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# Experimental analysis of external fixators for femoral bone elongation

ROMUALD BĘDZIŃSKI, JAROSŁAW FILIPIAK

Wrocław University of Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland

The purposes of this study were to analyse the stability of the system formed by the Ilizarov fixator and the thigh being elongated. The research was conducted under laboratory (tests on physical models) and clinical (tests on real objects) conditions during the process of the elongation of the femur bone. The aim of the laboratory investigation was to determine the displacement of the bone fragments as a function of the external load and construction of the fixator. The aim of the clinical study on real objects was to determine the state of the load acting on the particular supported rods of the fixator and its changes during elongation of the lower limb in the thigh section. The investigations have demonstrated that the stability of the system: the Ilizarov fixator–the thigh being elongated is a function of the mechanical properties of the adapted fixator structure and the forces acting on this system. Optimal spatial configuration of the fixator must be selected for the particular course of treatment.

*Keywords: external fixator, limbs elongation, strain gauges, speckle photography*

## 1. Introduction

The interest in the external fixation system for limbs developed by Ilizarov has been growing in the last decade. This is above all due to the high, in comparison with other fixators, effectiveness of treatment by the Ilizarov fixator of, e.g., complicated fractures of long bones, pseudarthrosis, and limb axis correction or shortening [6]. This high efficacy of the Ilizarov fixator results from, among other things, its modular design which allows one to create numerous configurations of the fixator, and to modify its spatial arrangement during treatment depending on the needs. Another advantage is that the fixator's mechanical properties are conducive to the preservation of the optimal biomechanical conditions at the place of the joint of the bone fragments. The Ilizarov fixator is a flexible stabilizer. This means that the loads acting on the bone are carried both by the fixator's structure and the place of the joint of the bone fragments, which ensures the axial dynamisation of the latter. As the examinations carried out by Geodship and Kenwight [5], and Lanyen and Rubin [8] – to mention but a few – have demonstrated axial mirco-movements of bone fragments in the fracture zone are a beneficial phenomenon, which stimulates the regeneration of the bone.

The elongation of the lower limbs is one of the more interesting, but highly complex – both in the clinical and mechanical aspects – cases of the application of the Ilizarov fixator. Though the clinical experience in the elongation of the lower extremities by means of the Ilizarov fixator is long, many disturbances and complications [11, 15] still frequently beset this process. This is particularly the case when the lower limbs are elongated in the thigh section where complex conditions of a load acting on the femoral bone in the hip joint occur in usually strongly developed muscle groups surrounding the thigh being elongated. The failures in the elongation are above all due to the still unexplained mechanisms of the effect of the fixator on the limb being elongated; and conversely, the effect of the soft tissue surrounding the treated bone on the fixator's structure.

Investigations of the mechanical properties of the Ilizarov fixator used for the elongation of shank bones are described in the literature. These are, for instance, works by: McCoy [10], Fleming et al. [3], Paley et al. [12], Podolski and Chao [14] and Będziński [2]. There are also papers by Leong et al. [9], and Wolfson et al. [16] in which changes of the forces acting on the distance rods of the Ilizarov fixator put on a patient subjected to the elongation of the lower leg are examined.

One should notice, however, that in the available literature is no information about the biomechanics of the elongation of the lower limb in the thigh section. But both the anatomic aspects and the design of the fixator mounted on the femoral bone indicate that the mechanical properties of such systems can differ from those of the systems used for the elongation of shank bones.

## 2. Aim of paper

The aim of this paper is to analyse the stability of the system formed by the Ilizarov fixator and the thigh being elongated. The size of the lateral displacements of the bone fragments has been adopted as a measure of this stability. The larger the lateral displacements of the bone fragments, the less stable the considered system, and vice versa. The research was conducted under laboratory (tests on physical models) and clinical (tests on real objects) conditions during the process of the elongation of the thigh.

