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FACULTY OF MEDICINE

ABSTRACT OF Ph.D. DISSERTATION

ASSESSMENT OF THE RESULTS OF ANKLE FRACTURE TREATMENT

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KEY WORDS: talo-crural joint, malleolar fractures, biomechanical study, bone suture, ankle fracture treatment.

Chapter I INTRODUCTION.

Functionally, the ankle and foot make up a complex structure and represent — after thigh and calf - the third main lever of the leg, structured and adapted to the complex functions that fall on it. Being a terminal lever, it is the point of connection between the body and the ground during current biomechanical actions (static, walking, running, etc.) [1] and is tasked to take and convey body weight force to the ground, allowing translational motion of the body in relation to the external reference system [2].

Without being protected by major muscular masses, talocrural joint is exposed to trauma to a greater extent than other segments, consequently ankle fractures are the most common fractures treated by orthopedic surgeons [3]. Their incidence is estimated at more than 100 fractures per 10,000 persons per year [4].

Being intra-articular lesions, these fractures in 30 to 94.6% of cases are accompanied by the displacement of fragments, subluxations of planta, advanced juxta-articular lesions, and the anatomical reduction of the fragments is a basic postulate in malleolar fractures treatment [5].

Multiple clinical and biomechanical studies suggest that any residual displacement, joint misalignment and residual ligament instability after inadequate treatment of ankle fractures, disturb ankle biomechanics by decreasing joint contact area, by redistributing considerably intra-articular pressure, by increasing pressure on the articular cartilage and implicitly developing deforming arthrosis [6][7][8][9][10].

Long-term treatment results are not always positive. Approximately one third of patients who underwent ankle fractures, show clinical signs of post-traumatic arthrosis. Radiological examination at 10-14 years after injury revealed that up to 76% of radiographs present radiological signs of post-traumatic arthrosis [11] [12] [13]. In a meta-analysis of 1822 patients with ankle fractures treated by open reduction and internal bone suture, good long-term results were observed only in 79.3% of the fractures which benefited by perfect reduction of movement [14].

Up to 78% of the patients who have operating indications for ankle arthrodesis or arthroplasty for painful arthrosis are of traumatic origin [15] [16].

One of the difficulties recently encountered in the treatment of ankle fractures is the increasing incidence of concomitant diseases such as osteoporosis and diabetes mellitus in elderly patients [17] [18] [19].

Talocrural joint immobilization in conservative treatment or as an adjunct method after surgery, causes ankle stiffness and degenerative changes of articular cartilage.

The prevention of these complications can be achieved through an internal bone suture sufficiently stable and rigid to ensure effective stability in the fracture seat and allow active joint mobilization in the early postoperative period [20] [21].

Chapter II PURPOSE OF THE PAPER

The purpose of the research is the scientific reasoning of choosing the optimum surgical bone suture technique of medial malleolus and peroneal malleolus among a few ones analyzed and the elaboration of analytical, virtual, experimental and clinical work methodology for the comparative study of bone suture assemblies, at the level of talo-crural joint, on purpose to reacquire the normal biomechanical properties of the bone and joint in the shortest time and with the best long-term results.

Chapter III OBJECTIVES

The highlighting of biomechanical tasks that act upon the ankle joint, in static regime and in dynamic regime; the emphasis of the relation between bone suture medical techniques of medial malleolus fracture and the articular biomechanical pattern considered, on purpose to theoretically determine the optimum variant of bone suture technique; revealing by experiment the advantages and disadvantages of every medical bone suture technique analyzed; evaluation of ankle fracture treatment surgically treated by open reduction and internal bone suture and choice of the optimum treatment method of those studied by using statistical methods.

GENERAL PART-PRESENT STAGE OF KNOWLEDGE

The general part includes chapters IV-XII and presents the journal literature on regional anatomy, biomechanics, etiopathogeny, classification, diagnosis, treatment, possible complications, prognosis and assessment criteria of the results of ankle fractures treatment.

SPECIAL PART-OWN CONTRIBUTION

A. EXPERIMENTAL STAGE

Chapter XIII RESEARCH METHODS

The research methods used in the thesis were: mathematical, for expressing static or dynamic equilibrium conditions; observation method, for the biomechanical pattern, used for testing the resistance of bone suture assemblies; analysis of observation sheets of the patients with ankle fractures; statistical, in order to analyze the data, computerized data analysis methods using the program package IBM SPSS for Windows.

Chapter XIV RESEARCH MATERIAL

The material used consisted of a series of technical equipment and specialized computer programs, which allowed the performance and analysis of the three types of biomechanical patterns proposed, namely: analytical, virtual and experimental: Kistler force plate, Kistler 5606 signal amplifier, PC CARD data acquisition board, BIOPAC measurement system, specialized programs BioWare and Acqknowledge, accelerometers TSD 109, MRI, specialized programs DICOM Viewer, MIMICS, SolidWorks, ProEngineering, ANSYS, assaying machine to axial stresses, FPZ 100, fixation systems for fracture fragments, numerical data processing program Excel, program package IBM SPSS for Windows.

Chapter XV THEORETICAL CONTRIBUTIONS REGARDING STATIC AND DYNAMIC MODELING OF ANKLE JOINT FOR THE BONE SUTURE OF MEDIAL MALLEOLUS FRACTURE

Forces and moments of the force which operate on the ankle

At foot level, weight force of foot segment, G_p, inertia force by its components along the three axes $m_p a_x$, $m_p a_y$, $m_p a_z$, reaction force between foot and ground, with R_{Sx}, R_{Sy} and R_{Sz} components, the force resulting from the ankle, decomposed along the three axes R_{gx}, R_{gy} and R_{gz}, and the moment resulting from the ankle, M_g, are discussed.

The value of the tension must be compared with the allowable value of bone tension under traction, compression, bending or torsion stress, depending on the predominant type of stress.

Definition of geometrical parameters of foot position

To write the equations of static or dynamic equilibrium of the foot, it is necessary to know the geometric positions of the application points of forces in relation to a reference axes system, in conformity with the three-dimensional structural pattern adopted.

