Software Simulation for Femur Fractures in Case of Frontal Car Accidents

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Abstract: - According to a study carried out by one of the authors at the County Clinical Emergency Hospital in Arad, over 40% of the accidents resulting in femur fracture take place on roads and highways.
This work briefly presents these results, and on the basis of bibliographical data regarding the mechanical behavior of bones and the classification of femur fractures occurring in expert literature, a simulation program of these fractures in the case of car accidents.
The aim of the program is to determine the pressure at which the femur is fractured in different conditions of mass and speed of the vehicle, braking distance, age of the victim, femur size, etc. The use of this program represents an exemplification method, as an alternative to direct expertise at the site.

Key-Words: - Simulation, Model, Femur, Biomechanics, Fractures

1 Introduction

The rapid development of information technologies has deep implications on the evolution of various fields, among which biomechanics. The realization of 3D models of the human muscular-skeletal system components by means of advanced programs, the kinematical and dynamic modeling of the latter, as well as the simulation of actions in which they are involved, are only a few examples. At the same time, computer animation techniques applied to medicine considerably extend the possibilities of experimentation and human body investigation.

As in other sciences, the integration of experimental and analytic models in biomechanics and medicine is critical for the acquisition of knowledge and for understanding the response of different bones of the skeleton to the action of mechanical factors. Experiments provide data which can subsequently be interpreted in different contexts. These investigations are particularly influenced by achievements in the area of graphic processing techniques, image processing, computational mechanics, genetics and biology. The integration of these techniques will lead to the provision of important data for research related to the human skeleton, its traumas and diseases [3], [16], [18].

The objective of simulation is to ensure that the means of calculation faithfully reproduces the behavior induced by the model. The behavior of the concentrated model must provide the possibility of distinguishing between the basic model and the one resulted from computer implementations or its solutions, in the same way as the behavior of the real system can distinguish itself through the validity of its models. The formal ideas associated with simulation include both the consistency and the ambiguity of computer implementations. The simulation process with a concentrated model can be a verification method. Many of the techniques employed in la validating models are also used in verifying simulations [3], [9] [17].

2 Particularities of Modeling in the Osteal-articular Biomechanics

Due to the complexity of bone structures and the insufficiency of biological and anatomical data on them, there are numerous possibilities of behavior in different conditions. Computer modeling and simulation techniques applied to the human body provide the possibility of analyzing it, without any physical interference [5], [6], [7], [16].

The modeling of biomechanical system charges must have in view a multitude of factors and conditions. For static problems, which are focused on obtaining a global image of the state of tension in a model, of a substructure or of an element of the osteal-articular system, relatively large charges will be applied. In these conditions, the proper weight of the bone, muscles and blood can be overlooked. The vast majority of long bones of the human skeleton are subject to relatively large charges that are applied to the ends of the bone, ends that are fixed in joints. In intermediary sections of the bone, one can also apply forces originating from the action of muscles and ligaments. A precise modeling of the charge is very difficult to achieve, because the joints are complex structures, with a complicated spatial geometry in which ligaments, muscles, cartilages work together [2], [11].

The natural variability of geometry and the mechanical properties of the osteal-articular system, from one individual to another, is one of the aspects generating noticeable additional difficulties in carrying out research in biomechanics and which must always be taken into account. Some of the modeling problems related to bone geometry and structure [1], [5], are:

- The vast majority of bone elements have complicated geometrical shapes, developed in space.
- The material in bone structure is heterogeneous and anisotropic. Bones have a very complex structure.
- The static and dynamic behavior of the muscular-skeletal system depends on both the stresses to which it is subject, and the specificity of each individual. The dimensions, shape, mechanical characteristics, elastic constants, physical constants, etc. of a biological system vary greatly from on individual to another, depending on a multitude of factors, the most important of which are: age, gender, size, profession, current physiological state, environment conditions [14].