The aim of the laboratory tests was to construct physical models of the system: an external Ilizarov fixator–femoral bone fragments–the soft tissue, and then to determine the displacement of the bone fragments as a function of the external load acting on the considered system and of associated selected parameters.

The goal of the clinical tests on real objects was to determine the conditions of the load acting on the particular distance rods of the Ilizarov fixator and its changes during the elongation of the lower limb in the thigh section.

## 3. Test on physical models

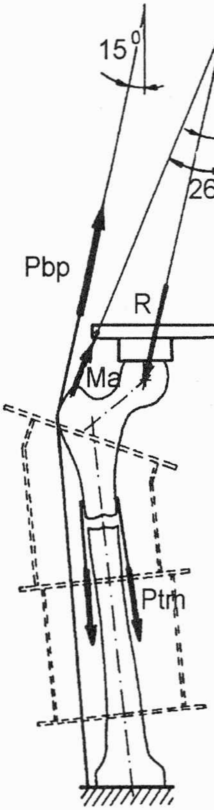

Fig. 1. A diagram of the loading system

Before the construction of a physical model of the system: the external Ilizarov fixator –femoral bone fragments–the soft tissue it was assumed that the model should be based, to as large extent as possible, on the real geometry of the analysed system and the conditions of its loading. For this reason, a freshly dissected femoral bone was used for the construction of the model. The bone was fixed at the distal part at an angle of about 9° from the perpendicular, which is a natural angle for the shaft of the femoral bone. This fixing of the femoral bone does not represent the real kinematics of the knee joint. Nevertheless, considering that the tested system's stability was to be analysed only in the frontal plane and that the knee joint's mobility in this plane is rather restricted, this simplification would not affect significantly the quality of measurements. An Ilizarov fixator – whose spatial configuration was modelled in the same way as the fixator used in the case of the elongation of the thigh carried out in the Orthopaedics Clinic of the Medical Academy in Wrocław – was mounted on the bone. This choice of a fixator allowed us to compare model test results with the observations made during the process of elongation conducted under clinical conditions. The adopted Ilizarov fixator configuration served as a starting point in producing its different variants which were obtained by changing the following parameters: span ($r$) of the implants' insertion zone, initial tension ($P_{nw}$) of the Kirchner wires, and the location of the bone's shaft osteotomy. The parameters were chosen by analysing clinical cases. After the fixator was mounted, the diaphysis was cut at a fixed point and the bone fragments were separated so that there was a 15-mm wide gap between them.

The system used for the loading of the tested model is a modified version of the system developed in our laboratory. The main component of the loading system is the first-order lever modelling the pelvic bone. The force $P_z$ – being the weight of the part of the body resting on the lower limbs (Fig. 1) – acts on one end of the lever. The force $P_z$ is balanced by the force $M_a$ coming from the thigh abductor muscles. The resultant is the force $R$ applied at the anatomic centre of the head of the femur.

The loading system incorporates also the action of the *tractus iliotibialis* ($P_{bp}$) which is believed to stabilize the hip joint and the femoral bone itself. The lower attachment of the *tractus iliotibialis* is situated on the lateral condyle of the tibia. Its upper end reaches the greater trochanter, on which it rests but to which it is not attached. The upper part of the band bifurcates. One branch becomes the *tensor fascia latae muscle* whose fibers run obliquely towards the side of the iliac spine where its attachment is situated. The other branch on the posterior side joins the tendinuous fibers of the *gluteas maximus*. In this way the iliotibial band is tensed, and moreover, the broad fascia (whose part the iliotibial band is) is tensed uniformly on its both sides by the two muscles, which prevents it from slipping off from the greater trochanter.

In the considered physical model, the *tractus iliotibialis* has been designed as a flexible connector running from the knee joint, where it is fixed, along the bone's shaft up to the pelvic bone. The flexible connector rests on the greater trochanter and it can slide on it. The action of the *tractus iliotibialis* modelled in this way produces an additional horizontal force, which stabilizes the hip joint.