To determine the coordinates of the points A, B, O and E, a mobile benchmark ($O'x'_1y'_1z'_1$) is taken first, rotated around the axis O'y with the angle φ_2, represented in figure XV-26. The rotation angle φ_2 represents the angle of plantar and dorsal reflection angle for the foot. The matrix of direction cosines is, in this case, of the form: $A_1' = \begin{vmatrix} \cos\varphi_2 & 0 & -\sin\varphi_2 \\ 0 & 1 & 0 \\ \sin\varphi_2 & 0 & \cos\varphi_2 \end{vmatrix}$ (Relation XV-5)

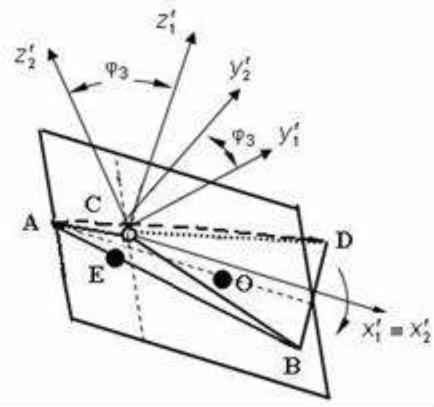

Figure XV-25 Foot inversion-eversion

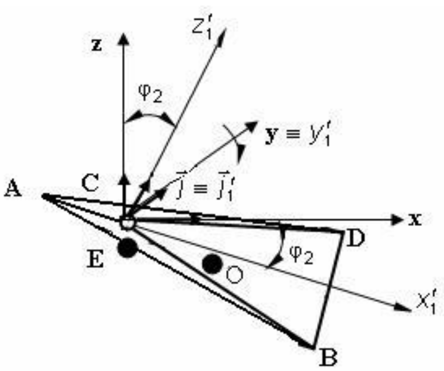

Figure XV-26 Foot dorsal-plantar flexion

From the previous position (figure XV-26), a rotation around the axis O' x_1', anterior – posterior axis respectively, takes place, with the angle φ_3, as represented in figure XV-25. The angle φ_3 determines the inversion – eversion movement for the foot.

Position vectors of these points in relation to *Oxyz* benchmark are obtained by using the matrices of direction cosines. The matrices associated to position vectors of the written points in relation to *Oxyz* benchmark are given by the relations:

$$\begin{aligned} r_B &= A_1'^T\left(A_2'^T r_{2E}'\right) \\ r_A &= A_1'^T\left(A_2'^T r_{2D}'\right) \\ r_E &= A_1'^T\left(A_2'^T r_{2F}'\right) \\ r_O &= A_1'^T\left(A_2'^T r_{2O'}'\right) \end{aligned} \quad \text{(Relation XV-9)}$$

The analytical expressions of position vectors for the considered points are:

$$\vec{r}_A = (-c\cdot\cos\varphi_2 - d_2\sin\varphi_2\cos\varphi_3)\vec{i} + (d_2\sin\varphi_3)\vec{j} + (c\cdot\sin\varphi_2 - d_2\cos\varphi_2\cos\varphi_3)\vec{k} \quad \text{(Relation XV-15)}$$

$$\begin{aligned} \vec{r}_B = &(a\cos\varphi_2 - b\sin\varphi_2\sin\varphi_3 - d_2\sin\varphi_2\cos\varphi_3)\vec{i} + (-b\cos\varphi_3 + d_2\sin\varphi_3)\vec{j} + \\ &+ (-a\sin\varphi_2 - b\cos\varphi_2\sin\varphi_3 - d_2\cos\varphi_2\cos\varphi_3)\vec{k} \end{aligned} \quad \text{(Relation XV-12)}$$

$$\begin{aligned} \vec{r}_E = &[\{d_1 - c\}\cdot\cos\varphi_2 - b\sin\varphi_2\sin\varphi_3 - d_2\sin\varphi_2\cos\varphi_3]\vec{i} + (-b\cos\varphi_3 + d_2\sin\varphi_3)\vec{j} + \\ &+ [(d_1 - c)\cdot\sin\varphi_2 - b\cos\varphi_2\sin\varphi_3 - d_2\cos\varphi_2\cos\varphi_3]\vec{k} \end{aligned} \quad \text{(Relation XV-18)}$$

$$\vec{r}_O = [(d_3 - c)\cdot\cos\varphi_2 - f\cdot\sin\varphi_2\sin\varphi_3 - d_4\sin\varphi_2\cos\varphi_3]\vec{i} + (-f\cdot\cos\varphi_3 + d_4\sin\varphi_3)\vec{j} + [-(d_3 - c)\cdot\sin\varphi_2 - f\cdot\cos\varphi_2\sin\varphi_3 - d_4\cos\varphi_2\cos\varphi_3]\vec{k} \quad \text{(RelationXV-21)}$$

From the above relations it is noted that the geometrical positions of the points A, B, E and O, defined by the position vectors $\vec{r}_A$, $\vec{r}_B$, $\vec{r}_E$ and $\vec{r}_O$, are variable mathematical functions of dorsal-plantar flexion angles and foot inversion-eversion.

Static biomechanical pattern of foot

Based on considerations of mechanical loads for different equilibrium positions of the foot, static relationships can be written:

- for static equilibrium of initial contact on heel:

$$\begin{cases} R_{sx} - R_{gx} = 0 \\ R_{sy} - R_{gy} = 0 \\ R_{sz} + R_{gz} - G_p = 0 \\ \vec{M}_g + \vec{M}_C(R_s) + \vec{M}_C(G_p) = \vec{0} \end{cases} \quad \text{(Relation XV-27)}$$

in which:

$$\vec{M}_C(R_s) = \vec{r}_A \times \vec{R}_s = \begin{vmatrix} \vec{i} & \vec{j} & \vec{k} \\ x_A & 0 & -z_A \\ R_{sx} & R_{sy} & R_{sz} \end{vmatrix} = \vec{i}\cdot(z_A\cdot R_{sy}) + \vec{j}\cdot(-x_A\cdot R_{sz} - z_A\cdot R_{sx}) + \vec{k}\cdot x_A\cdot R_{sy},$$

$$\vec{M}_C(G_p) = \vec{r}_O \times \vec{G}_p = \begin{vmatrix} \vec{i} & \vec{j} & \vec{k} \\ x_O & y_O & -z_O \\ 0 & -G_p & 0 \end{vmatrix} = \vec{i}\cdot(-z_O\cdot G_p) + \vec{k}\cdot(-x_O\cdot G_p),$$

from which the calculation expressions of unknowns result:

$$\begin{cases} R_{gx} = R_{sx} \\ R_{gy} = R_{sy} \\ R_{gz} = -R_{sz} + G_p \\ M_{gx} = -z_A\cdot R_{sy} + z_O\cdot G_p \\ M_{gy} = R_{sx}\cdot z_A + R_{sz}\cdot x_A \\ M_{gz} = -R_{sy}\cdot x_A + G_p\cdot x_O \end{cases} \quad \text{(Relation XV-28)}$$

Assessment of ground reaction force

To determine forces and moments of internal forces in ankle joint, $\vec{R}_g$ and $\vec{M}_g$, the reaction force between the foot and the ground, $\vec{R}_s$, must be known, split on the directions *Ox*, *Oy*, *Oz*, for the four support phases of the foot on the ground, stationary or when walking normally, for human subjects without neuromotor disabilities. The determination of the reaction force between the foot and the ground, $\vec{R}_s$, was done by experimental methods, using a Kistler force platform.

The reaction forces on the directions *Ox*, *Oy* and *Oz*, necessary for the numerical resolution of equilibrium equations, were determined by using BioWare program, for the case a human subject with a weight of 74.5 [kg] and a height of 1.71 [m], in all the four support phases of the foot on the force plate. The values of ground reaction forces determined experimentally were further used for the numerical resolution of foot static equilibrium, for the determination of ankle articular reaction forces respectively.

