ENGINEERING TRANSACTIONS • Engng. Trans. • **64**, 4, 621–627, 2016
Polish Academy of Sciences • Institute of Fundamental Technological Research (IPPT PAN)
National Engineering School of Metz (ENIM) • Poznan University of Technology

An Experimentally Validated Model for the Ilizarov Fixator Considering the Loss of Wire's Pretension

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The purpose of this study is to assess the biomechanical performance of the Ilizarov fixator and to attempt optimization of its configuration. Attention is focused to the quantification of the wires' pretension loss. The study is implemented according to a combined experimental and numerical scheme: The data of a long series of experiments are used to calibrate and validate a numerical model. The model is then used for parametric analysis of the factors which, according to clinical experience, influence the efficiency of the device. It was concluded that the most critical factors are the pretension of the wires, the angle between them and the rings' diameter; the role of the remaining factors is of rather minor importance.

Key words: Ilizarov fixator, pretension loss, axial loading, torsional loading, finite element method.

1. Introduction

The Ilizarov device was proposed by Gavriil Ilizarov in Kurgan (Siberia), in the early fifties, as an alternative fracture fixation technique. Its main novelty was the use of very thin wires (instead of thicker threaded pins), which before being affixed to the rings are pretensioned (from about 500 N to about 1300 N) and transformed into stiff pins [1]. The basic principles of the Ilizarov's fixator are different from the respective ones of traditional anatomical reduction and rigid internal fixation and that is why it may be successful where other methods may be proven inadequate. Nowadays it is accepted that the mechanical characteristics and the geometric configuration of external fixators influence the biologic environment around the fracture site. As a result, these engineering rather than clinical characteristics are considered as decisive factors which influence or even dictate the final outcome of a surgical procedure. Therefore the thorough study of the mechanical behaviour and response of the Ilizarov fixator appears as indispensable demand and the respective knowledge a valuable tool in the hands of the surgeons applying the technique in practice.

In this direction an attempt is described in the present paper to quantify the role of some of these 'engineering' factors with the aid of a combined experimental and numerical protocol. Attention is paid to the loss of pretension of the wires which is, perhaps, the most crucial parameter that deteriorates the effectiveness of the technique.

2. The experimental procedure

The gradual or abrupt loss of the pretension induced to the wires of the Ilizarov's fixator is its most serious limitation. Although the exact mechanism of the phenomenon is not as yet definitely determined it is believed that it is due to a combination of slippage of the wires and yielding of their material. The loss of pretension occurs in two stages, i.e. immediately after the tensioner is removed and during loading. Recently the phenomenon was studied experimentally using the assembly shown in Fig. 1a [2]. With the aid of an electrical strain gauge and a properly mounted extensometer both the axial strain and the slip were measured during the whole experimental procedure (including pretensioning up to a level of 1080 N followed by cyclic loading) and the results are plotted in Fig. 1b. It is observed that after the removal of the tensioner (point A) the wire slides (by about 30 μm) until the loading procedure starts (point B). During the loading phase (which included three loading-unloading loops from zero to

