Acta of Bioengineering and Biomechanics
Vol. 14, No. 1, 2012

Original paper

The impact of the type of derotation mechanism on the stiffness of the Ilizarov fixator

PIOTR MORASIEWICZ[1]*, JAROSŁAW FILIPIAK[2], MARCIN KONIETZKO[2], SZYMON DRAGAN[1]

[1] Department and Clinic of Orthopaedic and Traumatologic Surgery, Wrocław Medical University, Poland.
[2] Division of Biomedical Engineering and Experimental Mechanics, Wrocław University of Technology, Poland.

One of the applications of the Ilizarov apparatus is the correction of rotational deformities. There are several types of designs commonly used for derotation. Different types of derotators have different mechanical properties, which affect the stability of the entire Ilizarov apparatus. The aim of this study was to determine the stiffness of the Ilizarov fixator depending on the type of derotation mechanism. We analyse three types of derotators: the type Z, the type H, and the cubicoid derotator. The tests were conducted on physical models in which the fixator analysed was fitted to polyethylene pipe segments. The reference fixator was the Ilizarov apparatus in the configuration adapted for thigh lengthening. The pipe segments intersected at a point corresponding to the osteotomy site of the distal thigh. The fixator was assembled with one proximal arch fixed with two Schanz screws, a proximal ring fixed with two Kirschner wires (K-wires), a middle free ring, and a distal ring fixed with three K-wires. There were three different types of derotation mechanisms installed between the proximal and middle rings. We determined the axial stiffness k_A and the transverse stiffnesses of the compared fixators in two planes: frontal $k_{M–L}$ and sagittal $k_{A–P}$. The results of the research lead to two basic conclusions. Firstly, the use of any of the derotators analysed has no negative impact on the stiffness of the Ilizarov apparatus. Secondly, similar stiffness values of the fixators with different derotation mechanisms suggest their equal applicability and the choice between them can be made based on practical considerations. In the case of axial stiffness, the differences do not exceed 7.5%. The highest value of stiffness k_A was obtained for the type H derotator, while the lowest value was obtained for the type Z derotator. There is a greater difference in the case of transverse stiffness in the sagittal plane, which only concerns the fixator with the type Z derotators. The stiffness coefficient $k_{A–P}$ for that fixator is lower by approximately 19% compared to the reference fixator.

Key words: *Ilizarov external fixator, bone fragments derotation, bone elongation, fixator stiffness*

1. Introduction

The method of distraction osteosynthesis developed by Ilizarov is increasingly being used all over the world [3]–[5], [8], [10]–[12], [18]. One of its many applications is the treatment of rotational deformities [13]–[16], [19]. Rotational deformities are diagnosed ever more often but they are seldom treated due to the structural complexity of the Ilizarov apparatus after the addition of derotation mechanisms, the need for precise assembly and installation of the fixator on the patient, and the greater likelihood of treatment complications. There are several types of derotators, of which the most frequently used are the type Z, the type H (originally used by the Russians), and the cubicoid derotator made by Master-Med (MM). An external fixator installed on the lengthened limb segment forms a complex biomechanical system affected by external forces resulting from the influence of the gravitational field and internal forces coming from soft tissues reacting to lengthening. Such a system is characterised by certain mechanical properties, usually described by means of stiffness coefficients. The stiffness coefficients and the values of the forces acting on the treated limb segment defined for a given

---

* Corresponding author: Piotr Morasiewicz, Department and Clinic of Orthopaedic and Traumatologic Surgery, Wrocław Medical University, ul. Borowska 213, 50-556 Wrocław, Poland. Tel.: +48-71-734-32-00, e-mail: morasp@wp.pl