An attempt was made to incorporate into the loading system the action of the reactive forces of the stretched soft tissue ($P_{tm}$). This load was realized by a flexible connector–lever system, in which flexible connectors were fixed to the bone fragment on its two sides in the frontal plane. The flexible connectors were settled along the shaft of the bone (Fig. 1).

The values of the forces applied to the flexible connectors simulating the reactive forces of the stretched soft tissue were assumed on the basis of results of clinical studies (Będziński et al. [1]).

### 3.1. Measuring method

The physical model and the loading system were quite complex, whereby the access to the bone was rather difficult. For this reason, an optical method – speckle photography – was chosen for measuring [4, 13]. This method allows one to measure displacements in an object's plane without touching anything. Figure 2 shows a system for speckle photography recording. In this measuring method, values of displacements in an object's plane are calculated using the following relationships:

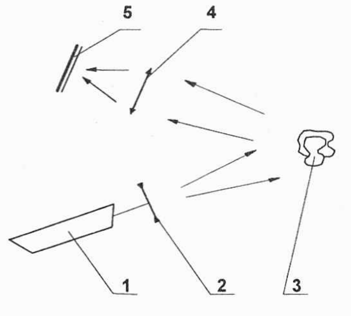

Fig. 2. A diagram of the system for speckle photography recording: 1 – laser, 2 – diverging lens, 3 – examined object, 4 – converging lens, 5 – plate coated with light-sensitive emulsion

$$d = \frac{\lambda L}{pa}, \quad u = |d| \sin\alpha, \quad v = |d| \cos\alpha,$$

where: $\lambda$ – the wavelength of the analyzing laser's light, $L$ – the distance of the screen from the specklegram, $p$ – enlargement, $a$ – the distance between spectral lines, $\alpha$ – the angle of the inclination of spectral lines.

### 3.2. Results of measurements

Displacements of bone fragments were determined as a function of the load acting on the tested system. During the measurements the values of the force $P_z$ were changed in the range from 0 to 250 N. Higher values of the force $P_z$ would produce very large displacements (larger than the diameter of the bone shaft cross-section at the height of the cut), particularly of the upper fragment, when the cut was located in the proximal part of the thigh.

The values of the force $P_{tm}$ which loaded the flexible connectors that modelled the reactive forces of the stretched soft tissue were changed from 0 to 200 N. The maximum value in this range was a mean of the tension forces in the stretched tissue recorded during measurements on real objects under clinical conditions.

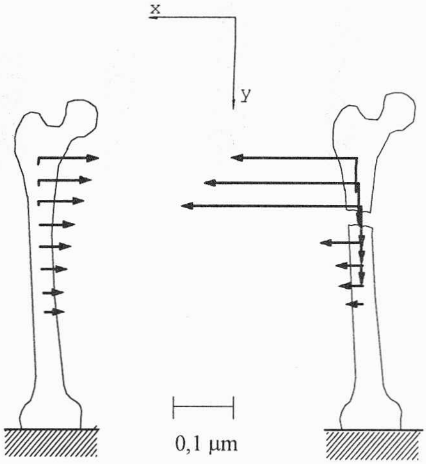

Fig. 3. Values of displacements determined for the bone before and after it was cut

Sample diagrams illustrating changes in displacements of the bone fragment as a function of the applied load ($P_z$, $P_{tm}$) and the fixator's design parameters are presented in appropriate figures. One should notice that these displacements of the bone fragment were a result of the force increment $\Delta P_z = 5$ N whose value was selected experimentally. This was determined by the peculiarities of the measuring method.

An analysis of the obtained results leads to a general conclusion that the bone fragments under the action of the assumed system of forces displace towards the external part of the thigh. The displacement of the upper bone fragment is a combination of three movements (Fig. 3): the rotation about the point coinciding with the anatomic centre of the head of the femur, the linear displacement towards the $z$-axis and the $x$-axis. Figure 3 shows displacements determined for the bone loaded with the same force system before and after osteotomy. This example illustrates the extent to which the dynamics of the bone can change after it has been cut.