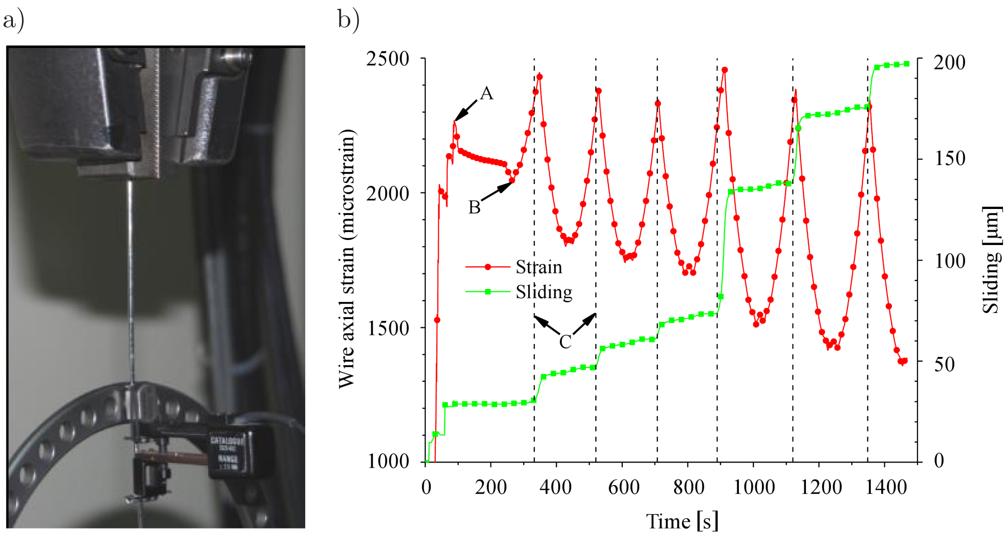

Fig. 1. a) The experimental set-up of the preliminary protocol, b) axial strain and slippage vs. time [2].

200 N, followed by three additional ones from zero to 250 N) it is noted that (as expected) the strain increases during the loading branch and decreases during the unloading one. However, slightly before the maximum load of each loop is reached, the wire starts sliding. As a result, the axial strain attains gradually lower levels (as the number of loops increases) both at the peak load and also at the zero load level, indicating loosening of the wire [2].

The above process becomes more complicated in case a whole Ilizarov frame is to be studied, since pretension of one wire inevitably influences the axial strain (and therefore the pretension) of its companion wire. In this direction, a complete frame made up of four rings was constructed, using components of the Smith and Nephew (S&N) collection. Each ring consisted of two semi-rings (diameter 150 mm, S&N 101305), hold in place with two bolt-nut pairs. The tightening torque applied was 15 Nm. The rings were connected to each other using threaded metallic bars (diameter 6 mm, S&N 102314). Four K-wires pairs (diameter 1.8 mm, S&N 102107) were used. An electrical strain gauge (HBM 1-LY11-0.6/120) was attached on each wire. The bone was simulated by two acetal bars (diameter 3 cm) with a 2 cm inter-fragmentary gap. The wires were fixed to the rings using cannulated bolts (S&N 100600). During the first step only one end of each wire was fixed.

As a second step the assembly was supported on an MTS miniBionix 858 frame (Fig. 2) and the strain gauges were connected to the data logger (TML TDS-530). In the third step the pretension (1080 N) was imposed using the S&N 103101 tensioner and then the wires were attached to the rings, as described

Fig. 2. The frame used to study the interaction between the wires.

previously, with the same tightening torque of 15 Nm. The specific procedure permitted quantification of the pretension loss of all four pairs of wires, both during the assembling stage and also during the loading scheme. A suitable clip gauge was attached to the "bone's" gap. The device was then submitted to axial and torsional loading-unloading loops.

In Fig. 3 the pretension of each wire before loading (i.e. during the assembling stage) is plotted, as it is represented by the axial strain. The wires of the same ring are indicated with the same colour. As it was previously observed the pretension of a specific wire decreases by about 20% just after the tensioner is removed and then it is stabilized. However, a significant increase of the wire's pretension (around 40%) is recorded when its counterpart (i.e. the second wire of each ring) is tensioned. This behaviour, systematically studied by Ryan *et al.* [3] for a single-ring fixator, is attributed to the finite stiffness of the rings: The ring is deformed from cyclic to elliptic during the pretension of the first wire and vice versa during the pretension of the second wire.

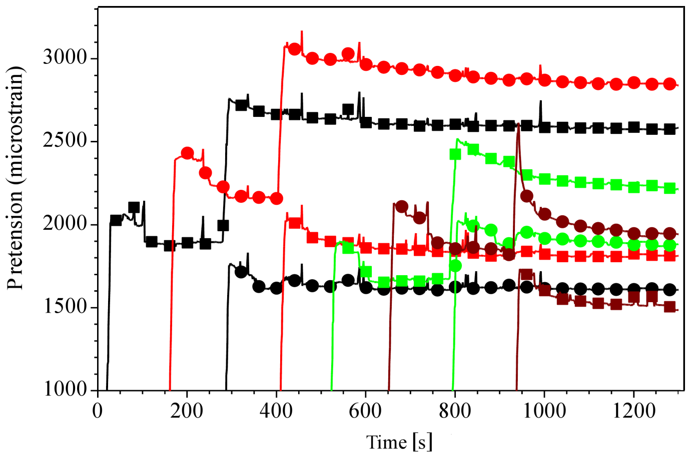

Fig. 3. Time variation of the pretension during the assembling stage.