Received: December 12th, 2011
Accepted for publication: March 1st, 2012

fixator configuration determine the kinematics of bone fragments. The amount and direction of bone fragment displacements are associated with the biomechanical conditions in the bone regenerate, which determine whether or not the treatment process will progress in an optimal manner. Cyclic displacements of bone fragments oriented in the direction of elongation are a factor generating mechanical stimuli advantageous from the viewpoint of proliferation and differentiation of the tissues in the regenerate. However, excessive axial displacements of over 2 mm and displacements in the transverse direction have an adverse effect on the formation of the bone regenerate in the distraction area [3], [7], [9], [10]. The above-mentioned types of derotators are characterised by different structural designs, which also translates into differentiation of their mechanical properties. There is no doubt that installation of a particular derotator type in the Ilizarov fixator will affect the mechanical parameters of the whole fixator structure. Corrections of rotational deformities are accompanied by torsional displacements of bone fragments, making the biomechanics of the regenerate even more complicated. Torsional displacements result in shear stresses that occur additionally in the regenerate, which can potentially lead to damage to the regenerating nutritive microcirculation of bone tissue. For this reason, in the case of corrections of rotational deformities, it is important to obtain appropriate stiffness parameters for the fixator structure. The aim of this study was to carry out a comparative experimental analysis of the mechanical properties of three Ilizarov fixator designs fitted with different derotators, i.e., the type Z, the type H, and the cubicoid type made by Master-Med. We analysed the case of the fixator configured appropriately for the task of the lengthening of the lower limb in the femoral segment. To the best of our knowledge, there are no works in the global literature examining the stiffness of the Ilizarov apparatus in relation to the type of the derotator applied.

2. Material and method

The tests were performed on physical models, in which comparable fixator designs were fitted on polyethylene pipe segments, modelling fragments of a femur being lengthened. We built four models of the Ilizarov apparatus, including a reference model without a derotator. The basic fixator design (the reference fixator) consisted of one proximal arch fixed with two Schanz screws, a proximal ring fixed with two K-wires, a middle free ring, and a distal ring fixed with three K-wires (figure 1). The site of inserting the K-wires and the Schanz screws into the bone fragments and their spatial layout were chosen taking into account the arrangement of anatomical structures of the thigh. In all the models, the K-wires were pretensioned (F_W) with the same force of 900 N, which was applied by a special torque tensioner. Wire tension was checked and adjusted before each test. The K-wires and the Schanz screws were fixed identically on all the models. The outer diameter of all rings was 195 mm, the diameter of the K-wires was 2 mm, and the diameter of the Schanz screws was 5 mm. The rings were made of 316L steel, as were the K-wires, whereas the Schanz screws were made of Ti6Al4V alloy.

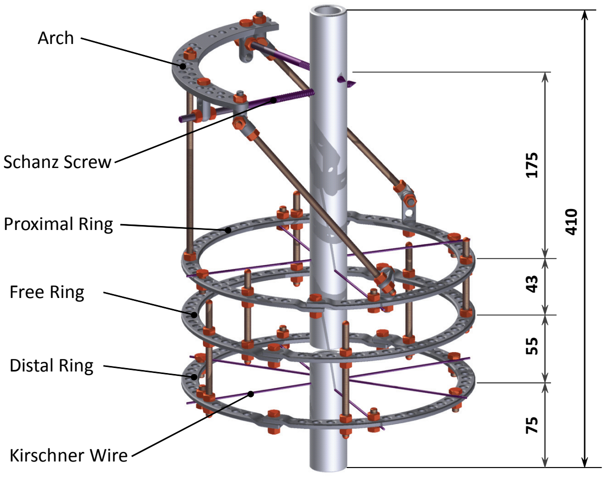


Fig. 1. Reference external fixator
– its structure and basic dimensions

A set of derotators was installed between the proximal and middle rings. In each of the cases analysed, the derotator set consisted of three derotation mechanisms of a specific type, evenly spaced every 120° on the circumference of the rings. The bone fragments were aligned coaxially with the rings. The symmetrical assembly of the derotators and coaxial arrangement of the bone fragments in relation to the rings served to minimise the translational displacements during derotation. In the tests, we analysed three types of derotators. The first derotation mechanism, the type Z (figure 2a), is built of a transversely threaded rod placed parallel to the rings and two vertical two-hole male connectors, one of which is fixed to the upper ring, and the other to the lower ring. The second derotation mechanism, the type H (figure 2b), consists of a threaded rod placed vertically, whose one end is connected perpendicularly to the free ring, while the other end is terminated with a slider enclosing the distal ring. On the rod there is a sleeve

a) b) c)

Fig. 2. Structures of the derotators analyzed: a) type Z, b) type H, c) cubicoid (MM)

(bushing) that can rotate about its axis. The sleeve is connected to a threaded rod running parallel to the plane of the rings. Its other end is fixed to a two-hole male connector attached to the distal ring. The third type of derotator is a translation and rotation device made by Master-Med (MM) (figure 2c). It consists of a rectangular enclosure made of aluminium alloy, with a hollow oval opening. Inside it there is a screw mechanism. The dial-powered mechanism provides smooth control of the angular displacement of adjacent rings connected to the derotator. This derotator type enables derotation within the range of 15°.

