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Comparative analysis of the reduction capabilities of orthopedic hexapod Ortho-SUV frame and its minimized (pediatric) version (experimental study)

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Abstract

Introduction Currently, orthopedic hexapods have been effectively used for long bone, foot and large joint deformity correction in both adults and children. Previous studies demonstrated the superiority of the reduction capabilities of the orthopedic hexapod Ortho-SUV Frame (OSF) in comparison with other designs of external fixation devices. However, the reduction capabilities of the minimized version of this hexapod (minimized Ortho-SUV Frame, OSFm) have not been studied yet. **Purpose** To identify the reduction capabilities of OSFm compared to OSF. **Materials and methods** The bench test was performed using plastic models of the tibia osteotomized at the middle third of the shaft. One-ring modules were used to fix each of the bone fragments. In the first series of the experiment, the reduction capabilities of OSFm with a standard strut size and in the second series OSF with a short strut size were studied. In each series of experiments, three groups were studied depending on the method of fixing the struts to the rings: directly to the ring, using straight plates, and using Z-shaped plates. Reduction capabilities were assessed by the maximum displacement of the distal bone fragment relative to the proximal one in distraction, translation, angulation, and rotation. **Results** The magnitude of the maximum distraction of OSF and OSFm with fixation of the struts directly to the rings and with the use of straight plates is the same ($p > 0.05$). With Z-plates, OSFm outperforms OSF by 27.3 %. OSFm surpasses OSF by 2.8-29.3 % in terms of the planar-parallel movement. OSFm surpasses OSF by 29.6-55.4% in terms of angular movement capabilities. The study of rotational movement found that OSFm exceeds the capabilities of OSF by 20.3-41.3 %. **Conclusion** The findings obtained indicate that OSFm, in comparison with OSF, has better deformity correction capabilities.

Keywords: transosseous osteosynthesis, deformity correction, orthopedic hexapod, reduction capabilities

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INTRODUCTION

Orthopedic hexapods have been used for multi-component multi-planar deformities of long bones and deformities of the midfoot and hindfoot [1-9]. This group of transosseous devices is equipped with a universal reduction unit, which operates on the basis of computer navigation and enables to eliminate all deformity components simultaneously without the need for multiple replacements of reduction units and with higher accuracy [10-13].

Currently, there have been more than 20 designs of orthopedic hexapods known in the world [1, 8, 14, 15]. One of them is Ortho-SUV Frame (OSF), which has been effectively used for deformity correction in both adults and children [1, 3, 4, 16-18]. Previous studies have reliably substantiated the advantages of reduction capabilities of OSF in comparison in comparison with other orthopedic hexapods [2].

However, the OSF, like other orthopedic hexapods, has some drawbacks in comparison with the Ilizarov apparatus such as a bulky size and heavy weight of the external frame. There is also an objective limitation for working with limb "short segments", when the supports are located close, at a distance of 10-12 cm or less. Such situations often occur in pediatric practice and in correction of foot deformities [12, 16, 17, 19]. The use of "extra short" sizes of the struts, Z-shaped plates and "dummy" rings does not allow solving this problem completely [4, 15, 20-23]. As an alternative, a "minimized version of the Ortho-SUV orthopedic hexapod" (minimized Ortho-SUV frame, OSFm) was developed [14, 17].

Purpose To assess the reduction capabilities of the minimized version of the orthopaedic hexapod Ortho-SUV Frame (OSFm) in comparison with the capabilities of the standard orthopaedic hexapod Ortho-SUV Frame (OSF).

MATERIALS AND METHODS

OSFm differs from OSF with a 5-mm reduced length of the universal joint (universal joint) and the strut length changing unit by 6 mm. Also, the dimensions of straight plates are reduced by 0.5 mm in height, 5 mm in length and 3 mm in width, and Z-shaped plates are reduced by 0.5 mm in height, 18 mm in length and 3 mm in width. Thus, the weight of the OSFm was decreased by 314 g (total weight 1001 g), by 518 g (total weight 1438 g) when equipped with straight plates, and by 614 g when equipped with Z-shaped plates (total weight 1618 g). The minimum possible length of the OSFm strut is 82 mm while in the OSF design it is 94 mm. The maximum possible length of the OSFm strut is 225 mm and that of the OSF one it is 213 mm.