Independent of the Ilizarov fixator's spatial configuration, the resultant from force increment $\Delta P_z = 5$ N the displacement of the bone fragment decreases as the initial load $P_z$ increases. When the shaft of the bone has been cut in the proximal part (1/3$L$), this displacement decreases nonlinearly, whereas when the cut is in the distal part (2/3$L$), it decreases linearly as the initial load $P_z$ increases. Once the action of the reactive force $P_{tm}$ of the stretched soft tissue is incorporated, the values of the displacements of the bone fragment go down on the average by 30% when the cut is at 1/3$L$ and by 12% for the cut at 2/3$L$; but the character of the changes remains the same (Fig. 4). When one scrutinises the influence of the initial tension of the Kirschner wires on the displacements of the bone fragment, it can be seen that as the force $P_n$ of the initial tension of the implants increases, the displacements of the bone fragment decrease (Fig. 5). Once the action of the reactive force $P_{tm}$ of the soft tissue is modelled, the difference in the effect of the implants' initial tension force on the displacements of the bone fragment becomes smaller. For example, when the force $P_{tm}$ = 0, the difference in the displacements of the bone fragment for the extreme values of the initial tension force, i.e. 500 N and 1100 N, is about 26%, and for the action of force $P_{tm}$ = 200 N this difference decreases to about 20%.

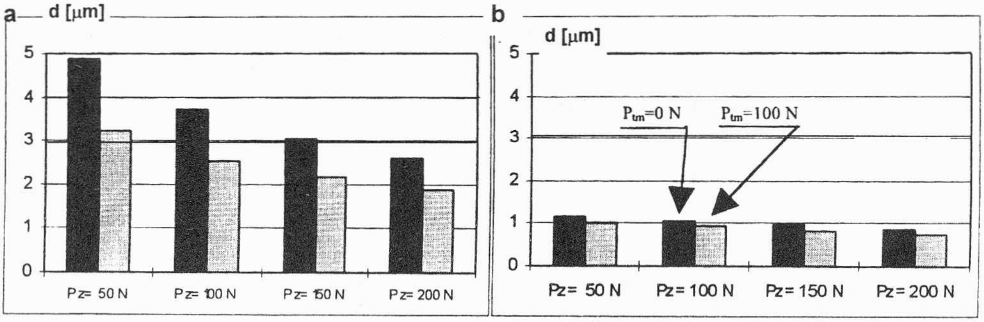

Fig. 4. Typical displacements of the bone fragment as a function of external load $P_z$ and soft tissue reactive forces $P_{tm}$: a) the cut at 1/3$L$, b) the cut at 2/3$L$

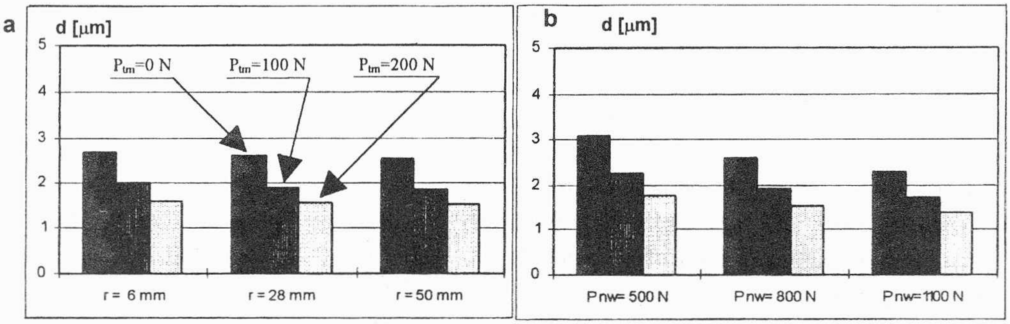

Fig. 5. Displacements of the bone fragments as a function of design parameters: a) the span $r$ of the implant's insertion zone, b) the initial tension $P_n$ of the implants, $P_{tm}$ – force of the soft tissue

The span of the implant's insertion zone has much smaller effect on the displacements of the bone fragment. The difference in these displacements for the extreme values of the considered parameter, i.e. 6 mm and 50 mm, amounts to 6.5%. The influence of this parameter becomes even smaller when the reactive forces $P_{tm}$ of the stretched soft tissue are taken into account (Fig. 5).