The three fixator models with derotators and the reference fixator were mounted on a polyethylene pipe segment, in which "osteotomy" was performed in the distal femur and the length ratios of the fragments were adopted as 3:1, which is characteristic of a case of limb lengthening at the level of the femoral segment in the distal part. The size of the interfragment gap was set at 10 mm.

It was assumed that the mechanical characteristics of the fixator would be described by the coefficient parameters of axial stiffness k_A and flexural stiffness determined in the sagittal k_{A-P} and frontal k_{M-L} planes. The stiffness coefficients were defined as the ratio of the load to the resultant displacement: $k_A = F_A/z$, $k_{A-P} = M_{A-P}/x$, and $k_{M-L} = M_{M-L}/y$.

In order to determine the stiffness coefficients, the physical models created were subjected to axial force F_A or bending moment $M_{M-L} = F_{M-L} \cdot a$ in the frontal plane and bending moment $M_{A-P} = F_{A-P} \cdot a$ in the sagittal plane, according to the diagrams presented in figure 3. The measurements were performed on an MTS MiniBionix 858 loading station. The course of each measuring test and measuring data acquisition were controlled by means of a FlexTest controller made by MTS. The fixators tested were mounted on the station using special purpose instrumentation appropriate for the executed specific loading condition. The loading was applied by means of an MTS 242.02 hydraulic actuator with the travel range of 100 mm. The force of reaction of the physical models tested was measured with the use of an MTS 661.19F-03 extensometer force transducer within the nominal range of ±1.5 kN. Displacements of bone fragments were measured with an MTS 630.12-50 extensometer with the measuring range of 12.5 mm.

Before the actual test each of the fixators tested was subjected to cyclically variable loads in order to

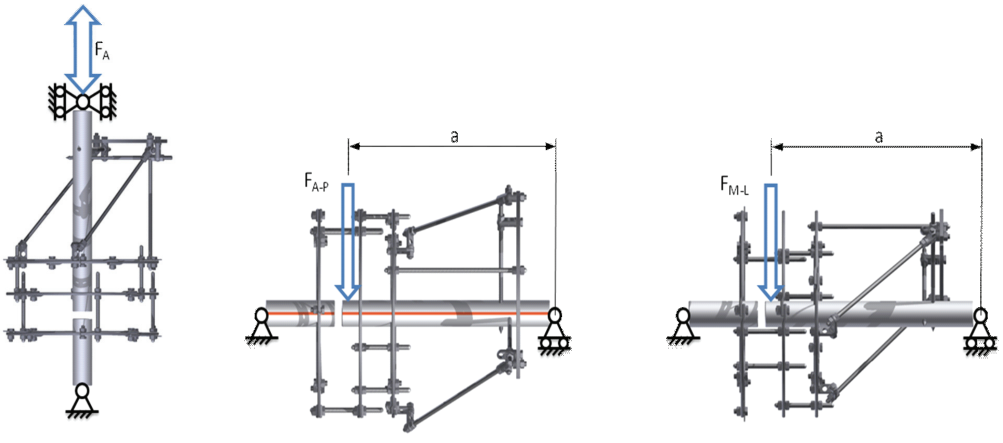
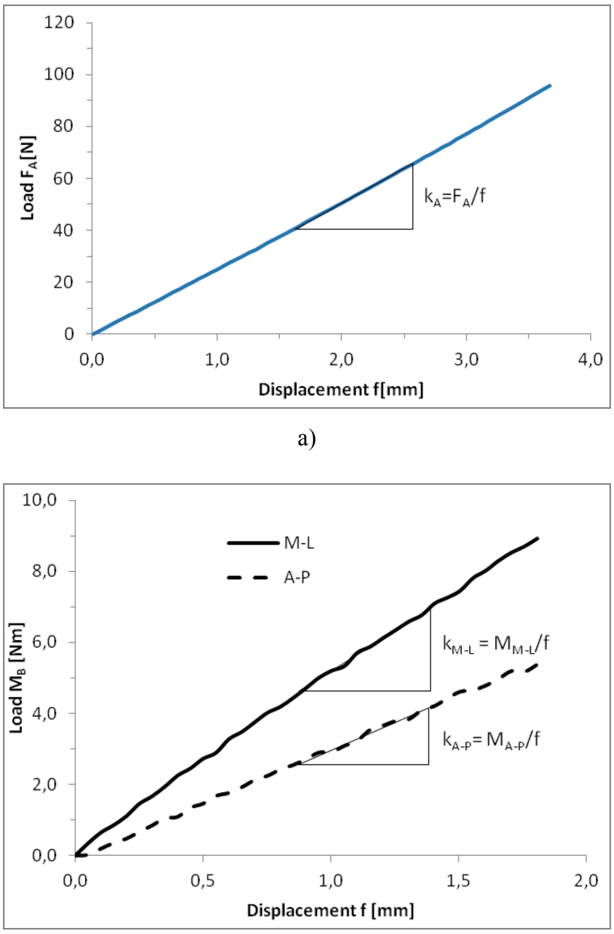