Numerical determination of the reaction force of the ankle in static regime

The reaction forces R_{gx}, R_{gy} and R_{gz}, as well as the articular moments M_{gx}, M_{gy} and M_{gz} were calculated for each of the four static equilibrium positions of the foot, which were analyzed. The biometric sizes of the analyzed subject were used in the numerical application, having the following values: M = 74,5 [kg] – total weight of the body; H = 1,71 [m] – total height of the body; mp = 1,16 [kg] – foot mass; Lp = 0,25 [m] – foot length which is equivalent to the notation AB in § 2.2; CA = 0,077 [m] – length between ankle joint rotation center and heel; CB = 0,196 [m] – length between ankle joint rotation center and the tip of the second instep bone.

An analysis of the components of the reaction force, shows that of the three only R_{gx}, in position corresponding to support phase I and R_{gz} for the position corresponding to support phases II and IV are those that influence greatly the ankle joint.

Maximum reaction force of ankle joint occurs during foot support phase on toe tips when plantar flexion and inversion angles are maximal.

Dynamic biomechanical pattern of foot

For each phase of foot – ground contact considered for three-dimensional dynamic pattern of the foot, the following calculation expressions can be determined:

- for the dynamic equilibrium of the initial contact on the heel,

$$\begin{cases} R_{sx} - R_{gx} = m_p \cdot a_x \\ R_{sy} - R_{gy} = m_p \cdot a_y \\ R_{sz} + R_{gz} - G_p = m_p \cdot a_z \\ \vec{M}_g + \vec{M}_C(R_s) + \vec{M}_C(G_p) + \vec{M}_C(F^i) = J_p \cdot \vec{\varepsilon}_p \end{cases} \qquad \text{(Relation XV-35)}$$

in which:

$$\vec{M}_C(R_s) = \vec{r}_A \times \vec{R}_s = \begin{vmatrix} \vec{i} & \vec{j} & \vec{k} \\ x_A & 0 & -z_A \\ R_{sx} & R_{sy} & R_{sz} \end{vmatrix} = \vec{i} \cdot (z_A \cdot R_{sy}) + \vec{j} \cdot (-x_A \cdot R_{sz} - z_A \cdot R_{sx}) + \vec{k} \cdot x_A \cdot R_{sy}$$

$$\vec{M}_C(G_p) = \vec{r}_O \times \vec{G}_p = \begin{vmatrix} \vec{i} & \vec{j} & \vec{k} \\ x_O & y_O & -z_O \\ 0 & -G_p & 0 \end{vmatrix} = \vec{i} \cdot (-z_O \cdot G_p) + \vec{k} \cdot (-x_O \cdot G_p),$$

$$\vec{M}_C(F^i) = \vec{r}_O \times \vec{F}^i = \begin{vmatrix} \vec{i} & \vec{j} & \vec{k} \\ x_O & y_O & -z_O \\ m_p \cdot a_x & m_p \cdot a_y & m_p \cdot a_z \end{vmatrix} = \vec{i} \cdot (m_p \cdot a_z \cdot y_O + m_p \cdot a_y \cdot z_O) + ,$$

$$+ \vec{j} \cdot (-m_p \cdot a_z \cdot x_O - m_p \cdot a_x \cdot z_O) + \vec{k} \cdot (m_p \cdot a_y \cdot x_O - m_p \cdot a_x \cdot y_O)$$

m_p, J_p – foot weight and mass inertia moment, respectively,

ε_p – angled acceleration of the foot,

F^i – foot inertia force,

from which the calculation expressions of the unknowns result:

$$\begin{cases} R_{gx} = R_{sx} - m_p \cdot a_x \\ R_{gy} = R_{sy} - m_p \cdot a_y \\ R_{gz} = -R_{sz} + G_p + m_p \cdot a_y \\ M_{gx} = -z_A \cdot R_{sy} + z_O \cdot G_p + J_{px} \cdot \varepsilon_{px} - m_p \cdot a_z \cdot y_O - m_p \cdot a_y \cdot z_O \\ M_{gy} = R_{sx} \cdot y_A + R_{sz} \cdot x_A + J_{py} \cdot \varepsilon_{py} + m_p \cdot a_z \cdot x_O + m_p \cdot a_x \cdot z_O \\ M_{gy} = -R_{sy} \cdot x_A + G_p \cdot x_O + J_{pz} \cdot \varepsilon_{pz} - m_p \cdot a_y \cdot x_O + m_p \cdot a_x \cdot y_O \end{cases} \quad \text{(Relation XV-36)}$$

The unknowns R_{gx}, R_{gy}, R_{gz} and M_{gx}, M_{gy}, M_{gz} depend linearly on the components of ground reaction R_{sx}, R_{sy}, and R_{sz}, on foot weight force G_p, on the components of linear and angled foot accelerations but, at the same time they depend on the biometric data of the foot, the geometrical position of the contact point between the foot and the ground, as well as on dorsal – plantar flexion and inversion – eversion angles.

Assessment of foot weight center accelerations

To determine foot acceleration during walking, an accelerometer, type SDT, was used, with which the values of linear acceleration components be found along the axes *Ox*, *Oy* and *Oz* while walking. In the experiment, the accelerometer was installed first on the foot of the human subject, on its posterior side, by tape fixing, after which measurements of foot acceleration were made during walking on a treadmill with adjustable speed.

Numerical determination of ankle reaction force in dynamic regime

The numerical calculation of unknowns for the analyzed human subject, led to the acquirement of the following values:

- for foot support phase I:
  - R_{gx} = 47.15 [N], R_{gy} = 16.29 [N], R_{gz} = - 625.36 [N],
  - $R_g = \sqrt{R_{gx}^2 + R_{gy}^2 + R_{gz}^2}$ = 627,34 [N],
  - M_{gx} = 0.92 [Nm], M_{gy} = - 20.86 [Nm]; M_{gz} = 1.35 [Nm],
  - $M_g = \sqrt{M_{gx}^2 + M_{gy}^2 + M_{gz}^2}$ = 20.92 [Nm].

Using the calculated values, the variation graphs of the reaction forces R_{gx}, R_{gy} and R_{gz}, represented in figure XV-40 and of ankle articular moments M_{gx}, M_{gy} and M_{gz}, represented in figure XV-39, were drawn.