Even though modeling in the osteal-articular system biomechanics is subject to the same general laws and principles employed in engineering, some differences limiting the possibilities of this research method must be taken into consideration. Thus, in biomechanics, it is rarely and only to a little extent, that the results obtained through the study of a model can be verified with those obtained on the original system, the human body. A substitution of this inconvenient can be made by carrying out comparative studies, on different modeling variants of the real phenomenon. Although each model is obtained by simplifying the original phenomenon, different variants are comparable one to another, the comparison serving to optimization.

3 Aspects Regarding Mechanical Traumatisms at the Femur's Level

Mechanical traumatisms are produced in consequence of some stresses through shock, when a sudden velocity variation acts interferes with a bone. The shock is the consequence of the contact between the bodies, produced during an extremely short lapse of time. Following the shock, a very large force of contact is produced, which is very difficult to evaluate.

In the area of contact between the bodies that clash into one another, very large local unilateral efforts are produced, usually followed by the emergence of permanent deformations. Apart from these, the shock is propagated, with a lesser effect, in the entire mass of bodies being hit. Because of these two effects, a local and a general one, the study of the shock presents a lot of difficulties is the object of numerous researches.

In the dynamics of the material point and of the rigid body it has been considered that, all throughout the motion, velocity vector $\vec{v}$ and therefore its corresponding impulse, vary continuously with respect to time. There are also cases when the velocity vector, or its elements: magnitude, direction and course can present relatively large variations during an extremely small lapse of time, variations that can be considered as a discontinuity of the velocity vector.

The phenomenon in which velocity vector $\vec{v}$, and the impulse respectively, vary suddenly in a very short lapse of time, bears the name of collision. The collision phenomenon can occur when two bodies of different velocities meet at a given moment. Another form of the collision phenomenon consists of suddenly applying a new rigid connection to a body in motion. The sudden dissolution or loss of a connection is not a collision phenomenon because in this case velocities and impulses vary continuously.

If the support of the relative velocity with which a body is hit is normal at its surface, the collision is normal. In the opposite case, it is oblique. If the support of this velocity passes through the centers of mass of the two bodies that collide, the collision is called central.

In the study of collision phenomena, some simplifying hypotheses are made:

- The forces that are not due to the collision such as: weights of the bodies, elastic forces, are overlooked with respect to those emerging during the collision and which attain particularly high intensities.
- It is considered that the very short time during which the collision phenomenon occurs, material points and respectively the bodies that collide have no finite motions, only deformations.
- It is supposed that for two given materials, the ratio between the normal components of the percussions in the two phases of the collision, in the recoil phase and in the compression phase, is constant.

In consequence of the various mechanical shocks to which the human body can be subject, several traumatisms can occur at the level of the osteal-articular system. In the case of the femur, mechanical traumatisms, namely fractures, can be classified as follows [4]:

Fractures of the proximal epiphysis:

- Femoral cervix fractures which are quite frequent and are produced especially in older people by falling in forced abductions or contortion motions. According to studies of expertise 2/3 of the femoral cervix fractures are produced indoors, and the rest of them in the street, on slippery roads, or in car accidents.

- Cervical-trochanteral and trans-trochanteral fractures, which are produced by hitting a hard body or through an indirect mechanism.

Fractures of the diaphysis:

- Sub-trochanteral fractures which are rarer and are produced through a direct or indirect mechanism.

- Fractures situated in the middle of the diaphysis which are usually transversal through a direct mechanism (hitting, falling) or spiroidal (contortion). Possible complications are the osteal-myelitic processes, pseudo-arthroses, delays or vicious consolidations.

Fractures of the distal epiphysis:

- Super-condylar fractures which are pretty frequent. The mechanism of production is by direct hitting, falling on legs and rarely through an indirect mechanism such as contortion.

- Fractures of femoral condyles which are rare. They can be uni-, or bicondylar.

4 The biologic support of the simulation software

The first step in developing our concept was to observe de dynamic and the action of the osseous/bone tissue under physical stress. Inside of The Anatomy Lab of the „Vasile Goldis" Western University we have osseous pieces. Before and after the preparation protocol the osseous pieces had been measured. For this experiment we used long bones as: Humerus, Radius, Ulna, Femur and Tibia. These bones had been tested in The Universal Trying Machine, and they as tested for bending, compression and extension. We had 147 bone pieces, 72 for the compression test, 21 for the extension test and 54 for the bending test.

