Elastoplasticity analysis of the nails used in long bone fractures

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Abstract. Elastoplastic endomedullary nail-insertion system in long bone fractures is a method which allows generating forces, moments, frictions and stress states in parts of the bone previously selected. Adding previous knowledge on the distribution of forces and acting moments over the bone fragments to be threaded, as well as on the elastoplastic and mechanical properties of the nails to be inserted (designing a special, specific structure for each case), the results, coming from 26 years of applying this technique, have been promising. It is from this perspective that we call this threading and anchoring procedure “Selective Tension System” (STS). Physicochemical analyses and mechanical trials on elastoplastic nails used in the osteosynthesis in long bone fractures are presented. The magnitude of the forces produced by flattening the nails and the reacting forces at both ends are measured. It is expected that the evidence provided on the elastic variability of these nails will be useful as guidance on the availability and choice of the elastoplastic combinations that best fit each patient.

Key Words: Elastoplastic nails, long bone fractures, plastic deformation, elastic force, nail bone interface.

1. Introduction

The Selective Tension System (STS) method enables reducing bone fragments applying elastic forces that remain in time, from which permanent strain-stress states are generated in the bones, promoting their consolidation.

This procedure facilitates selecting the magnitudes, direction and application points of the elastic forces applied to the fractured bone fragments.

In summary, the advantages of the STS technique are: low aggression to the bone tissue during insertion of the nails, the formation of a spatial structure that replaces the loss of resistance in the area...
of the bone fracture and, finally, the simultaneous stimulation for the formation of new bone over the area of the fracture.

The osteosynthesis method (STS) is based on pre-stressed concrete beams technique, but with the opposite aim: the exerted forces are not meant to prevent a fracture, but to repair a previously fractured structure.

These nails are inserted into the medullar canal from an area as distant to the fractured region as possible. Bone fragments are strung together. The nails are flattened as the result of the insertion in the bone, thus modifying their initial level of curvature determined from preoperative imaging studies in order to provide forces in the fracture zone.

To illustrate the technique, the repair of a distal third femur shaft fracture for a woman (age 83, weight 750 N) is presented. The figure 1 and figure 2 corresponds to the pre-surgery radiographs in the frontal and sagittal plane of mentioned fracture. In this case four elastoplastic nails were introduced. Nails are secured with screws (figure 3), joining and releasing the superior ends (figure 4). Figure 3 shows the additional screw in order to fix the femoral intercondylar fissure present on this fracture.

The nails that have been inserted are joined together in bundles and fixed to one of the fractured fragments in order to make sure stress forces remain unchanged. This allows to balance the forces, and the flexor-compression, torsion and shearing momentum tending to displace bone fragments.

The forces exerted by the nails on the bone fragments produce stress fields (tension-deformation) on the contact areas.

The distribution of these forces is the result of the elastic properties of the system, which depends on the number of nails used, the elastic properties of the bone, the friction forces between nails and between the nails and the bone, and the kind of fixation between the nails. It consists, from a structural standpoint, a hyperstatic system, being the nail preconformation determinant for the generation of stresses in the osseous matrix.

An elastoplastic nail is a straight nail with a bending made before their introduction to obtain an appropriate arch and level of curvature that flattens when the nail is inserted into the medullar canal of a long bone. The remaining elastic deformation of the nail acts exerting forces on the contact areas of the intramedular cortex.
The prior conformation of the arches and the crushing of the nails during the introduction to the bone are essential in the STS, because this will depend on the three-dimensional state of stress and consequent bone formation. Figure 5 shows a repaired fractured tibia outlining the comments above.

By modifying the number of nails, their diameters, shapes, constituting materials and superficial treatments, elastoplastic properties and their mechanical and tribological characteristics can be modified. This fact is widely well known [1-4], and it is why knowing the elastoplastic properties of the nails is of great relevance for the right deployment of this technique.

This paper focuses on two aspects related to the elastoplastic properties of the nails. First determine the values for the percentage residual elastic coefficient (%REC) from a set of 23 elastoplastic nails. A protocol of progressive flattening for the arched preformed nails allowed to determine the values of maximum force and the %REC. The estimate of the maximum magnitude of the forces exerted by the nails is indicative of the reactions exerted by the bone, once the nail is inserted. Second, in order to study the diversity and behavior of the anchoring, symmetrical and asymmetrical configurations showed the order of magnitude of the forces exerted on the fixing points.