The location of the femoral bone cut turns out to be the factor, which determines to the largest degree the displacement of the bone fragment. A comparison of cases where the cut is in the proximal part (1/3*L*) with the ones where the cut is in the distal part (2/3*L*) shows that in the latter case, the displacements of the bone fragment are on an average 70% smaller than in the former case.

## 4. Test on real objects

The tests were conducted in the Orthopaedics Clinic of the Medical Academy in Wrocław. They consisted in the recording the forces in the distance rods of the Ilizarov fixators mounted on patients undergoing thigh elongation. The forces were measured in all the rods connecting the rings between which the bone's shaft had been cut. In contrast to other research centers [7, 9, 16], the changes in the forces were recorded and analyzed separately for each distance rod. It was presumed that knowing the load patterns for the particular rods and their distribution around the bone being elongated, it would be possible to determine which groups of muscles acted stronger, and which, weaker on the system: the bone fragments–the Ilizarov fixator, and how these actions change during the whole process of elongation.

### 4.1. Measuring method and procedure

Specially adapted extensometer converters built into the distance rods of fixators mounted on patients undergoing thigh elongation were used for the measurements of

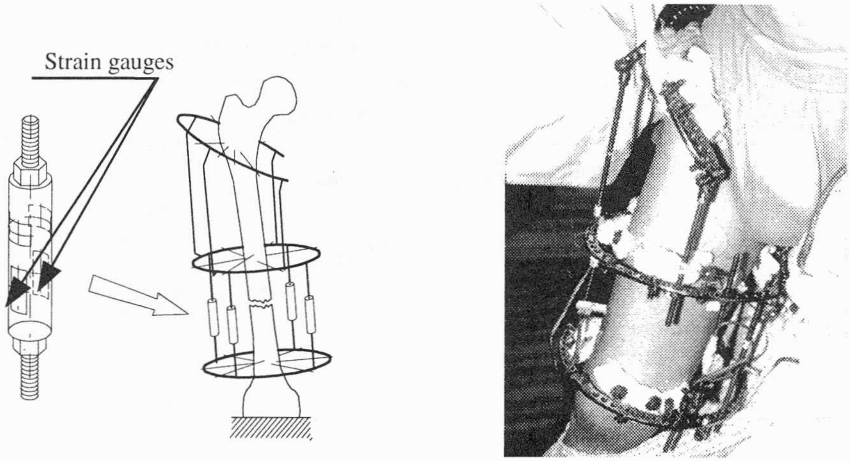

Fig. 6. Force transducers and their localisation in distance rods of external fixator

the forces acting in the distance rods (Fig. 6). The measurement covered ten cases of thigh elongation by the Ilizarov fixator. Measurements were made once a day at a fixed time, immediately before and after the application of a distance rod length increment. To achieve possibly the highest repeatability of measurement conditions, indications of the instrumentation amplifier were recorded in the same position assumed by the patient each time. During the measuring the patient remained in the erect position so that his/her weight rested on the healthy, not-to-be-elongated lower limb, and the one that was being elongated was hanging loosely.