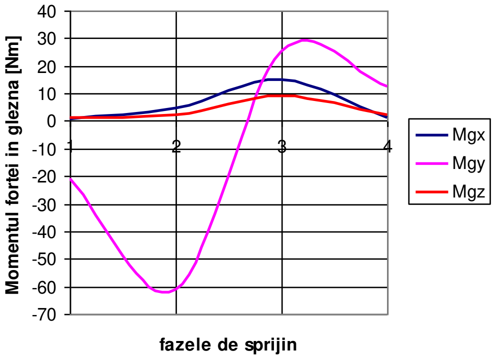

Figure XV-40 Variation charts of ankle force components

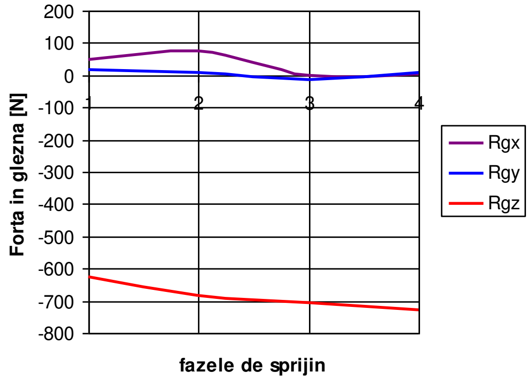

Figure XV-39 Variation charts of the components of ankle force moment

After analyzing the graphs in Figures XV-40 and XV-39, it is noted that the most important component of the force which stresses the ankle joint while driving, is the one acting along the axis Oz, and with regard to the moment of force, the component that produces the rotation around the axis Oy, which means the moment that opposes to dorsal-plantar flexion movement.

CHAPTER XVI VIRTUAL MODELING OF ANKLE JOINT WITH APPLICATIONS IN THE BONE SUTURE OF MEDIAL MALLEOLUS AND PERONEAL FRACTURE

Description of stages for obtaining virtual three-dimensional pattern

The techniques used for collecting and analyzing virtual 3D pattern of ankle - foot anatomical assembly started from the existence of a sequence of MRI images, in 2D representation of the section and the specialized software used in medical imaging computer. MRI images were read initially by Centricity DICOM Viewer program of GE Healthcare IT Company, after which MIMICS and MedCad modules from Materialise Company were used. The entire software package of Materialise Company, intended for processing medical image, represent the interface between the technical system of medical imaging, such as a medical scanner and CAD system. MRI images, numbering 988, are input data in DICOM format for virtual modeling process. Reading and processing of DICOM files involves sorting and displaying images in consecutive groups of three images corresponding to the three anatomical planes (frontal, sagittal and transverse) for each section investigated.

The retrieval of 3D virtual pattern of each bone structure which composes ankle joint was performed by applying the segmentation procedure for each bone, applying grey masks to each bone and then assigning a different color to each grey nuance.

The third main stage of virtual modeling is the 3D reconstruction of anatomical interest elements, which is achieved by obtaining different color masks for each anatomic element.

After completing the 3D reconstruction phase, the virtual pattern is geometrically usable, and one can proceed to "finishing" the surfaces by specific CAD techniques. The steps outlined above, to obtain 3D virtual pattern can not be applied to a parameterized system, only to a personalized one by well-defined images. 3D patterns obtained can be imported in different specialized software (such as SolidWorks, Pro / Engineer, etc.) where they can be subjected to specific CAD modeling techniques.

CAD modeling of tibia for obtaining fracture fragments

With CAD modeling techniques, which also use medical specialized programs such as MedCAD module, biomechanical systems such as bone – bone suture implant can be analyzed, thus achieving the virtual connection between the 3D pattern of the tibia and the 3D pattern of bone suture implants of malleolus fracture. The virtual pattern obtained from 3D reconstruction must be turned into IGES format type using specific CAD techniques. Starting from IGES surface of the tibia, the basic structure of the bone was first CAD modeled, in order to obtain different osseous layers and malleolar fracture fragments.

Malleolar fracture fragments were then performed from SolidWorks virtual pattern by cutting with a transverse plane on the medial malleolus and separating the bodies obtained.

CAD modeling of fibula for obtaining fracture fragments

In order to obtain 3D virtual pattern of the fibula, compatible with CAD, this was done similarly to tibia pattern. Thus, after segmenting and editing MRI images of the lower leg and partially the foot and obtaining the 3D pattern using Modeler module, the fibula was isolated, and then CAD modeling methodology was applied to it in order to obtain the 3D pattern in IGES format.

By going through the same assembling stages of different bone structures as for the tibia, the 3D pattern of the fibula in CAD SolidWorks programs was finally obtained. This pattern was further used for the analysis with finite elements for the bone suture of peroneal fracture.

CAD modeling of bone suture implants of medial malleolus fracture

CAD modeling of implants for medial malleolus fracture considered the following three categories of surgical bone suture techniques: bone suture with malleolar screw; bone suture with two Kirschner wires and bracing wire introduced proximally through two holes in the bone; bone suture with two Kirschner wires and bracing wire with cortical screw.

In order to obtain each bone suture implant CAD design technique was used, technique which is specific to various specialized programs (SolidWorks, ProEngineering, Mechanical Desktop etc.) which are based on the standard procedure in AutoCAD.

Realization of bone – malleolar fixation screw assembly

To assemble the two malleolar fracture fragments, each fragment consisting of six osseous structures, the function "by default" was used, by which the coordinate systems of the components corresponded in order to reproduce the designed assembly as realistically as possible, the function “cut out” was used in order to eliminate the osseous tissue in the fixation areas of the screw.

Finite elements analysis of bone suture with malleolar screw

For the evaluation of the stresses and distortions that occur in bone structure induced in osseous interface by bone suture malleolar screw, the assembly bone – bone suture implant has undergone finite element numerical analysis, under the conditions of traction stress.

CAD modeling of bone –Kirschner wires – metal wire binding system and finite elements analysis of bone suture assembly

CAD modeling of Kirschner wires (two) was performed with ProEngineering program, the wire being modeled as a steel rod.

The analysis of stress and distortion state was performed with the same program ANSYS, fracture fragments being eliminated after the simulation, in order to be able to see the stresses and distortions existent in the wires.

CAD modeling of Kirschner wires, metal bracing wire binding and cortical screw and finite elements analysis of virtual assembly

In the case of the third bone suture technique of the analyzed medial malleolus fracture, in addition to the previous technique, the cortical screw and the specific form of bracing wire for binding the cortical screw with the two Kirschner wires were modeled virtually.

After assembling the wires in the fractured tibia by using the specialized program ProEngineering, the cortical screw was introduced in the shaft of tibia at a distance of 75 [mm] to the end of the malleolus, in cross section through the bone. The positioning of this screw can be easily modified in order to find the optimal biomechanical place.

Also with the aid of the program ProEngineering, the CAD pattern of the entire bone suture assembly, formed by the two Kirschner wires, the cortical connection screw and the bracing wire, was obtained.

Bone suture technique with Kirschner wires, cortical screw and bracing wire provides a very good stability of fracture fragments.

CAD modeling of bone suture implant of trans-syndesmotic fibula fracture and analysis with finite elements

Using 3D modeling technique of the fixation screws of bone suture plate, by the help of ProEngineering program, a virtual pattern of a screw was obtained, using its measured dimensions and then the pattern was multiplied in six copies necessary for plate holes. The assembling between the bone, plate and screws was done by resorting to the functions "by default", "align axis" and "matte surface" of the program ProEngineering.