After the pretension of the wires the assembly was subjected to compressive loading-unloading loops at three different load levels (see Fig. 4a). For each load-level three loading loops were implemented. The load-displacement curves for the above loading scheme are shown in Fig. 4a. It is interesting to observe that the response of the fixator is non-linear already from relatively low load levels. Moreover the stiffness of the system decreases with increasing load level. This behaviour could be explained considering Fig. 4b, in which the axial strain in all wires is plotted versus time. It is seen that after each loop the axial strain attains lower values (obviously due to the slip of the wires, see Fig. 1b) both at the peak and also at the minimum load level. As a result each loop starts from

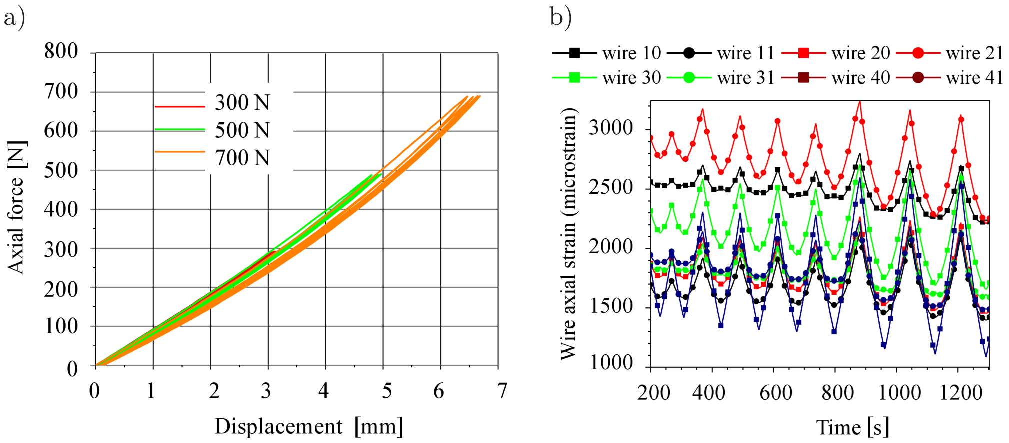

Fig. 4. The axial force versus the displacement of the "bone" (a) and the time variation of the pretension of all wires during the loading-unloading loops (b).

a lower pretension and the stiffness of the assembly degrades. The behaviour of the assembly is quite similar (qualitatively) when it is subjected to torsional loops. The specific results will be presented in a forthcoming paper [4].

3. The numerical model and its validation

A numerical model was then constructed using the Finite Element Method and the commercial software ANSYS (Fig. 5a) with special elements permitting simulation of wires' slippage. The model simulated accurately all the geometrical details of the assembly used in the experimental protocol, the load

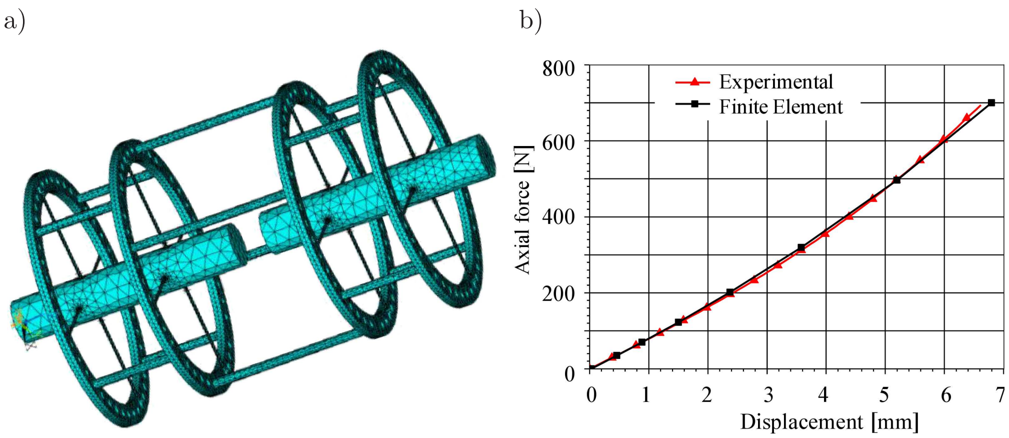

Fig. 5. The finite element model (a) and its validation according to the experimental data (b).