The result was observed in dynamic, in this way resulting experimental models for each part of the experiment.

The experimental study was made on more bone groups belonging to anatomy of the lower and upper limb. The bone elements were prepared, using bodies of old persons with ages from 60-70 years, having a poor nutrition so the bones were demineralized. The preparation of the bone elements consisted in bodies' injection with formalin solution 10% and the bodies were kept in formalin bath for 4-6 month. After 6 month the limbs were disjointed, and to eliminate the existent formalin in the tissue which blocks the cleaning of these tissues by boiling, the limbs were introduced in water for 48 hours. To dilute and extract better the formalin, the water was chanced 3-4 times. After this operation the bone elements were covered by muscular tissue and were boiled until the tissue detached by itself. Finally the pieces were consecutively washed in hot water, then NaOH solution 19%, hot water again and after that keep for dry at the room ambience without sun exposure.

The results were corroborated with the ones meet in the literature. We must mention that the value of the bone density of the studied elements between the initial value and after preparation was under 3%. (p=0,03).

In both cases the bone density was determined by using CT technique, utilizing the Computer

Tomograph Siemens Somtom Plus 4. The density for the pieces sectioned to both parts and which was exposed to compression forces, was 0,175 +/- 0,01Kg/cm 3 (p = 0,03).

To obtain the pieces expose to tissue, the elements were sectioned to both parts eliminating the proximal and distal epiphyses. We do this to be able to fix the pieces in the Universal Trying Machine for its sensors being able to give us more accurate data.

Fig. 1 Femur – testing piece

Fig.2 Tibia – testing piece

To be able to calculate more efficient the forces that appears during tests, we apply to a simplification of the geometric formula for the bone elements. So for the compression test we used the following trapeze:

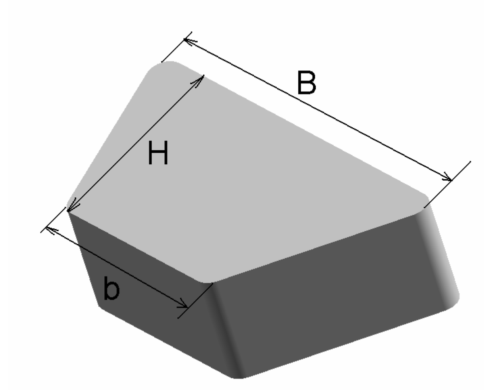

Fig. 3 The section surface in compression test

For bending test we used the triangle model:

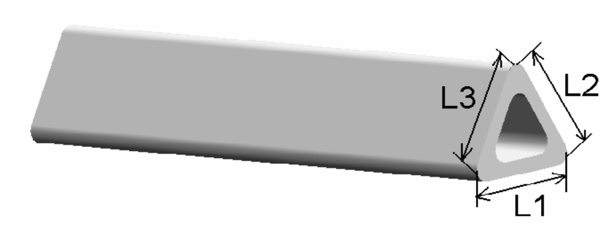

Fig.4 The section surface in bending test

For the femur geometry we have as examples the following measurements:

Pieces no.	Femur			
	b [mm]	B [mm]	H [mm]	Atrapeze [mm^2]
1	43.0	83.0	59.0	3717
2	41.0	77.0	65.0	3835
3	37.0	67.0	61.0	3172
4	37.0	77.0	56.0	3192

Table no.1- the exemplification of the values obtained in the compression test

Pieces no.	Femur			
	L1 [mm]	**L2 [mm]**	**L3 [mm]**	**$A_{triangle}$ [mm^2]**
1	29.5	30.0	30.0	299.35
2	27.5	29.0	27.0	269.76
3	28.0	26.5	27.5	262.52
4	28.5	26.0	27.5	262.52

Table no.2- The exemplification of the values obtained in the bending test.

After measurements were taken we determined the criteria for entering in test. To not advantage results and to observe the behavior of the similar bone pieces, for each part of the test it was determined similar groups as values.