In this experimental study, we consider the concept of "reduction capabilities" as the ability of the Ortho-SUV to move the distal bone fragment relative to the proximal one at a certain distance or at a certain angle. The experiment was performed using plastic models of the tibia 370 mm long, transversely dissected at the level of the middle third. The bone fragment simulators were located in the center of the 140-mm ring supports. The initial distance between the supports was determined by the average length of the strut of the minimized Ortho-SUV orthopaedic hexapod and was 200 mm. Two transosseous elements were used for fixation of each bone fragment, which was sufficient for stable fixation of bone fragments for this type of the study. According to the method of unified designation of external fixation (MUDEF), the assembly of the apparatus is indicated as follows:

$$\frac{\text{II,12,90; III,}\mathbf{9}\text{-3}}{140} - \text{OSF} - \frac{\text{VI,}\mathbf{3}\text{-9; VII,12,90}}{140}$$

In the first series of experiments, the reduction capabilities of OSFm with a standard size of struts were investigated. In the second series, the reduction capabilities of OSF with short struts were studied. The struts were fixed to the supports in such a way that the universal joints were the vertices of equilateral triangles. Strut 1 was always located along the anterior surface of the base ring. The markers of the scales of the strut length changing units in each struts were set to the average value. In each series of experiments, three groups were studied depending on the method of strut fixation to the rings: directly to the ring, using straight plates, and using Z-shaped plates. The method of fixation with straight and Z-shaped plates means that all six pieces were used simultaneously on the proximal and distal rings. Fixing the struts to the rings with the help of Z-shaped plates was possible only if they were located inwardly between the supports, that is, towards each other. The simultaneous location of all six Z-shaped plates outwards from the supports was limited due to the lack of length of the struts.

Reduction capabilities were assessed by the maximum displacement of the distal bone fragment relative to the proximal one:

1) along the longitudinal axis (distraction) (Fig. 1);

2) planar parallel in the frontal plane (medial and lateral) and in the sagittal plane (anterior and posterior) (Fig. 2);

3) at an angle in the frontal plane (varization and valgization) and in the sagittal plane (antecurvatum and recurvatum) (Fig. 3);

4) during rotation (internal and external) (Fig. 1).

For assessment of planar parallel displacements and displacement along the longitudinal axis, the edges of the cortical plates on the side to which the movement was performed were taken as control points.

For assessment of the angulation, the model with the maximum possible position of the bone fragment was photographed with a digital camera strictly in the frontal or sagittal planes. On the obtained digital images, the angle formed by the mid-diaphyseal lines of the bone fragments was measured using the Adobe Photoshop graphics editor.

To assess the amount of rotation in the proximal and distal bone fragments in position 12, threaded pins were introduced strictly opposite each other that formed an angle during rotational displacement of the distal fragment. The angle between these threaded pins was determined by photographing the model in a strictly horizontal plane with a digital camera with the maximum possible rotation of the distal bone fragment. Then, the angle was measured on the obtained digital images using the Adobe Photoshop graphics editor.

Linear displacements were measured in millimeters (mm) while angular displacements were measured in degrees (°). The movement was stopped when any of the struts reached its minimum or maximum possible length, which was a limitation for the subsequent movement of the fragment. Six of each of the studied models were assembled. To obtain statistically significant data, the experiment with each of the six models was repeated five times. Thus, a total of 180 series of the experiments were performed. The obtained quantitative data were statistically processed in the Statistica v10.1. To compare biases, the Mann-Whitney test, median chi-square, and ANOVA module were used. Differences between groups were considered statistically significant at $p < 0.05$.