The analysis of stress and distortion state was also performed with ANSYS software, as it was performed for the tibia, by importing the 3D pattern of the assembly bone – bone suture plate - fixing screws.

From the analysis of stresses, the fact that the fracture area is subdued to tensions between 341 [Mpa] and 681 [Mpa] is observed.

Chapter XVII EXPERIMENTAL MECHANICAL TESTES OF BONE SUTURE TECHNIQUES IN MEDIAL MALLEOLUS FRACTURE

A special machine for traction and compression testing from the Laboratory for physical-mechanical tests within S.C. Mitall-Steel Iaşi was used for the experimental testing.

Results of experimental testing

For the experimental testing of traction stress the following two adjustments of resistance test machine were performed: the maximum traction force and the movement speed of the mobile head of the machine. For the maximum traction strength it was first considered that it would not exceed 1000 [N], meaning approximately 100 [kgf] and thus this value was imposed when testing malleolar screw bone suture technique. Regarding the movement speed of the mobile head of the machine, a value of 1.5 [mm / min] was chosen for the same first bone suture technique tested. The results displayed on paper revealed a much lower maximum breaking strength than expected and the need for choosing higher speed when moving the mobile head of the machine. The recording speed onto paper had a constant value for all tests, namely 60 [mm / min].

The numerical values of the force depending on time for the three tests performed were determined from the recordings made on paper, considering the following scale ratios:

- for the first bone suture technique tested:

$$k_F = \frac{F_{max}[N]}{numar\ diviziuni} = \frac{1000[N]}{100[div]} = 10\,[N/div]\,;\, k_t = 60\left[\frac{mm}{min}\right] = 1\left[\frac{mm}{s}\right] \text{(Relation XVII-1)}$$

- for the second and third bone suture technique tested:

$$k_F = \frac{F_{max}[N]}{numar\ diviziuni} = \frac{400[N]}{100[div]} = 4\,[N/div]\,;\, k_t = 0.5 \cdot 60\left[\frac{mm}{min}\right] = 0.5\left[\frac{mm}{s}\right] \text{(Relation XVII-2)}$$

In the relations (XVII-1) and (XVII-2), k_F represents force scale on the ordinate, and k_t represents time scale on the abscissa. The difference of values for force scale can be explained by considering maximum traction forces different from the first test, on one hand and the second and third test, on the other hand, 1000 [N] versus 400 [N] respectively. With regard to the time scale, the difference in values is explained by the different speeds of the mobile head of testing machine, 1.5 [mm / min] versus 3 [mm / min] respectively, leading to a doubling of the number of seconds per millimeter unit, i.e. if a second corresponds to a millimeter on the time axis in the first test, two seconds correspond to the same millimeter in the other two tests.

Variation graphs of traction force depending on time, with the numerical values for the three experimental tests performed, are represented in figures XVII-12, XVII-13 and XVII-14 respectively.

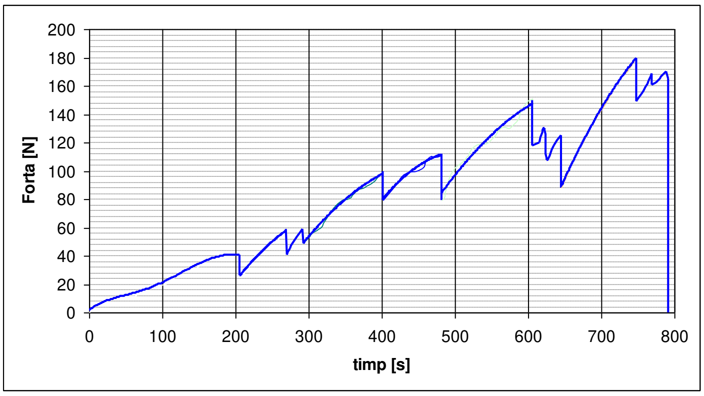

Figure XVII-12 Variation of traction force in the first technique tested

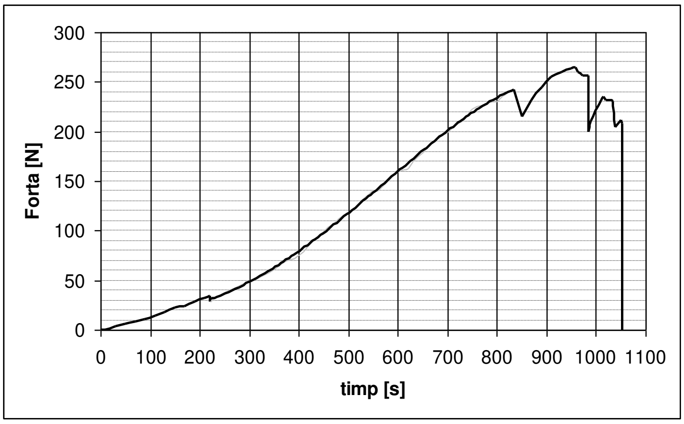

Figure XVII-13 Variation of traction force in the second technique tested

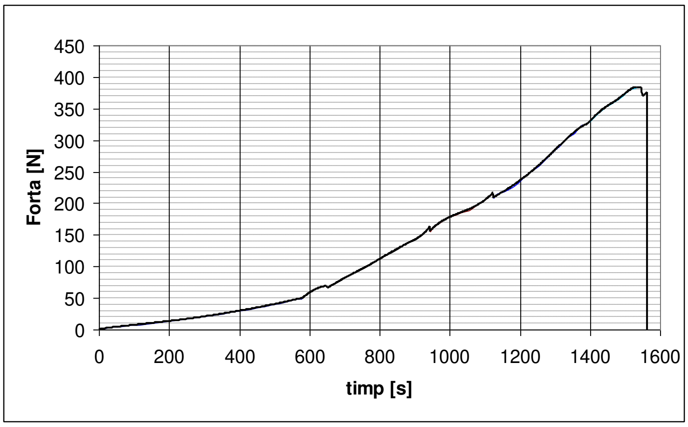

Figure XVII 14 Variation of traction force in the third technique tested

Comparing the three graphs it is observed that the best behavior from traction test has the third bone suture technique, namely the one in which two Kirschner wires, cortical screw and bracing wire are used. In this case, both the maximum traction force, 384 [N] versus 180 [N] respectively in the first case tested and 264 [N] in the second case tested, and the time that is considered to destroy the relationship between the fragments found in contact, 1562 [s] versus 792 [s] in the first case tested and 1054 [s] in the second case tested, increase.

