loading cycle will affect the median area of the medial part of the insert, the stair ascending and descending activities having their maxima located in the posterior parts of the insert.

As expected, due to the geometry of the contact (the joint surfaces are a toroidal surface for femoral condyle and a plane surface for tibial insert) it is clear that the contact spot will have an elliptical form with the major axis oriented transversally to the saggital plane of the femoral condyle.

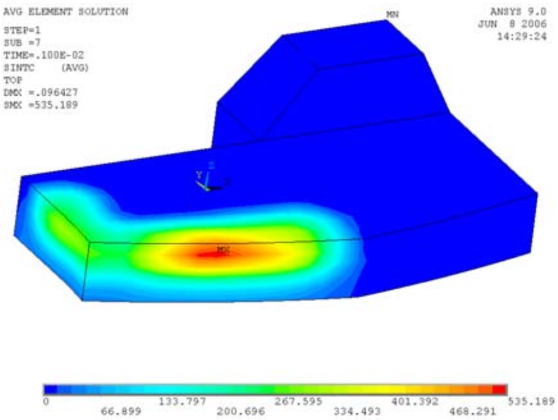

Fig. 5. The damage score map

The contact pressure could be important as estimator of loading magnitude, but even more important for estimating the fatigue wear will be the maximum shear stress, as being the parameter used in the damage estimator stated by formula (1). From the contact mechanism (which involve both rolling and frictional sliding) it results that the maximum shear stress will be located under the contact surface at a distance depending of the aspect ratio of the contact elliptic spot.

Using the cumulative estimator defined in formula (2) the areas were the damage is likely to occurs could be identified from the cumulative distributions plotted in Fig. 5 (the L-shaped region of different colour). One could see that the most affected areas are the medial and posterior parts of the tibial insert. One could notice also that the maximum damage will occur in the subsurface of the insert (where the shear stresses from normal walking are maximal), which is usual the starting plane of severe delaminations. The magnitude of the damage estimator (~477 MPa^2 at the surface and ~535 MPa^2 in the subsurface) are in concordance with the results of Sathasivam and Walker [14] which obtain a damage score of ~230 MPa^2 for a constant loading of 1,000 N (approx. 120% BW) which represent one half of the maximum loading from normal walking or from stair ascending or stair descending activities.

5. CONCLUSIONS

First of all, fatigue wear was identified as the main phenomenon responsible for massive wear of the polyethylene insert. Clinical studies shown that even for one revised tibial component of different reasons (migration of the implant, creep etc) there could be observed obvious signs of fatigue wear (cracks under the contact area, pits, delaminating, large polyethylene pieces detachments).

The experimental results are in good agreement with the theoretical predicted results for trajectory control, showing the possibility of practical implementation of control strategies for the knee prosthesis simulator (KPS) by using PLCs (Programmable Logical Controller). The high reliability is obtained by using PLCs in Open Architecture structure [17]. The developed method is also useful for the validation of the analytical models which are to be further developed to portray the dynamic behaviour and timeline behaviour of the knee prosthesis

The cumulative nature of the fatigue wear phenomenon need a quality and quantitative evaluation of the transfer mechanism of the mechanic loading on the joint and the method to consider and reconsider the diversity of the human activities. The first part was assessed by intermediate of some dynamic finite element analyses of the joint contact mechanism. For the second part, we assumed that normal walking, stair ascending and stair descending are the regular activities dominant for the phenomena. So, for all three activities the finite element analyses are performed and a damage score was computed. Finally, a cumulative damage score (that accounts for all three activities) was determined and the areas were the fatigue wear is likely to occur are identified.

A closer look to the distribution of damage score reveals that the maximum damage is likely to occur not at the contact surface but, rather, in the subsurface. The presence of maxima values in an area were other studies (see Ries et al. [9]) identifies an increase of the percentage cristalinity and the presence of subsurface oxidation peak induced by the gamma-irradiation and ageing of the prosthesis could be an explanation of the early delamination of the polyethylene inserts.

Acknowledgements. The authors wish to express their gratitude to Romanian Academy and the Research and Education Ministry (MEC) for its support of the program of work reported herein. The work took place as part of the research projects no. 120/2004-2006 and 127/2003-2004 in the framework of Grants of CNCSIS (Romanian National Council for Scientific Research)

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