2. Methods
2.1. Chemical and metallurgical properties of elastoplastic nails.
Average chemical composition of the studied nails (AISI 316 stainless steel) was as follows: 0.07% carbon, 16.4% chrome, 10.7% nickel, 1.98% molybdenum. Complementary metallographic studies
and uniaxial traction studies were published [5-6]. An austenitic structure appearing from a strong deformation in cold was observed [5].

2.2. Study of the elastoplastic properties
The need to understand the elastoplastic properties was announced from the beginning of the use of the technique of inserting nails [7-13].

Elastoplasticity studies shown along this work belong to 23 nails (nationals and imported), from different manufacturers (see column 6, Table 1). The lengths and diameters of each nail are shown in columns 2 and 3, Table 1. The diameters were measured with a micrometer Palmer (±1x10⁻⁵ m) and the length was measured with a ruler (±1x10⁻³ m).

In order to perform these studies, a special device was designed. This device allows placing preformed nails in a vertical plane and measure the value of the arch sag (see figure 7). A flexible metal bracket was made in order to keep the arches of the tested nails on a vertical plane. A screw system allows applying force, in a controlled manner, on the middle of the nails. The free nail ends were separated 300 mm from each other. The forces were registered in Newton (±2x10⁻¹ N). In this arrangement the maximum bending moment occurs in only one section of the sample.

Table 1. The 23 elastoplastic tested nails. A sub-index in column 6 indicates the procedence of the elastoplastic nails used for this measurements: (1)Argentina, (2)Austria, (3)United States. L: nail length (m), D: nail diameter (m), %REC: percentage residual elastic coefficient, as defined in equation (1).

| No. | L (±1 x 10⁻³ m) | D (±1 x 10⁻⁵ m) | Max. F (± 0.2 N) | % REC | Origin |
|-----|----------------|----------------|------------------|-------|--------|
| 1   | 0.401          | 0.00471        | 16.5             | 51.8  | IOA¹    |
| 2   | 0.339          | 0.00464        | 12.7             | 53.0  | IOA    |
| 3   | 0.390          | 0.00438        | 13.3             | 61.5  | FICO    |
| 4   | 0.427          | 0.00433        | 15.6             | 63.5  | FICO    |
| 5   | 0.341          | 0.00438        | 14.3             | 49.1  | FICO    |
| 6   | 0.358          | 0.00424        | 11.5             | 54.0  | FICO    |
| 7   | 0.386          | 0.00421        | 10.9             | 55.0  | FICO    |
| 8   | 0.353          | 0.00450        | 13.0             | 51.8  | FICO    |
| 9   | 0.433          | 0.00450        | 15.1             | 66.8  | UKH²    |
| 10  | 0.420          | 0.00440        | 13.5             | 59.0  | FICO    |
| 11  | 0.409          | 0.00433        | 12.2             | 53.4  | FICO    |
| 12  | 0.398          | 0.00445        | 13.3             | 56.2  | FICO    |
| 13  | 0.430          | 0.00451        | 13.1             | 50.1  | FICO    |
| 14  | 0.395          | 0.00470        | 14.7             | 46.9  | FICO    |
| 15  | 0.430          | 0.00450        | 15.6             | 68.6  | De PUY³ |
| 16  | 0.375          | 0.00446        | 13.3             | 57.7  | FICO    |
| 17  | 0.375          | 0.00448        | 14.7             | 63.5  | FICO    |
| 18  | 0.370          | 0.00438        | 16.2             | 72.0  | FICO⁴   |
| 19  | 0.370          | 0.00400        | 9.5              | 65.9  | De PUY  |
| 20  | 0.375          | 0.00422        | 15.3             | 62.8  | FICO    |
| 21  | 0.285          | 0.00359        | 19.3             | 85.5  | De PUY  |
| 22  | 0.375          | 0.00422        | 11.7             | 54.4  | FICO    |
| 23  | 0.495          | 0.00449        | 16.8             | 70.8  | De PUY  |
The flattening force is applied on the central point of the arch as shown in figure 6 a). Progressive flattening in 17 steps of 3 mm was applied on the arches. The value of the progressively flattened arches was measured, as well as the corresponding force values. A graph (figure 11), was made based on this data (see section 3).

The deflection arrived at its maximum force, see figure 6 b), then the force is released gradually to cancel and measure the residual deflection from where the percentage of residual elastic coefficient of the nails (%REC) is determined.