Fig. 5 Image regarding the assortment of the bone pieces together with the result obtained to the test

We display the results for the femur, the bone for which the software were developed and which was intensely studied to realize a high fidelity image of the behavior during the test and extrapolated at meeting phenomena in car accidents.

The results obtained at bending tests for femur were:

- 11 pieces were tested
- The charge value of the equipment was 4.0218 MPa
- Standard deviation was 2.3957 MPa
- Confidence value was 1.9703 MPa
- The variability was 5.7395 MPa2

The results obtained during the compression tests of the proximal extremities for Femur were:

- 12 pieces were tested
- The charge value was 1.6005 MPa
- Standard deviation was 1.0364 MPa
- Confidence value was 1.7046 MPa
- The variability was 1.0740 MPa^2

The results obtained during the compression test of the distal extremities for femur were:

- 12 pieces were tested
- The charge value was 1.6828 MPa
- Standard deviation was 1.1403 MPa
- Confidence value was 1.8756 MPa
- The variability was 1.3002 MPa^2

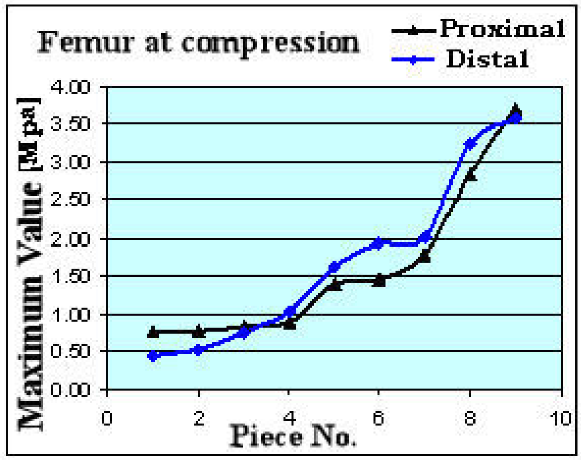

Fig. 6 Comparative chart regarding the behavior of the femur extremities during the compression test

Although the stretching phenomena is not very important for the construction of the experimental model made by the software, but we considered this phenomena too, because of the existence of some exceptions in which the contondant assembly (the car bumper) act under an angle Ø where through induces a move which subluxates the femur because of some complex elements realized by brawn tendons and the ligaments of coxofemorale joint, these do not allow the unshackle of the femur from the acetabular cavity and it is arrived a force which action in femur to expense finally determining lesions like fissure and fracture.

The results obtained at extension tests for femur were:

- 7 bone pieces were tested
- The charge value of the equipment was 4.4168 MPa
- Standard deviation was 1.9974 MPa
- Confidence value was 1.1488 MPa
- The variability was 3.9895 MPa^2

Fig. 7 Image regarding de femur resistance to the extension

All results were after verified using mathematical methods.

Polynomial regressions were fixed to be able to use the experimental results to prognoses the mechanic behavior for different bones. They are presented in no. 3 table together with R^2 value. The value of R^2, very close to 1, approving the accuracy of the polynomial functions fixed for the variation limits of the maximum stress, for all tests.

Bone	Test	Polinomic regression	R2
Femur	Compression-Proximal	y = -0.0011x6 + 0.0318x5 - 0.3625x4 + 2.0207x3 - 5.6654x2 + 7.4168x - 2.6765	0.9959
	Compression-Distal	y = -0.0015x6 + 0.0448x5 - 0.5053x4 + 2.7783x3 - 7.6581x2 + 9.9582x - 4.1842	0.9928
	Stretching	y = -0.0444x5 + 0.8322x4 - 5.8237x3 + 18.749x2 - 26.356x + 13.15	1
	Bending	y = -0.0761x3 + 1.2293x2 - 2.8043x + 3.7155	1

Table no.3 polynomial regressions for each test and R^2 values

In accordance with R^2 values, the medico-legal expertise in car accident having as consequence the fracture of these bones can use these regressions of which affinity with the real dates is almost perfect.

Also these polynomial regressions were verified with the aid of Panjabi equation, stabilizing with a better accuracy the average of the values statistically evaluated after repeated tests.