### 4.2. Results of measurements

Figures 7 and 8 show typical variations in distance rod loads as a function of time recorded for selected cases. An analysis of the results recorded for the particular cases shows that in most of them, the increments of forces in neighbouring rods were similar both in their character and in the variation of their values. On the basis of this observation, calculations were made which yielded fractions for pairs of rods dominant in the carrying of loads acting on the bearing elements of the Ilizarov fixator. The fractions can be expressed by the following general relationship:

$$u_d = \sum_{d=1}^{2} P_d \Big/ \sum_{i=1}^{4} P_i ,$$

which means that the value of this fraction is equal to the ratio of the sum of the increments of forces in a pair of dominant rods (e.g. medial or external, anterior or posterior) to the sum of the increments of forces in all the distance rods. The defined in this way fractions were calculated for each day of the elongation process in all the investigated cases. Then regression functions defining the changes of the fraction $u_d$ in time were determined for each of the cases. These regression functions have been compiled in the Table.

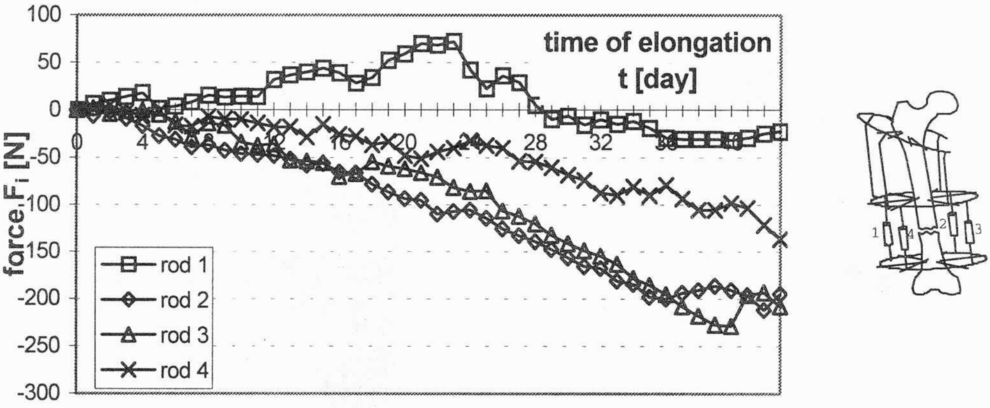

Fig. 7. Distraction load measured in function of time; Patient 5, rate of elongation: 4×0.25mm per day

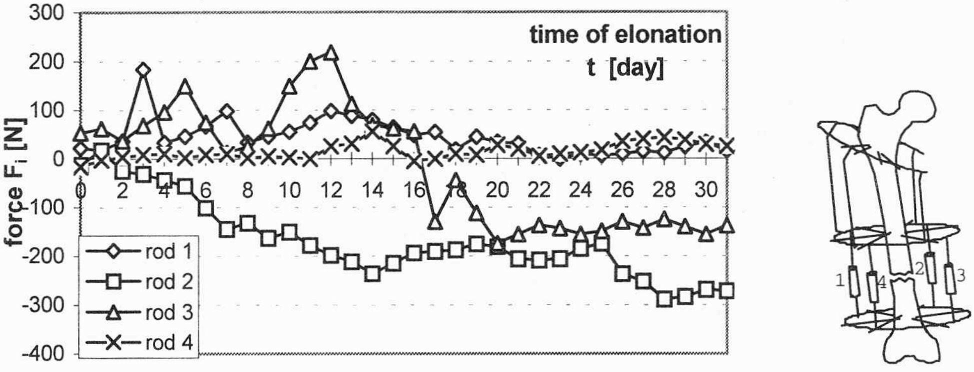

Fig. 8. Distraction load measured in function of time; patient 7, rate of elongation: 4×0.25 mm per day