B. ASSESSMENT STAGE OF TREATMENT RESULTS

Chapter XVIII ANALYSIS OF TREATMENT RESULTS OF 271 PATIENTS WITH ANKLE FRACTURES

Clinic study

Prospective research was carried out during 2004-2012 in the orthopedic section within the surgery department of Medgidia Municipal Hospital. The inclusion criteria were the diagnosis of malleolar fractures aged between 16 and 80 with indications for surgical treatment. The exclusion criteria from the study were open fractures, severe associated diseases, multiple injuries, presence of sequelae after other fractures incompletely healed and recovered from the functional point of view, which are able to impede active postoperative mobilization of operated patients and to distort the results of treatment.

For the development of the study, a database was elaborated, which included demographic data such as age, sex, area of origin, type of fracture, type of operative and postoperative surgical treatment used, after the informed consent of the patients.

The patients were assessed postoperative after 1 year, and the results were introduced in the database. The assessment of the results was performed by using Gray and Evrard scale (1962) [5].

Research group

The research group comprises a number of 271 patients of which 135 men (49.8%) and 136 women (50.2%).

Table XVIII-1 Distribution of patients according to age group

	Frequency	Percent	Valid percent	Cumulative percent
Under 30 years	44	16.2	16.2	16.2
30-40 years	40	14.8	14.8	31.0
40-50 years	38	14.0	14.0	45.0
50-60 years	64	23.6	23.6	68.6
60-70 years	44	16.2	16.2	84.9
Over 70 years	41	15.1	15.1	100.0
Total	271	100.0	100.0	

Depending on the type of fracture, the most frequent were the fractures type B2.2 – 67 cases, 24.72%, followed by the fractures type B1.2 – 53 cases, 19.56% and fractures type B1.3 – 32 cases, 11.8%. Fractures type B3.3 – 31 cases, 11.4% are at a small distance, being followed by the fractures type B2.3 – 26 cases, 9.6%, B2.1 – 24 cases, 8.9% and C – 20 cases, 7.4%. The other types of fractures have an incidence lower than 10 cases.

Table XVIII-4 Influence of age group on the typology of fractures

		Age group						Total
		Under 30 years	30-40 years	40-50 years	50-60 years	60-70 years	Over 70 years	
Type of fracture	B1.1	0	1	2	3	1	0	7
	B1.2	13	10	8	9	8	5	53
	B1.3	3	3	7	7	8	4	32
	B2.1	3	3	6	6	5	1	24
	B2.2	9	9	4	22	13	10	67
	B2.3	5	3	1	4	4	9	26
	B3.2	1	0	2	3	0	2	8
	B3.3	2	8	4	7	2	8	31
	A	0	0	1	0	2	0	3
	C	8	3	3	3	1	2	20
Total		44	40	38	64	44	41	271

In terms of surgical technique for medial malleolus, a total of 119 patients received the surgical technique based on 2 wires with bracing wire and tibial screw (43.91%), 20 patients were operated by malleolar screw bone suture technique (7.38%) and 7 patients received other operational techniques of bone suture with wires (2.6%).

For the fibula, 180 patients (66.42%) benefited by bone suture with 1/3 posterior semi-tubular plate, 57 patients (21.03%) were operated using bone suture with 1-2 cortical screws, 12 patients (4.43%) were operated using bone suture with external semi-tubular plate with 1-2 compaction screws, 12 patients (4.43%) were operated using bone suture with centro-medullary wire, and 3 patients (1.1%) were operated using bone suture with centro-medullary wire with wire cerclage.

Assessment of treatment results

94% of the patients treated surgically had good and very good results, and 6% were assessed with satisfactory results. No pseudarthrosis cases were registered among the patients of the study group. In order to compare efficiently the treatment results of the patients with malleolar fractures treated by using various surgical procedures and postoperative recovery methods, the mean of assessment score was elaborated and served as a comparison index.

Treatment results have the amplitude of 9 points comprised between a minimum of 6 and a maximum of 15 (according to Gray and Evrard evaluation criteria). The assessment mean is 13 points, with a standard variation of 1.8, the median score being 15, and the category with the highest frequency is represented by the score 15.

Table XVIII-5 Statistical inventory of the assessment of treatment results

N	Valid	271
	Absent	0
Mean		13.51
Median		14.00
Mode		15
Standard variation		1.805
Range		9
Minimum		6
Maximum		15

The evaluation of surgical techniques was performed by using mono-various variation analysis through which we will study the effects generated by the surgical techniques used in the treatment of medial malleolus and fibula fractures on the results of treatment assessment. The independent variables are represented by the two surgical techniques, and the dependent variable is Evrard Gray score.

Table XVIII-6 Effects exercised by surgical techniques on the assessment of results

	Sum of quadrates	df	Mean of quadrates	F	Sig.
Adjusted pattern	184.151	4	46.038	23.138	.000
Interceptions	6589.568	1	6589.568	3311.887	.000
Medial malleolus	2.763	1	2.763	1.389	.241
Fibula	**73.460**	**2**	**36.730**	**18.460**	**.000**
Medial malleolus * Fibula	.018	1	.018	.009	.925
Errors	238.761	120	1.990		
Total	23029.000	125			
Adjusted total	422.912	124			

After the analysis, the existence of a significant main effect of the surgical techniques used the treatment of fibula fractures on the results of the treatment, is ascertained ($F_{(2,124)}$=18,46; p<0,01).

Table XVIII-7 Effect generated by the surgical techniques used for the treatment of fibula fractures

(I) Operative technique for fibula	(J) Operative technique for fibula	Mean of differences	Standard error	Sig.
Bone suture with 1-2 cortical screws	Bone suture with 1/3 posterior semi-tubular plate	**-3.24***	**.354**	**.000**
	Bone suture with 1/3 external semi-tubular plate with 1-2 cortical compaction screws	**-1.46***	**.551**	**.028**
Bone suture with 1/3 posterior semi-tubular plate	Bone suture with 1-2 cortical screws	3.24*	.354	.000
	Bone suture with 1/3 external semi-tubular plate with 1-2 cortical compaction screws	**1.78***	**.469**	**.001**
Bone suture with 1/3 external semi-tubular plate with 1-2 cortical compaction screws	Bone suture with 1-2 cortical screws	1.46*	.551	.028
	Bone suture with 1/3 posterior semi-tubular plate	-1.78*	.469	.001

The meaning of the effect determined by the surgical techniques used for the treatment of fibula fractures on the treatment results was analyzed by using post-hoc analyses based on Bonferroni statistical test. Thus the surgical technique using 1/3 posterior semi-tubular plate leads to significantly better results compared to the bone suture technique with 1-2 cortical screws (MD=3.24; p<0.01). Concurrently, bone suture technique with 1/3 external semi-tubular plate with 1-2 cortical compaction screws also leads to significantly better results compared to bone suture technique with 1-2 cortical screws (MD=1.46; p<0.05).

Between the bone suture technique with 1/3 posterior semi-tubular plate and the bone suture technique with 1/3 external semi-tubular plate with 1-2 cortical compaction screws there is a difference under the aspect of treatment results in the sense that the first one leads to significantly better results compared to the second one (MD=1.78; p<0.01).