5 The Realization of the Simulation Program Femur Fractures

Following a study carried out on 4-year period at the orthopedics section of the County Clinical Emergency Hospital in Arad, it was found that, out of a number of 120 patients with femur fractures, 50 of them were caused by car accidents, 41 by household accidents, 18 were due to the existence of a pathology at the femur level and 11 for which the exact causes are not known because of the data insufficiency.

Taking into account that the great number of fractures produced by car accidents as well as the didactic utility of an application, and that related to forensic medicine expertise, we have considered the program to simulate femur fractures for this type of accidents.

The application was designed in one of the most popular and complete programming environments, Delphi 6.

The first step in realizing the project was the study of mechanics problems [8], which concern the dynamics of the car and the forces being exerted at the moment of the impact [7].

Thus, the kinetic energy developed as a result of the impact is:

$$E_c = \frac{Mv^2}{2} \quad (1)$$

where:

E_c = kinetic energy,
M = mass of the vehicle and passenger,
v = speed of the car at the impact.

At the impact, this energy is partly converted into mechanical work which dislocates (breaks) the bone through shearing forces, partly dissipated due to the friction, into heat, partly through the deformation of the bar at the impact, and partly it is dissipated through mechanical waves in the soft tissues above the bone (clothes, skin, subcutaneous tissue).

We assume that for a quotient k<1 of the kinetic energy of impact, E_c comes to actually break the bone. Thus:

$$E_i = k\, E_c \tag{2}$$

The law of energy variation shows that this energy is transformed into mechanical work of bone deformation:

$$dL = dE_i \tag{3}$$

Since mechanical work L is:

$$L = \vec{F} \cdot d\vec{r} \tag{4}$$

where:

$\vec{F}$ = force of interaction at impact, considered as constant (or as a calculated average)

$d\vec{r}$ = bone displacement / deformation

Velocity can be written as:

$$\vec{v} = \frac{d\vec{r}}{dt} \tag{5}$$

It results that:

$$\vec{F} = \frac{L}{\vec{v}dt} = \frac{E_i}{\vec{v}dt} = k\frac{E_c}{\vec{v}dt} = k\frac{Mv^2}{2\vec{v}dt} \tag{6}$$

where:
dt – duration of the impact.

In order to calculate pressure $\vec{p}$, with respect to force $\vec{F}$ impact surface S, we combine definition formulas:

$$\vec{p} = \frac{\vec{F}}{S} = k\frac{Mv^2}{2S\vec{v}dt} = k\frac{Mv^2}{2Sd\vec{r}} \tag{7}$$

where $d\vec{r}$ is the critical displacement of the tissue and bone, where the shearing (breakage) of the bone occurs.

Since the entire construction of de equations is in fact a very complicated structure from a mathematical point of view and it would be reduced anyway to determining the value of critical displacement by solving a calibration problem (that is, a virtual experiment or the results of real experiment, from which to result the value of critical displacement), it is much easier to take into consideration the dimension of a fascicle of bone tissue (that is, the breadth of the bundle of bony cells with the crystallines in them) or simpler „ad burtibus", that is a value of 0,001 – 1 mm. Consequently, we shall consider the dimension of the bone tissue fascicle of 0,5 mm.

The value of quotient k depends on the type of the bar (from the car manufacturer), as cars as built so as to dissipate as much energy as possible at the deformation of the bar, to the purpose of protecting passengers (ISO 9002 security norms). Taking into account that k<1, we shall consider the value of k = 0,8.

The second step was the implementation in the programming language of the formulas obtained above. Depending on the initial data, if, in consequence of the impact, pressure exceed the critical threshold (4,4168 MPa in the case of stretching forces and 4,0218 MPa in the case of bending forces), the program establishes whether the femur remains intact or a fracture will be produced at its level. The program also makes it possible to establish the type of fracture.

The third step was the graphic representation of the experiment. To this effect we chose to employ 3D graphics, namely the most powerful instrument in the field, 3D Studio Max.