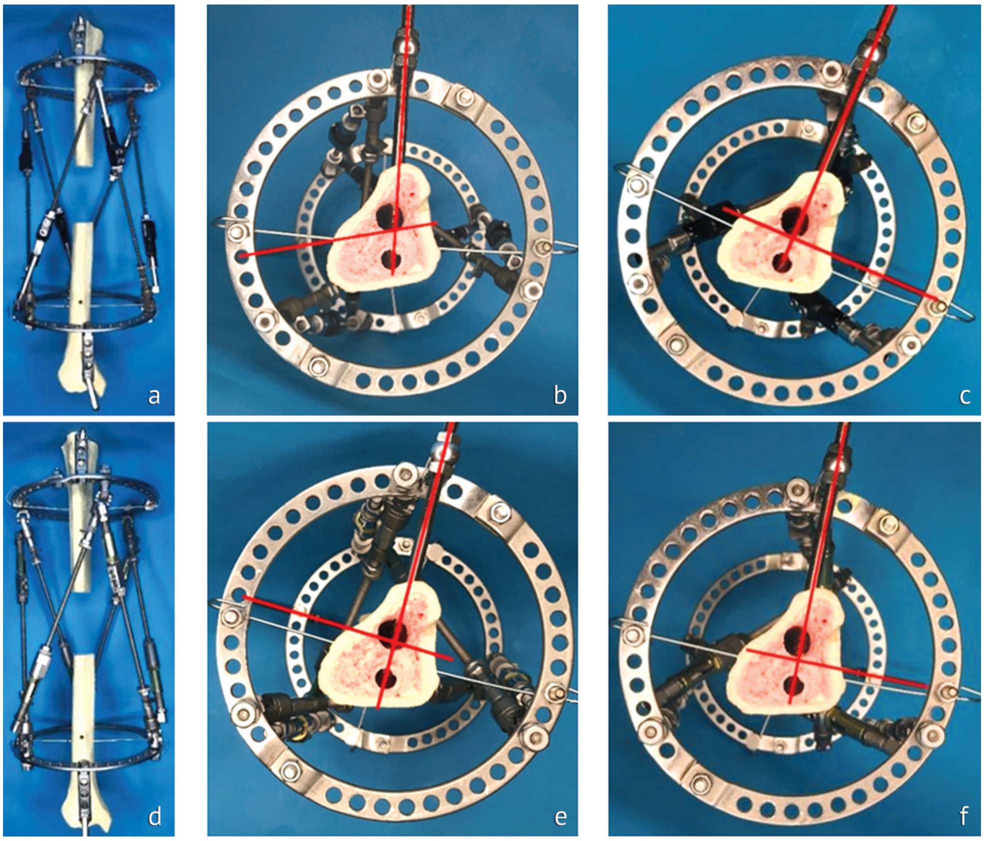

Fig. 1 Movement of the distal bone fragment: *a* along the length with the OSFm; *b* during internal rotation with the OSFm; *c* during external rotation with the OSFm; *d* along the length with the OSF; *e* during internal rotation with the OSF; *f* during external rotation with the OSF