Fig. 3. The physical model of external fixator – bone fragments' system and scheme of the loading set up

eliminate the influence of assembly stress on the fixator structure. In each case, 200 cycles of the sinusoidally variable loads were applied at an amplitude equal to the maximum force and the frequency of 1 Hz. The second stage was the actual test, in which the fixators tested were subjected to quasi-static loading. In the case of the axial stiffness test, the force F_A was applied until axial displacement of the fragments reached 3 mm. In the case of the bending test, transverse loading (F_{A-P}, F_{M-L}) was continued until displacement of the loaded fragment reached 2 mm. During the bending tests the force loading the system examined was applied to just one, longer fragment. Such a procedure was due to the asymmetry of the structure of the fixator tested and the associated uneven length of the fragments modelling osteotomy in the distal thigh. In each case, the loading force increased at a constant speed of 10 N/s. During the measurements we recorded the values of displacement of the fragment in the direction of the force and the value of that force. The measurements were repeated five times ($N = 5$) for each of the models examined.



a)

b)

Fig. 4. Examples characteristics of the force–displacemnet recorded for the references external fixator:
a) during the axial stiffness k_A determination,
b) during the flexural stiffness k_{M-L} and k_{A-P} determination

3. Results

The tests conducted determined the values of axial and transverse stiffness of the Ilizarov fixator in the configuration applied to the lengthening of the femoral segment of the lower limb, depending on the derotator used. In the case of fixators with the type Z and the type H derotators, we considered two configuration scenarios that differed in their derotation range, i.e., up to 15° and up to 30°. In the case of the fixator equipped with the type MM derotator, due to design limitations we considered one configuration enabling derotation of fragments by a 15° angle.

Based on the measurements conducted we determined the characteristics that showed how displacement changes depended on the load applied (figure 4). Those characteristics enabled us to determine the stiffness coefficients: k_A, k_{A-P}, and k_{M-L} (figures 5–7).

The values of axial stiffness of the fixators examined range from 24.5 N/mm to 28 N/mm, which is typical of the Ilizarov fixator design used to elongate the lower limb in the femoral region [6], [20]. Comparison of the results obtained shows that only the fixator equipped with the type Z derotator reaches a value of the coefficient k_A which is lower than the value characteristic of the design of the reference apparatus (figure 5). In the case of the fixator with a derotator in the Z-15 configuration, that difference is just 2.3%, whereas for the Z-30 configuration it can be as high as 5.1%. In the case of the fixator with the type H-15 derotator, we can observe a 7.2% increase in the axial stiffness. In the case of the MM derotator, the values of the coefficient k_A are comparable to the reference design.