Table. Regression functions illustrating the changes of the ratio $u_d$ in time determined for the investigated cases

| Patient | Fraction* | Curve equation | Equation coefficients | Correlation coefficient R | $R^2$ [%] |
|---|---|---|---|---|---|
| Pat. 1 | $u_z$ | $u_z = a + b\,t$ | $a = 0.805$<br>$b = -2.083\cdot10^{-3}$ | 0.86 | 74.77 |
| Pat. 2 | $u_w$ | $u_w = a\,t^b$ | $a = 0.425$<br>$b = 0.072$ | 0.91 | 82.88 |
| Pat. 3 | $u_w$ | $u_w = a\,t^b$ | $a = 0.433$<br>$b = 0.109$ | 0.89 | 79.21 |
| Pat. 4 | $u_z$ | $u_w = a\,t^b$ | $a = 0.447$<br>$b = -0.096$ | 0.88 | 77.41 |
| Pat. 5 | $u_w$ | $u_w = a\,t^b$ | $a = 0.621$<br>$b = 0.055$ | 0.82 | 67.55 |
| Pat. 6 | $u_p$ | $u_w = a\,t^b$ | $a = 0.312$<br>$b = 0.074$ | 0.92 | 85.87 |
| Pat. 7 | $u_w$ | $u_w = a\,t^b$ | $a = 0.468$<br>$b = 0.126$ | 0.88 | 78.15 |
| Pat. 8 | – | – | – | – | – |
| Pat. 9 | $u_w$ | $u_w = a\,t^b$ | $a = 0.559$<br>$b = 0.136$ | 0.90 | 81.06 |
| Pat. 10 | $u_w$ | $u_w = a\,t^b$ | $a = 0.891$<br>$b = -0.142$ | 0.875 | 76.56 |

[*] $u_w$ – a ratio of the sum of the force increments recorded in the medial rods to the sum of the force increments in all the rods. $u_z$ – a ratio of the sum of the force increments recorded in the external rods to the sum of the force increments in all the rods. $u_p$ – a ratio of the sum of the force increments recorded in the anterior rods to the sum of the force increments in all the rods.

In five cases it was found that the rods situated on the medial side of the thigh were more loaded than the external ones. For these cases, the ratio $u_w$ of the increments in the forces acting in these rods to the sum of the force increments in all the rods was following an exponential curve during the elongation, and its value was growing in time. The above cases differed in the spatial configuration of the Ilizarov fixator, but their common feature was that the bone shaft cut was located in the distal part. It is also characteristic that in this group of cases, the relative transverse displacements of the bone fragments did not exceed 4 mm during the whole process of elongation. The displacements were determined on the basis of the X-ray pictures (which were taken regularly every few days during bone elongation, depending on the needs of the treatment). Taking into account the results of the measurements and the positive clinical evaluations of the course of elongation in the considered group of five cases, one can assume that the curves in Fig. 9 – illustrating the time-dependent changes of the ratio of the sum of the increments of the forces in the medial rods to the sum of the force increments in all the distance rods – represent a set characterising those cases of thigh elongation whose course was correct.

The force increments recorded in the distance rods of the Ilizarov fixators were produced by the reactive forces of the surrounding soft tissue stretched together with the regenerated bone. Therefore one can assume that there is a relationship between the distribution of force increments in the pairs of rods situated on both sides of the elongated bone in the frontal plane and the proportion of the distribution of the reactive forces of the stretched soft tissue to the longitudinal axis of the thigh bone in the frontal plane. If this is so, one can assume that higher values of the reactive force of the soft tissue are found on the medial part of the thigh. This is validated by the pres-