Therefore, the surgical technique that generates the best results is represented by the bone suture with 1/3 posterior semi-tubular plate. This is followed by a significant bone suture difference with 1/3 external semi-tubular plate with 1-2 cortical compaction screws. The worst results are obtained after using bone suture technique with 1-2 cortical screws.

Table XVIII-8 Effects exercised by surgical techniques on the assessment of results for type B fractures

	Sum of quadrates	df	Mean of quadrates	F	Sig.
Adjusted pattern	177.431[a]	3	59.144	35.105	.000
Interceptions	503.345	1	5035.345	2988.793	.000
Medial malleolus	.802	1	.802	.476	.492
Fibula	**60.959**	**2**	**30.480**	**18.091**	**.000**
Medial malleolus * Fibula	.000	0	.	.	.
Errors	192.061	114	1.685		
Total	21902.000	118			
Adjusted total	369.492	117			

In this case, similarly to the entire group of patients, we observe the existence of a significant main effect determined by the surgical techniques used for treating fibula fractures on the treatment results ($F_{(2,117)=}$18.09; p<0.01)

Table XVIII-9 Effect generated by the surgical techniques used for the treatment of fibula fractures for type B fractures

(I) Surgical technique for fibula	(J) Surgical technique for fibula	Mean of differences	Standard error	Sig.
Bone suture with 1-2 cortical screws	Bone suture with 1/3 posterior semi-tubular plate	**-3.38***	**.342**	**.000**
	Bone suture with 1/3 external semi-tubular plate with 1-2 cortical compaction screws	-.29	.660	.157
Bone suture with 1/3 posterior semi-tubular plate	Bone suture with 1-2 cortical screws	**3.38***	**.342**	**.000**
	Bone suture with 1/3 external semi-tubular plate with 1-2 cortical compaction screws	**2.08***	**.595**	**.002**
Bone suture with 1/3 external semi-tubular plate with 1-2 cortical compaction screws	Bone suture with 1-2 cortical screws	1.29	.660	.157
	Bone suture with 1/3 posterior semi-tubular plate	**-2.08***	**.595**	**.002**

The meaning of the effect is given by the fact that bone suture surgical technique with 1/3 posterior semi-tubular plate leads to significantly better results compared to the bone suture surgical technique with 1-2 cortical screws (MD=3.38; p<0.01) in the case of the patients with type B fractures. Concurrently, bone suture surgical technique with 1/3 posterior semi-tubular plate generates significantly better results compared to the surgical technique with 1/3 external semi-tubular plate with 1-2 cortical compaction screws (MD=2.08; p<0.01).

In order to assess the effect determined by early active mobilization of the operated extremity on work disability duration, the test of significant difference between the means of two populations was used, from which the samples were extracted –Student t test.

Table XVIII-10 Standard means and variations of the two samples

	State of immobilization	N	Mean	Standard variations	Standard error of the mean
Duration of work disability (days)	Without immobilization	182	61.66	2.388	.177
	With immobilization	89	97.04	7.974	.845

Table XVIII-11 Significance of the differences between means

		Levene test of variation equality		T test of mean equality				
		F	**Sig.**	**t**	**df.**	**Sig.**	**Mean of differences**	**Standard error**
Duration of work disability (days)	Equal variations	23.631	.000	-55.107	269	.000	-35.382	.642
	Unequal variations			-40.969	95.799	.000	-35.382	.864

The duration of work disability in patients with active mobilization in early postoperative period is significantly lower compared to the duration of work disability in patients who were immobilized after surgery and performed post-immobilization recovery treatment ($t_{(95)}$=40.96; $p<0.01$). Thus, we were able to demonstrate the effectiveness of surgical techniques used in the peroneal malleolus fracture (bone suture with 1/3 posterior semi-tubular plate with screws) and medial malleolus (bone suture with 2 wires and bracing wire with tibial screw) with regard to the stability of bone-bone suture complex that allows early active mobilization as well as shorter treatment time.

Chapter XIX PERSONAL CONTRIBUTIONS

The following personal contributions result from Ph.D. dissertation:

- elaboration of a space analytical biomechanical pattern of ankle joint and its use both in the analysis of static equilibrium and in the dynamic analysis for foot support positions on the ground during walking;
- use of two degrees of freedom of the ankle in three-dimensional analytical pattern, dorsal-plantar flexion and inversion-eversion foot movements respectively, with the callout of position matrices by successive passing from one angled position to another, considered as independent geometrical dimensions;
- determination of the systems of 6 static and dynamic equilibrium equations, for each equilibrium position analyzed;
- elaboration of mathematical methodology for obtaining a biomechanical analytical pattern at the level of a joint with two degrees of freedom;

- determination of calculation expressions for the resulting reaction forces and the moments of reaction forces, in static regime and in dynamic regime, for the four foot support positions on the ground; the calculation matrices were developed for the moments of all forces of three-dimensional analytical pattern;
- acquirement of virtual patterns for tibia and fibula based on 988 MRI images and simulation of tension and distortion state per bone suture assemblies, using the method of finite elements;
- acquirement of virtual bone suture assemblies for the simulation of tension and distortion state and the comparison of these values with the critical ones resulted from the literature;
- effectuation of experimental testing for the assaying of traction resistance of three bone suture assemblies of medial malleolus, in order to confirm the previous two patterns, analytical biomechanical and virtual biomechanical;
- classification, from the virtual biomechanical point of view and experimental point of view, by the assaying of traction resistance of the three bone suture techniques analyzed and confirmation of these results by the clinic study performed;
- emphasis of usability and also confirmation or not between the three biomechanical patterns analyzed, analytically, virtually and experimentally respectively.

Chapter XX FUTURE RESEARCH DIRECTIONS

Following the documentation and completion of this thesis, the following research trends in the field have been identified:

- development of biomechanical analytical patterns which comprise more body segments and joints, with complex movements, with more degrees of freedom, as close to the reality described as possible;
- development of more evolved computer programs in order to obtain easily and in real time the three-dimensional virtual images, readable in formats adequate to the simulation of tension and distortion state in bones or bone suture assemblies;
- development of new simulation methods, by using the cybernetic concepts between the analytical patterns and the virtual ones, by feed-back, data transfer in real time, creation of stratified information etc.;
- elaboration of more efficient technical equipment for the determination of body movement parameters and contact forces between human body and external environment and the transfer of these data directly to biomechanical, analytical and virtual patterns;

- acquirement of new bone suture techniques by performing multiple simulations and confirmation by in vitro assays;
- flexibility of mechanical resistance assays for complex stress types, so that they come near to the reality met in orthopedics;
- development personalized training methods of the orthopedic surgical action by effectuating virtual simulations of various bone suture techniques in an acceptable period of time.