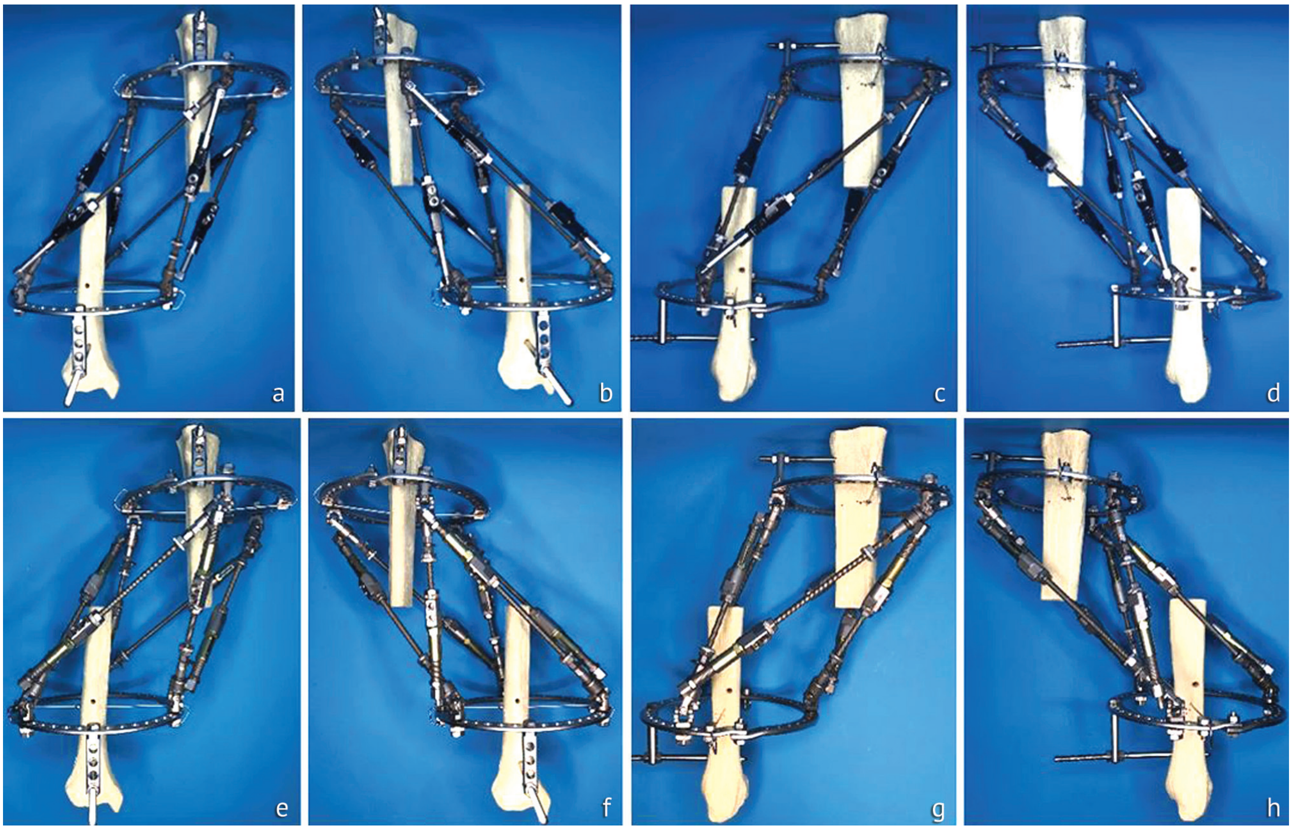

Fig. 2 Planar parallel movement of the distal bone fragment: *a* in the frontal plane outwards using the OSFm; *b* in the frontal plane inwards with the OSFm; *c* in the sagittal plane anteriorly with the OSFm; *d* in the sagittal plane posteriorly with the OSFm; *e* in the frontal plane outwards with the OSF; *f* in the frontal plane inwards with the OSF; *g* in the sagittal plane anteriorly with the OSF; *h* in the sagittal plane posteriorly with the OSF