The interface is intuitive (figure 8), the display can be modified according to the user's desire. Also, the three-dimensional space exploration is extremely simple, by pressing directional keys.

Fig. 8 The interface of the application
a) before the impact b) after the impact

In the control panel (figure 9) the following data can be introduced: speed of the car before braking, distance to the pedestrian, weight of the car and braking force. There is also the possibility of choosing the pedestrian's age.

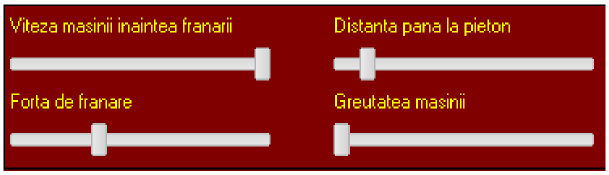

Fig. 9 Administration panel

Another facility is represented by the "replay" mode which has, as effect, the decrease in the number of fps (frames per second) or in other words the view of the experiment in replay. The position of the camera (view angle) can be set at will, using the mouse or the keyboard. At the same time, the user is provided with the "in car" mode which places the camera behind the vehicle in order for the experiment to be viewed from the driver's perspective.

After applying the experiment, depending on the value of pressure on the femur, which will be displayed on the screen, the femur will be fractured or remain in intact.

5.1. Data management

The project consists of 3 big modules: centre of application (core), graphic interface and bridge classes.

By core we understand objects and methods which implements mathematical and physical formulas which underline application. It deals with the calculation of pressure, speed, weight, s.o. In order that simulation can be made we build a mathematical model which evolves in time. The formulas results at a certain period, give the pressure exert on femur. According as this value the impairment degree is established. [10]

The graphic interface has a single role: to represent in an interactive form the values returned by the core. For each equation or part of equation there is a representation in the graphic interface. To give a realistic note we used the 3D graphic, more exactly OpenGl standard.

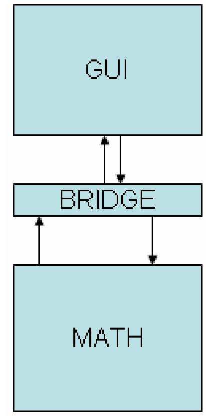

Fig. 10 The modular representation of the application

The core and graphic interface of the application are different; this is why we must build bridge classes. There are closed in role which Adaptor classes from Addapter Pattern. In their turn, these appeal the classes form 3D interface module to realize the graphic representation of the formulas.

5.2. Implementation details

The application is mostly based on 3D geometry. We used concept like: rotation, translation, lines and geometric solid. In the 3D space of the application any object is considered to be a cube, as the testing medium, as the car and the footer. Each cube contains a 3D object, bridged at the center of the cube. We choose this strategy to simplify the thinks as regarding the organization of the objects in space. Any operations on the objects, including collision are made referring to father-cube.

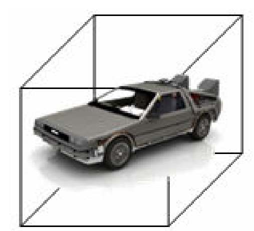

Fig. 11 The representation of an object with its father-cube

The moves of the object are made by moving father-cube and because the object is bridged by the bar center of this, it modifies its position too. It is already evident the choice of the cube as universal abstract form. It is the most simple object form in 3D space.

By moving the object we understand the

mathematical sense of the word namely: translations and rotations. In Euclidean geometry the translation represents the modification of the position of each point, with a certain constant k and in a specified direction. Also the translation can be interpreted as an adjunction of a constant vector at every point, or the modification of the coordinate system origin. The operator of the translation could be represent as follows: $T_\mu f(v)=f(v+\mu)$, which means that the translation distance is μ.. In our application we considered that each object has coordinate system common with origin form the bar center. To make translation moves on the object we modified the origin coordinate of the father-cube.

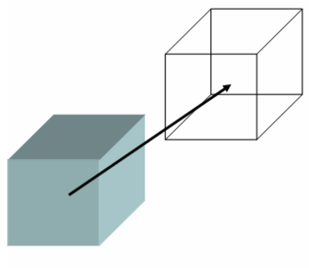

Fig. 12 Translation

Also as we said before, the move of the objects in the space is not limited to the translations. The rotation is more complicated. It will be made, as in translation case, according the bar center of the cube.