Chapter XXI FINAL CONCLUSIONS

The selection of an orthopedic surgical technique, at some point, is based on two types of motivation, namely: subjective motivation and objective motivation. Subjective motivation, to a lesser or greater extent, takes into account the previous experience in the field, the techniques used more, statistically speaking, by the doctors in a hospital or of a geographical area, the medical knowledge gained through medical retraining in professional centers that are better equipped technically, the innovative spirit of the doctor and his flair, the administrative aspects concerning work materials and clinical investigation equipment etc. Objective motivation, in its turn, is based on clinical studies, analytical and experimental research, scientific findings, technological progress in the field and so on, so that the decision can be made on a scientific basis.

This paper attempts to make available for those interested in orthopedic surgery a scientific instrument for comparing several surgical techniques currently used and methodology necessary for reasoning, from the interdisciplinary point of view, in favor of one or other of the techniques to be chosen.

Interdisciplinarity can substantiate objective motivation arguments when scientific instruments and methods are reproducible and available for the specialists interested.

Following the interdisciplinary study of ankle joint, orthopedic surgical techniques used in the medial malleolus fracture and clinical study in thesis theme, made between 2004 and 2012, the following general aspects resulted (the particular ones are outlined separately in the chapters of the paper):

- with the biomechanical pattern of the joint, the resulting reaction force and the moments of ankle reaction force for orthostatic equilibrium or walking were determined, without being necessary to know the muscular forces, by applying method of reduction of forces at a given point;

- the method of reducing forces in a point, used by us, has the advantage of embedding the entire action of internal forces (muscular, ligamentous, contact etc.) in the anatomic system lower leg-foot, in a resultant reaction force and a moment of reaction force acting on ankle joint, force and moment which can be determined numerically;
- ankle joint is subjected to mechanical loads both with regard to the force and the moment of force, thus resulting in complex mechanical stresses, combinations of fundamental stresses respectively (traction, compression, bending, shear and torsion);
- in the dynamic regime of walking, the joint is strained at significant values both by the vertical component of reaction force and the reaction force moment;
- in orthostatic equilibrium with full foot support, on heel or toe tips, the most important mechanical loading of the ankle is given by the reaction force moment, not by reaction force, and the explanation can be given by the fact that the entire muscular system which contributes to equilibrium state acts by moments of muscular forces so that a moment must appear in the ankle for equilibrium, namely the reaction force moment;
- the dynamic regime of walking with regard to the force and reaction force moment can be analyzed by applying the inverse dynamic analysis methods, by which certain parameters of foot movement along with the anthropometric characteristics of human body are known as initial, input data;
- knowledge of some of the movement parameters, in our case the components of the acceleration of a point assimilated to foot weight center, supposes the performance of experimental measurements;
- the combination of force reduction method in a given point with the inverse dynamic analysis methods does not eliminate the determination of the external reaction force between the foot and the ground, so that experimental measurements are also necessary for this physical dimension;
- experimental measurements assumed technical equipment and specialized computer programs which where previously standardized for the experiment;
- tension and distortion state in joint bones, in our case the tibia mainly and fibula, in case of a fracture, required the creation of a virtual pattern of each osseous component;
- numerical determination of the equivalent stresses in the bone and distortions suffered due to mechanical loadings was performed by simulation on the virtual pattern, using a specialized software of finite element analysis, also used in industrial design;
- to achieve the virtual model of the tibia two virtual reconstruction techniques of bodies with complex geometry, scanning with a hand-scanner and processing of MRI images

performed in multiple sections, with the distance of 1 mm between planes of section respectively, were tried out;

- due to the inaccuracies obtained and to non-convergence when assembling them, virtual modeling with hand-scanner was dropped out;
- MRI images used in virtual reconstruction assumed a large number of sections, a total of 988, due to the reconstruction precision, transversal images being "clothed" on the contour, step by step, from the planes situated at a distance of 1 mm from each other;
- virtual reconstruction followed two main phases, namely: obtaining DICOM formats for image files and IGES formats for working in specialized programs with finite element analysis;
- the first phase of obtaining the virtual pattern followed, in its turn, three main stages of work, each stage containing specific computer processing techniques of the images; the segmentation stage of the body identified on MRI images was the most laborious one among the three stages, due to the need of correct delimitation of the contour and identification of homogeneous regions which lead to the convergence or non-convergence of the assembled contour surfaces;
- the second phase of obtaining the virtual pattern went through all three main stages, leading to the possibility of recognition by specialized programs of mechanical simulation of the solid body (tibia) along with the characteristic properties of a solid body (mass, geometrical dimensions, elasticity modulus, Poisson coefficient); the fracture fragments were also obtained after this work phase;
- the acquirement of IGES format for tibia and fibula gave the possibility of virtual assembling with technical systems used in the surgical techniques of medial malleolus fracture (screws, wires, bracing wires);
- the tension state on the fractured bone in malleolar area and assembled by one of the surgical techniques analyzed had to be compared with the experimental data necessary to validate or not the virtual pattern analyzed by finite element method, by simulation;
- the simulation on the virtual pattern was performed under conditions of mechanical loading provided by the dynamic biomechanical pattern, the resultant reaction force and the moment of the reaction force in the ankle, respectively;
- the virtual pattern was validated by the experimental results, effectuated on a traction assaying machine, which confirmed the differences among the three surgical techniques analyzed with finite element method, by simulation on the virtual pattern, the conclusions being the same both for the virtual simulation and for the experiment;

- experimental assays of bone suture assemblies also confirmed the analytical biomechanical pattern, by comparing the critical force in the experiment with the resultant reaction force in the biomechanical pattern;
- experimental tests required the preparation of fracture fragments so that these were able to be anchored by the bits of the traction assaying machine; two ways of fixing the fractured small malleolar fragment were tried, the first one with synthetic resin, and the second one by separation with a sheet plate having two hooks for anchorage on the machine bit;
- the mechanical solution with plate separation plan and anchorage hooks was mostly used due to the good fixation offered to the small fracture segment;
- a low movement speed of the machine bits, 1.5 [mm/min] respectively, was chosen on the traction testing machine, in order to detect the most accurate moment of bone fragment separation and to start the destructive mechanical charge of the bone on the part of the elements corresponding to the surgical technique analyzed (screws, wires, bracing wire);
- the experiment performed for the traction charge of bone suture assembly made the connection and confirmed the other two modeling performed.
- the surgical technique which generates the best results in the treatment of fibula fractures type 44B is represented by the bone suture with 1/3 posterior semi-tubular plate;
- bone suture with 2 wires and bracing wire with tibial screw generated the consolidation of medial malleolus in 100% of the cases. No pseudarthrosis cases or failure of mounting with secondary movement during active mobilization with active support of ankle joint in early postoperative period were observed;
- the efficiency of the surgical techniques used for peroneal malleolus fracture (bone suture with 1/3 posterior semi-tubular plate with screws) and medial malleolus fracture (bone suture with 2 wires and bracing wire with tibial screw) was statistically proved with regard to the stability of bone-bone suture material complex which allows early active mobilization, diminution of treatment period as well as the acquirement, by far, of the best functional results compared to the other types of bone suture tested.

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