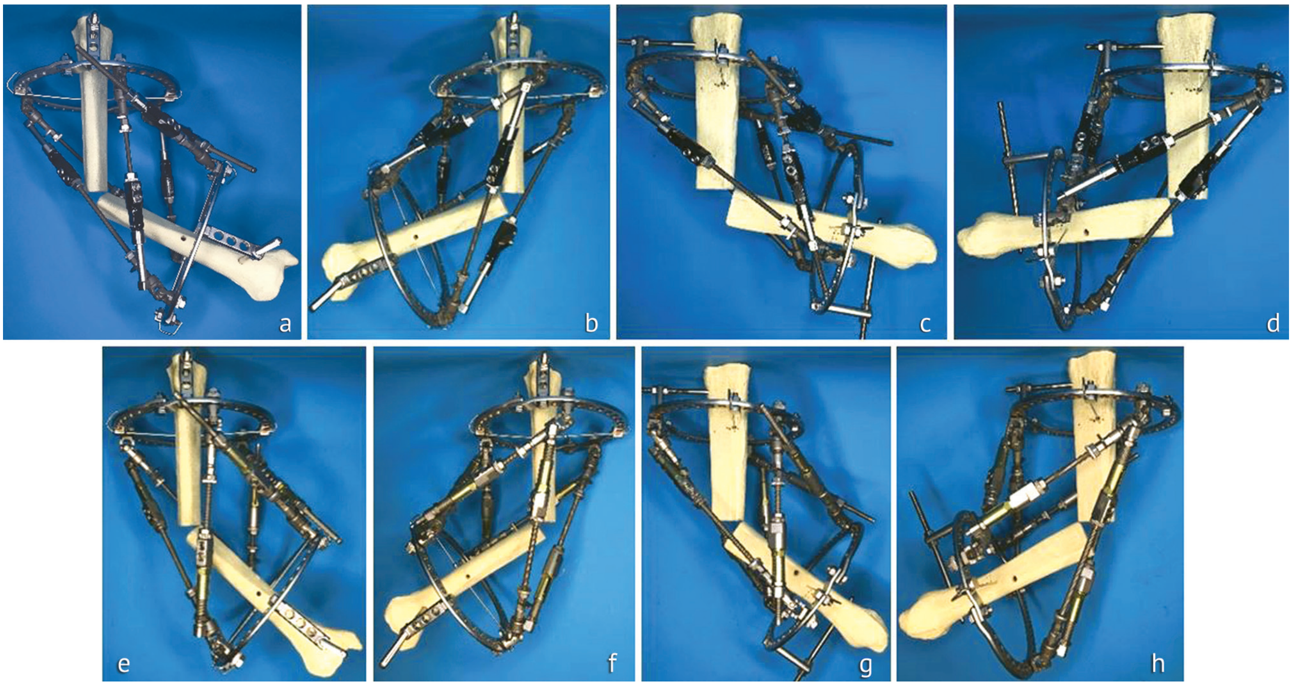

Fig. 3 Angular movement of the distal bone fragment: *a* varus in the frontal plane using the OSFm; *b* valgus in the frontal plane with the OSFm; *c* antecurvatum the sagittal plane with OSFm; *d* recurvatum in the sagittal plane with OSFm; *e* varus in the frontal plane using the OSF; *f* valgus in the frontal plane with the OSF; *g* antecurvatum in the sagittal plane with the OSF; *h* recurvatum in the sagittal plane with the OSF

RESULTS

The results of the studies of "distraction" and plane-parallel movement are shown in Figure 4, angular and rotational displacement in Figure 5. It was found that there were no significant differences between OSF and OSFm ($p > 0.05$) while studying the "distraction" if the struts were fixed directly to the rings or using straight plates. With Z-plates, OSFm outperforms OSF by 25.3 mm ($p < 0.05$) (Fig. 4). The results of planar parallel, angular and rotational displacements for all methods of strut fixation demonstrate statistically significant differences between OSFm and OSF ($p < 0.05$).

In terms of *planar parallel* movement outwards, the OSFm with fixation of the struts directly to the rings exceeds OSF by 6 mm and inwards by 3.3 mm. Accordingly, for straight plates, OSFm outperforms OSF outwards by 6.1 mm and inwards by 5.2 mm, and by using Z-shaped plates by 21.6 mm outwards and by 15.8 mm inwards. During planar parallel movement in the sagittal plane, OSFm anteriorly with fixation of the struts directly to the rings exceeds OSF by 9.8 mm and posteriorly by 11.3 mm. Accordingly, OSFm outperforms OSF anteriorly by 7.3 mm and posteriorly by 8.5 mm when using straight plates, and when using Z-shaped plates, OSFm outperforms OSF anteriorly by 27.5 mm and posteriorly by 29.4 mm (Fig. 4).

In terms of the possibilities of *angulation* in varization, OSFm with strut fixation directly to the rings exceeds OSF by 18.8º and in valgization by 19.5º. Accordingly, OSFm outperforms OSF in varization by 19.2º and in valgation by 18.1º if straight plates are used, and when using Z-shaped plates in varization by 17.4º and in valgation by 20.1º.

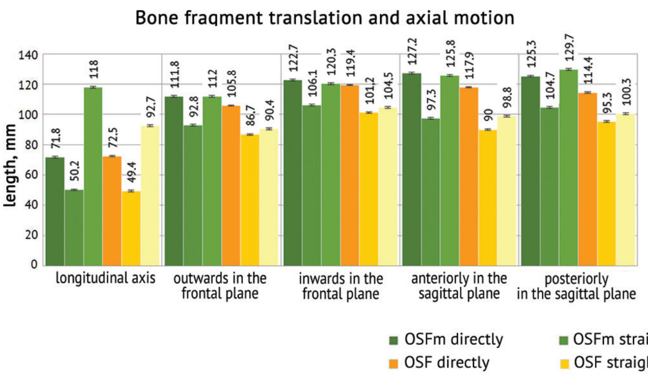

Fig. 4 Diagrams of the maximum possible values of bone fragment planar parallel and distraction movement

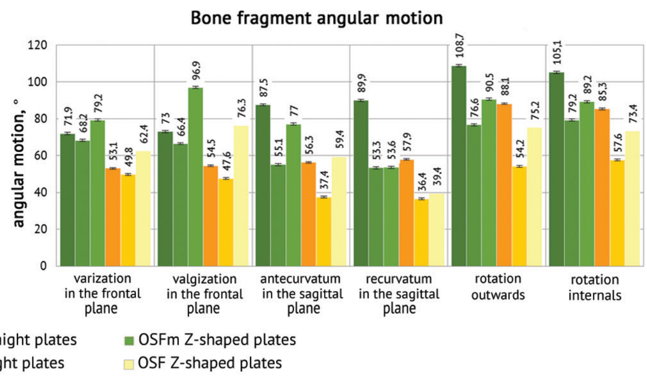

Fig. 5 Diagrams of the maximum possible values of bone fragment angulation and rotation