This percentage was calculated from the relationship of the arches sag as shown in equation (1):

\[
%REC = \frac{A_r - A_M}{A_0 - A_M} \tag{1}
\]

Where \(A_r\) is the residual arch sag (without external force); \(A_M\) the minimum arch sag (maximum force) and \(A_0\) the initial arch sag (without force).

The values of maximum force and the %REC obtained, in each case, are presented in the fourth and fifth column of Table 1, respectively.

As a consequence of the arch sag of the nail, nail-bone contact areas increase in number; this allows the nails to act as a bridge, exerting elastic forces on both ends of the fractured bone.

2.3 Characteristics of the forces on the extremes of the nails

Two digital force platforms range 0-1500 N (± 0.2 N), Soehnle (Germany), were used to measure the reaction force on each of the extremes of the nails. A weight of approximately 50 N was suspended from the upper area of the arches, (symmetric, partial skew and maximum skew). The rough, undulated platform surfaces prevent the nails from sliding (fixed extremes). The horizontal and secant straight lines between the extreme of the nail and the weight exertion point were used as reference for the measures of the angles of the semi-arches (figure 8, figure 9 and figure 10).
When the nail curvature is symmetric, (figure 8) reaction forces in the extremes of the nail are equal. When the arch is skewed towards one of the extremes (figure 9) the reaction force is skewed in the same direction. Under extreme skew conditions, the reaction force is concentrated on the skewed extreme of the nail, with the other extreme barely uncharged (figure 10).

![Figure 9. Nail under partial skew condition. The major reaction force is in this extreme skew arch of the nail.](image)

![Figure 10. Nail under extreme skew condition. The reaction force is concentrated on the right with the other extreme uncharged.](image)

3. Results

3.1. Experimental determination of elastic forces

Figure 11 shows the flattening forces versus arch sag of the various studied nails (Table 1). As can be observed on the upper curves, the highest values of force are between 95 N and 162 N.

![Figure 11. Flattening force [N] vs. arch sag [mm] of the nails tested (separation of the support points 300 mm). The lines between points are only to guide the eye.](image)

The mean percentage of residual elastic coefficient (%REC), regardless of nail geometry and origin, was 59.71%.

Following the method described in section 2.3 the magnitude of the forces at the ends of the nails is determined.
Based on the images shown on figure 9 and figure 10, the force values corresponding to different anchoring methods can be observed.

This study allows highlighting the magnitude of the internal forces that would take place inside the bone given its interaction with the nail. The shape of the arch is critical in this way. The chosen nail has a mean elasticity value.

Since the properties of the bone matrix will most likely differ from those of any artificial system as the one used for this experiment, the results must be interpreted as a study of the differences between the forces at the extremes according to the curvature, instead of the values themselves.

This qualitative knowledge is fundamental for the design of the architecture of the reparation using STS, given the fact that hyperostosis will depend on it.

4. Discussion and Conclusions

This paper presents the percentage residual elastic coefficient (%REC) measurements from 23 elastoplastic nails, maximum force values for each case (Table 1) and force values for each arch sag (figure 11), showing the variability of these properties and the qualitative behavior and order of magnitude for the reaction forces on the anchors.

These studies aim to achieve a wide understanding of the elastoplastic properties of the nails used on the repair of long bones using STS.

The osteosynthesis by Selective Tension Systems method is the result of the theoretical and experimental proof of the materials used, and the effects they can produce in the repair of long bone fractures. This task has been carried out thanks to the constant and permanent interaction between the medical and clinical-surgical.

An accumulated experience of 26 years of follow-ups on patients who had fractures repaired using STS is assessed. People with fractures also present great variations in size, cortical thickness, collagen and mineral matrix densities, skeletal tissue and body mass. These characteristics can be used as selection criteria in the usage of elastoplastic nails, according to the kind of elastic capabilities and forces that best agree with on each case.

All treatments were conducted by the same group of doctors specialized in traumatology and orthopedics. This article is intended for guidance in the selection criteria of the nails.

Osteosynthesis using elastoplastic nails -of which their plastic deformation and reaction elastic force characteristics- are already known, allows the surgeon to act in both aspects, statically and dynamically. Statical, through the number of nails to be used, the sum of their individual structural endurance and the quality of the fixation of the nails, and dynamically, as a result of the directions, magnitudes and application points of the forces exerted by the nails in the fixed extreme at one of the osseous fragment and over the bone area in contact with the flattened nail.

This double approach, both dynamic and static, is considered to be a new and promising prospect in future treatments of long bone fractures.

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