We observe a similar situation in the case of the transverse stiffness coefficient determined in the sagittal plane ($A–P$). The fixator fitted with the type Z-15 derotator is characterised by the coefficient k_{A-P} lower by 19% than the value determined for the reference fixator. The same fixator in the Z-30 configuration reaches the value of the coefficient k_{A-P} comparable to the reference fixator (figure 6). The highest value of the transverse stiffness in the sagittal plane is demonstrated by the fixator with the MM derotator, which is 5.2% higher than that of the reference fixator. Similarly, in the case of the transverse stiffness coefficient in the frontal plane ($M–L$), the fixator with the type MM derotator shows the value 8% higher compared to

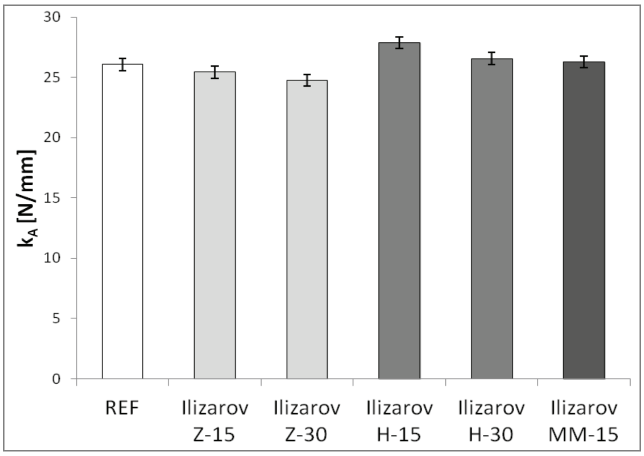


Fig. 5. Axial stiffness coefficient k_A (N/mm) determined for tested external fixators with compared derotators ($p < 0.05$)

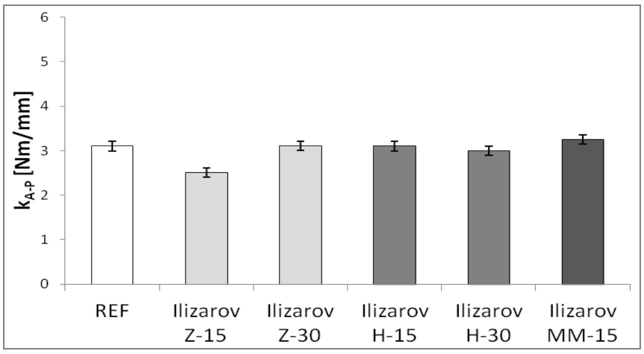


Fig. 6. Flexural stiffness in sagittal plane k_{A-P} (Nm/mm) determined for compared external fixators ($p < 0.05$)

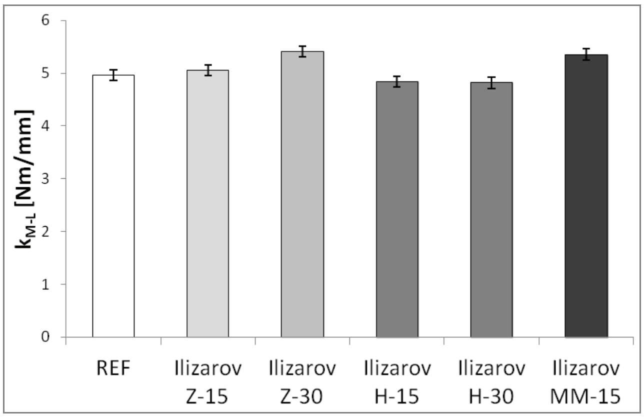


Fig. 7. Flexural stiffness in frontal plane k_{M-L} (Nm/mm) determined for compared external fixators ($p < 0.05$)

that of the reference fixator (figure 7). However, the highest increase in the value of the stiffness coefficient k_{M-L} can be observed in the fixator with the type Z-30 derotator, where it amounts to 8.5%. The lowest stiffness k_{M-L} was obtained by the H-15 fixator, where it was just 2.5% lower than that of the reference fixator.