From mathematical point of view, the rotation as opposed to translation is a rigid circulation which implies the maintaining of a fixed point. In our case the problem is more complicated because of the fact that the action takes place in a 3D space. In accordance with the Euler theorem, the circulation must take place after a hole fixed line (for example after axes). The rotation around x, y and z axes will be called principal rotations. Any other rotation can be realized by composing principal rotations, so by rotating around x followed by a rotation around y axes and followed a rotation around z.

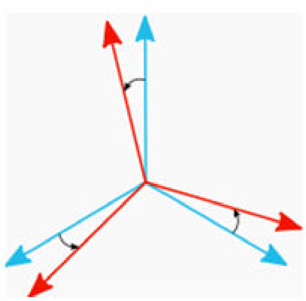

Fig. 13 Rotation in 3D

In accordance with Euler theorem a 3D rotation around an axis is similar with 2D one in the plane made by the other 2 axes. Mathematically the rotation around OX axis can be represented as follows:

$$\mathbf{A}_X = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{bmatrix}$$

Any move in 3D space can be expressed as a compose rotations and translations. In our case we assumed that car moves linear while the footer gets diverse paths according to the impact.

Another problem of the 3D implementation is the impact itself which we simulated by means of the notion of collision. The collision represents an insular event where through two or more bodies exert pressure each other. If they are afoot, after event their speeds are modified. Certainly in real world, the collision is a physical phenomenon, absolutely normal and ordinary, but in the case of a simulation it is necessarily a mathematical model.

In the case of this application the object that entered in collision is father-cube. Each cube has a dimension, and by dimension we understand the geometrical position. The collision takes part when the intersection of the geometrical position occupied by two cubes is not void.

Although the problems appear to be simple, it is not. We detected the moment when the collision is produced but we didn't solve the speed problem, the pressure and other physical properties which are modified together with the collision. In our application there is an implementation for the tic of the clock. In this way we can observe the simulation moments. In every moment the objects have some properties, for example, in the case of the car: the traveling speed, the acceleration, the brake power, the distance steamed, s.o. In the moment of the collision with the footer, an image of these values is made for all the objects which entered collision. Next, they will be modified according with some physical relations. By these values we understand the stage of the objects.

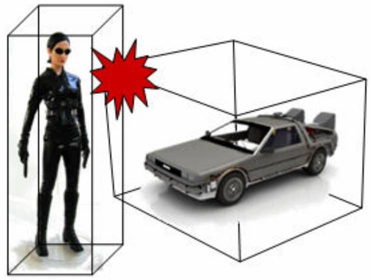

Fig. 14 The simplify representation of the collision

Once the modifications are made, the objects entered thru another stages. For examples the car after busts a footer because of the collision it entered in partial breaker stage. Certainly to optimize the detection process we build a father cube small enough to give the sensations that the car busts the footer. [12]

From the programming point of view the simulation moments or the time axis represent a knot in the apart execution clue. At every each iteration the stage of the objects is actualized. In the case of a collision it is calculated the pressure exert at the impact moment and the stage of the objects entered the collision are actualized. After determining the pressure of the impact the application makes an appropriate representation of the femur for the result value and constants referring to the person, expressed in the beginning of the experiment.

6 Conclusion

This work has had in view to carry out an experimental software application which would reproduce, virtually, a mechanical traumatism on the femur eliminating deliberately and selectively other associated injuries, these being considerate from the start as minor (scratches, bruises, shallow wounds).

Experimental studies of car accidents simulate the real case and study, by means of collision tests in given conditions, the effect on the human body components, in our case, on the femur. When emerging transposition problems are solved, important information on the real accident is obtained. Theoretically, real elements are replaced by models that have been tested through detailed calculation with different parameters and whose results have been compared.

The existence of such programs is particularly useful in the case of certain judicial test cases, where forensic medicine expertise issues are involved.

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