application mode (torsional and axial) and the mechanical characteristics of the materials. The rings were modelled as cylinders with inner and outer diameters 150 mm and 178 mm, respectively and length 4.8 mm. 44 holes were created to each ring with 6 mm radius. The rods were modelled as solid cylinders with 6 mm diameter and were rigidly attached to the rings. Both rings and rods were meshed using 8-node prismatic solid elements (solid185). They were considered as linearly elastic materials with modulus of elasticity $E = 200$ GPa and Poisson's ratio $\nu = 0.30$. The polyethylene bar was modelled as a cylinder of diameter equal to 30 mm. Cylindrical holes (1.8 mm diameter) were created to the bar for the wires to pass through. The wires were modelled as cylinders (1.8 mm diameter). The part of the wire passing through the bone was meshed with 8-node prismatic solid elements (solid185) and the remaining part with 3D quadratic beam elements (beam188). The material properties for the wires and the polyethylene bar were determined experimentally using specimens made of materials from the specific batch [2]. The stress-strain curves obtained were simulated by multilinear isotropic hardening models.

The wire-bone interfaces were modelled using contact elements so that the wires were free to slide within the bone, along the wire axis. The area of the holes of the polyethylene bar was meshed with 3D 4-node surface-to-surface contact elements (conta173) and the external area of the solid185 elements of the wire was meshed with 3D target segment elements (targe170). The wires was rigidly attached to the rings. The final model contained 56347 'solid185' elements and 152 'beam188' elements. All nodes on the lower surface of the distal "bone" were fully constrained. An axial displacement was induced to all the nodes on the upper surface of the proximal "bone".

The model was calibrated using data for the strains and validated with the aid of the "force-displacement" and the "torque-angle" experimental curves. The results were very satisfactory for the torsion and excellent concerning the axial loading (Fig. 5b).

4. Results of a preliminary parametric analysis and conclusions

The as above validated model was then used for a thorough analysis of various parameters affecting the mechanical response of the fixator. The parameters studied were the ones which according to clinical experience enhance the system's response, i.e. the rings' diameter, the initial pretension, the wires' diameter, the bone's location, the distance between the rings and the angle between the wires. Critical factors were proven to be the pretension (increase of 200 N increases the torsional stiffness by 20%), the rings' diameter (increase from 150 to 180 mm decreases the axial stiffness by 20% without increasing the torsional one) and the angle between the wires. The latter's role is shown in Fig. 6. The

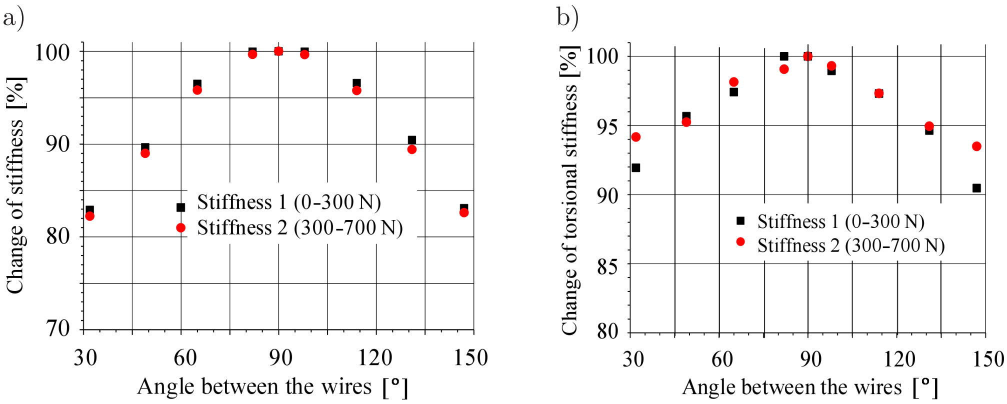

Fig. 6. The influence of the wires' angle on the fixator's axial- (a) and torsional-stiffness (b).

influence of the remaining factors was less important. The study is in progress and the overall conclusions will be included in a forthcoming paper [4].

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Received October 14, 2016; accepted version November 24, 2016.