4. Discussion

In literature, there is little description of correcting rotational deformities using the Ilizarov method. Those are mostly clinical reports, presenting treatment methods and outcomes. In the global literature, there are no papers dealing with the results of the studies on mechanical properties of the Ilizarov fixators equipped with derotation mechanisms. The results obtained show that the use of one of the three derotators analysed has a small effect on the mechanical properties of the Ilizarov fixator in a configuration intended for lengthening the femoral segment of the lower limb. This statement applies in particular to the value of the axial stiffness coefficient. In this case, the differences are small and do not exceed several percent. From a practical point of view such a result should be considered to be positive because incorporation of the derotator module in the fixator structure does not change its stiffness in the axial direction. This means that biomechanical conditions in the regenerate are not subject to change and the axial mechanical stimulation will take place with the intensity comparable to that of the reference fixator. On the other hand, the analysis of transverse stiffness coefficients shows an increase in their values in the case of the fixators equipped with derotators. This increase ranges from several to almost twenty percent. One exception is the fixator with the type Z derotator, but only in the Z-15 version (figure 6). Higher values of transverse stiffness of the fixators with derotators should be regarded as a positive effect because higher transverse stiffness provides a better stabilisation of the fragments. Although the impact of transverse displacements of bone fragments is not yet fully understood, the dominant view is that displacements of bone fragments in the horizontal plane must be minimised [1], [2], [17]. Good transverse stability of the Ilizarov apparatuses with derotators creates in the bone regenerate the area of the biomechanical conditions conducive to correct development and differentiation of bone structures. This is especially important in the case of limb lengthening in the femoral segment where, in contrast to the lower leg, the anatomical and mechanical axes do not coincide. The literature shows that the values of axial and transverse stiffness of an external fixator are significantly affected by a set of parameters associated with the implants, and in particular their spatial location [9], the amount of pretension of the K-wires and the uniformity of their tension [12] as well as the possibility of joint application of hybrid implant systems, i.e., K-wires and Schanz screws in one design [3], [6], [20]. While installing additional elements in the Ilizarov fixator structure in the form of derotation mechanisms, care must be taken that that they do not limit the ability of optimal spatial configuration of the implants. Taking the above into account, the best results are obtained by the type Z derotator. Derotators of the type H and the type MM require more space for their installation and operation, which in practice usually forces a suboptimum distribution of the implants.

It is interesting to compare the stiffness of the fixators equipped with derotators of one type but adapted to different angular ranges of derotation, i.e.: 15° and 30°. Specifically, in the case of axial stiffness, irrespective of the type of derotator, those differences are small (at a level of 3%). Significant differences appear in the case of transverse stiffness of the fixator with the type Z derotator. Interestingly, transverse stiffness of the fixator in the case of Z-30 is higher than that in the case of Z-15. The value of the coefficient $k_{A–P}$ is higher by more than 19%, and the value of the coefficient $k_{M–L}$ is higher by 7%. Such a result for the fixator with the type Z derotators points to favourable mechanical properties of that fixator enabling one-step treatment in a wide derotation range (at a level of 30°). Clinical observations show that one-stage treatment of rotational deformities provides a better outcome compared to two-stage treatment.

The practical aspects of applying the analysed types of derotators also seem to be important. The type Z derotator offers the following advantages: simple design, quick assembly, and the ability to correct a large rotational deformity. It is relatively easy to use by the patient, as it requires just three steps to perform a derotation. Operation of the type H derotator requires taking five steps due to its significantly more complex design. Cubicoid derotator MM made by Master-Med is a complex design which, however, is easy to assemble and by far the easiest one to use by the patient. Its drawback is the ability to correct only a small rotational deformity within the range of up to 15 degrees.

The results of the tests conducted lead to two basic conclusions. Firstly, the use of any of the derotators analysed has no negative impact on the stiffness of the Ilizarov apparatus, creating favourable biomechanical conditions for the formation of the bone regenerate. This may help to shorten the treatment time and to reduce the risk of complications as well as provides better outcome and increases patient satisfaction. Secondly, similar stiffness values of the fixators with different derotation mechanisms suggest their equal applicability. However, on the basis of the determined stiffness parameters we can attempt to formulate some application preferences for the derotators analysed. In the case of small rotational deformities, it is advisable to use the type MM fixation clamp derotators because they are very easy to use by the patients, highly stabile, and simple to install. After correction of large rotational deformities (up to 30°) it is advisable to use the type Z derotators. The use of the type H derotators is least favourable from a practical point of view, mostly due to their complicated design, difficult assembly, and laborious operation, each time requiring the performance of five steps.

In this paper, we presented the results of the first stage of a research project on derotation of bone fragments during the process of lower limb lengthening in the femoral region. In the next stage of the research, we plan to determine the values of the circumferential forces generated during the performance of derotation in clinical setting. In our opinion, the test results will enable optimisation of the fixator design in order to ensure the most favourable biomechanical conditions in the bone regenerate.