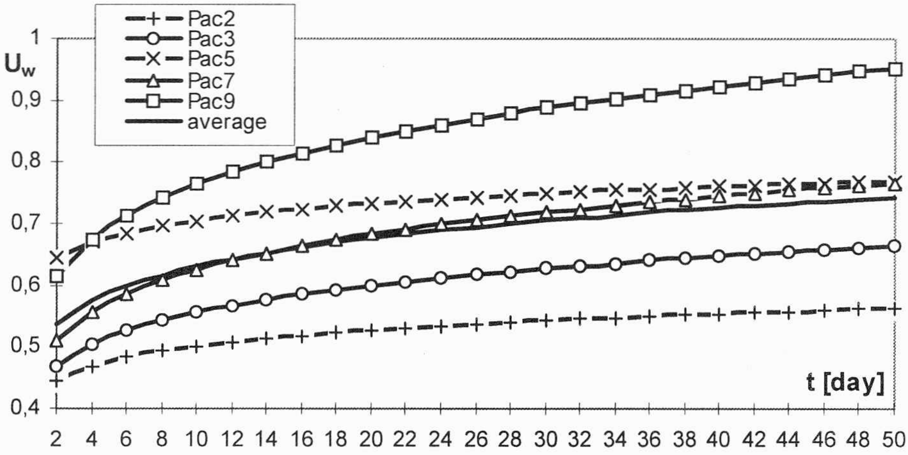

Fig. 9. Changes of the ratio ($u_w$) of the increments of the forces vs. time

ence of the group of shank flexor muscles in the thigh's medial part. These are diarticular muscles whose upper attachments are located on the pelvic bone, and the lower attachments are on the tibial bone. The muscles are a chord of the arc formed by a part of the pelvic bone, the femoral bone, and the condyles of the tibia. After the cutting of the femoral bone (e.g., in the distal part of the shaft) and the gradual pulling away of the bone fragments from one another, the reactive force of these muscles increases. As a result, the bone fragments are being displaced towards the outside of the arc. This is corroborated by the higher values of forces recorded in the distance rods situated on the medial side of the thigh.

## 5. Recapitulation

The investigations carried out both under laboratory conditions (on physical models) and under clinical conditions (on real objects) provided a basis for an analysis of the effect of the factors involved in the system: the Ilizarov fixator–the thigh being elongated on the stability of this system. For the first time the problem associated with the elongation of the lower limb in the thigh section has been considered so extensively. The available literature on the subject is rather scanty. Usually these are papers of a medical nature, devoted to, among other things, the practical application of the Ilizarov fixator to the treatment of shortenings of the lower limbs at the height of the thigh. Most often this literature describes statistically different methods of treatment, outcomes of the elongation process, and possible failures. Such deliberations, however, do not explain the biomechanics of the collaboration between the fixator's construction and the segment of the limb, which is being elongated.

The investigations have demonstrated that the stability of the system: the Ilizarov fixator–the thigh being elongated, measured in values of the transverse displacements of the bone fragments, is a function of both the mechanical properties of the adopted fixator structure and the distribution of the forces acting on this system.

The obtained results allowed us to determine the effect of particular geometric parameters, i.e. the initial tension of the Kirschner wires, the span of the implants insertion zone, and the location of the bone shaft cut, on the stability of the analyzed system. The tests have shown that higher values (in the order of 1000–1100 N) of the initial tension of the implants result in increased stability of the system: the Ilizarov fixator–the thigh being elongated. A similar effect, though to a lesser degree, is observed when the span of the implants insertion zone is extended. The tests, carried out both on physical models and under clinical conditions, have demonstrated that the location of the bone fracture is an extremely important parameter for the system: the fixator–the thigh being elongated. It should be stated that when there are no indications, it is more beneficial for the considered system to fracture the femoral bone in its distal part. This location of the fracture results in smaller undesirable transverse displacements of the bone fragments, due to external and internal forces, than when the fracture is situated in the proximal part of the thigh.

The clinical studies allowed us to determine the distribution of loads in the particular distance rods of the Ilizarov fixator and the variation of the loads as a function of the elongation time.

The clinically developed and applied measuring method allows one to control continuously the correctness of the course of the elongation of the limb by analysing the conditions of the loading of the particular rods of the Ilizarov fixator and the changes of these loads as a function of the elongation time.

The studies conducted under clinical conditions have indicated that the preliminary assessment of the patient's physical condition – above all the degree to which the muscles surrounding the bone to be elongated are developed and trained, whether scars and pathological changes are present – is of major importance. When the mechanical properties of the soft tissue have been taken into account, and the effect of internal and external forces on the stability of the considered system is known, then the optimal spatial configuration of the fixator can be selected for the particular course of treatment. This means that in clinical practice the adopted goal will be achieved in the shortest time without complications.

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