References

[1] ARO H.T., WAHNER H.T., CHAO E.Y., *Healing patterns of transverse and oblique osteotomies in the canine tibia under external fixation*, Journal Orthopaedics Trauma, 1991, 5, 351–364.

[2] AUGAT P., BURGER J., SCHORLEMMER S., HENKE T., PERAUS M., CLAES L., *Shear movenent at the fracture site delays healing in a diaphyseal fracture model*, Journal of Orthopaedic Research, 2003, 21, 1011–1017.

[3] BARAN O., HAVITCIOGLU H. et al., *The stiffness characteristics of hybryd Ilizarov fixator*, J. Biomech., 2008, 41, 2960–2963.

[4] CATAGNI M. et al., *Cosmetic bilateral leg lengthening*, J. Bone Joint Surg. Br., 2005, 87, 1402–1405.

[5] CHOI I. et al., *Correction of the genu recurvatum by the Ilizarov method*, J. Bone Joint Surg. Br., 1999, 81, 769–774.

[6] FILIPIAK J., MORASIEWICZ L., *Assessment of the effect of hybrid implant systems in the Ilizarov fixator on stability of fragments of the femur subjected elongation*, Acta Bioeng. Biomech., 2001, 3, 15–24.

[7] FILIPIAK J., KRAWCZYK A., MORASIEWICZ L., *Distribution of radiological density in bone regenerate in relation to cyclic displacements of bone fragments*, Acta Bioeng. Biomech., 2009, 3, 3–9.

[8] GROSS R., *Leg lengthening*, Lancet, 1999, 354, 1574–1575.

[9] GRUBOR P., GRUBOR M., ASOTIC M., *Comparision of stability of different types of external fixation*, Med. Arhc., 2011, 65, 157–159.

[10] ILIZAROW G.A., *The tension–stress effect on the genesis and growth of tissues*. Part I. *The influence of stability of fixation and soft-tissue preservation*, Clin. Orthop. Relat. Res., 1989, 238, 249–281.

[11] KĄCKI W., TĘSIOROWSKI M., ZARZYCKA M. et al., *Wydłużanie podudzia metodą Ilizarowa*, Chir. Narządów Ruchu. Ortop. Pol., 1994, Supl. 1, 111–114.

[12] La RUSSA V., SKALLERUD B. et al., *Reduction in wire tension caused by dynamic loading. An experimental Ilizarov frame study*, J. Biomech., 2011, 44, 1454–1458.

[13] MANNER H.R., HUEBL M., RADLER C. et al., *Accuracy of complex lower-limb deformity correction with external fixation: a comparison of the Taylor Spatial Frame with the Ilizarov Ringfixator*, J. Child. Orthop., 2007, 1, 55–61

[14] MOENS P., LAMMENS J., MOLENAERS G. et al., *Femoral derotation for increased hip anteversion*, J. Bone Joint Surg. Br., 1995, 77, 107–109.

[15] MYLLE J., LAMMENS J., FARBY G., *Derotation osteotomy to correct rotational deformities of the lower extremities in children. A comparison of three methods*, Acta Orthop. Belg., 1993, 59, 287–292.

[16] PALEY D., TETSWORTH K., *Operative Orthopaedics*; Chapter 61: *Deformity Correction by the Ilizarov Technique*, 1993, 937–948.

[17] SCHELL H., EPARI D.R., KASSI J.P., BRAGULLA H., BAIL H.J., DUDA G.N., *The course of bone healing is influenced by the initial shear fixation stability*, Journal of Orthopeadic Research, 2005, 23, 1022–1028.

[18] SYNDER M., NIEDZIELSKI K., FABIŚ J., *Zastosowanie aparatu Ilizarowa do wydłużania kończyn dolnych*, Chir. Narz. Ruchu Ortop. Pol., 1994, Supl. 1, 125–128.

[19] THEIS J.C., SIMPSON H., KENWRIGHT J., *Correction of complex lower limb deformities by the Ilizarov technique: An audit of complications*, J. Orthop. Surg., 2000, 8, 67–71.

[20] YILMAZ E., BELHAN O., KARAKURT L., ARSLAN N., SERIN E., *Mechanical performance of hybrid Ilizarov external fixator in comparison with Ilizarov circular external fixator*, Clinical Biomechanics., 2003, 18, 518–522.