During angular displacement in the sagittal plane in antecurvatum, OSFm with fixation of struts directly to the rings exceeds by 17.3º and in recurvatum by 17.4º. Accordingly, for straight plates, OSFm indicators exceed OSF in antecurvatum by 18.4º and by 17.9º in recurvatum and by 18.7º for Z-shaped plates in antecurvatum while in recurvatum OSF exceeds OSFm by 16.9º (Fig. 5).

The study of rotation found that OSFm exceeds the capabilities of OSF by strut fixation directly to the rings outwards by 20.6º and inwards by 19.8º; when using straight plates outwards by 22.4º and inwards by 21.6º; when using Z-shaped plates outwards by 15.3º and inward by 15.8º (Fig. 5).

The results of studies of planar parallel, angular and rotational displacements of bone fragments using OSF and OSFm orthopedic hexapods are presented in the table.

Table

Features of reduction capabilities of orthopaedic hexapods OSF and OSFm
(in regard to bone movement type and bone fragment fixation manner)

Types of movement	Fixation method	OSF	OSFm
Along the longitudinal axis	Directly to rings	72.5 ± 1.5	71.8 ± 1.3
	Straight plates	49.4 ± 1.4	50.2 ± 1.5
	Z-shaped plates	92.7 ± 1	118 ± 1.5
Lateral in the frontal plane	Directly to rings	105.8 ± 1.6	111.8 ± 1.4
	Straight plates	86.7 ± 1.4	92.8 ± 1.7
	Z-shaped plates	90.4 ± 1.8	112 ± 1.8
Medial in the frontal plane	Directly to rings	119.4 ± 1.6	122.7 ± 1.1
	Strait plates	101.2 ± 1.5	106.1 ± 1.7
	Z-shaped plates	104.5 ± 1.5	120.3 ± 1.6
Anteriorly in the sagittal plane	Directly to rings	117.9 ± 1.5	127.2 ± 1.2
	Straight plates	90 ± 1.7	97.3 ± 1.4
	Z-shaped plates	98.8 ± 1.5	125.8 ± 1.7
Posteriorly in the sagittal plane	Directly to rings	114.4 ± 1.4	125.3 ± 1.3
	Straight plates	95.3 ± 2	104.7 ± 1.5
	Z-shaped plates	100.3 ± 1.5	129.7 ± 1.7
Varization in the frontal plane	Directly to rings	53.1 ± 1.4	71.9 ± 1.4
	Straight plates	49.8 ± 1.7	68.2 ± 1.4
	Z-shaped plates	62.4 ± 1.8	79.2 ± 1.8
Valgization in the frontal plane	Directly to rings	54.5 ± 1.2	73 ± 1
	Straight plates	47.6 ± 2	66.4 ± 2.1
	Z-shaped plates	76.3 ± 1.7	96.9 ± 1.7
Antecurvatum in the sagittal plane	Directly to rings	56.3 ± 1.3	87.5 ± 1.4
	Straight plates	37.4 ± 2	55.1 ± 1.8
	Z-shaped plates	59.4 ± 2	77 ± 1.8
Recurvatum in the sagittal plane	Directly to rings	57.9 ± 1.7	89.9 ± 1.5
	Straight plates	36.4 ± 1.4	53.3 ± 1.6
	Z-shaped plates	39.4 ± 1.5	53.6 ± 1.7
External rotation	Directly to rings	88.1 ± 1.4	108.7 ± 1.2
	Straight plates	54.2 ± 2	76.6 ± 1.8
	Z-shaped plates	75.2 ± 1.6	90.5 ± 1.5
Internal rotation	Directly to rings	85.3 ± 1.9	105.1 ± 0.9
	Straight plates	57.6 ± 1.8	79.2 ± 1.7
	Z-shaped plates	73.4 ± 1.6	89.2 ± 1.6

Note: significance level $p < 0.05$

DISCUSSION

Currently, orthopaedic hexapods have been used not only to correct multi-component multi-planar deformities of long bones, but also to correct foot deformities, eliminate chronic dislocations and subluxations in large joints, and also in the treatment of contractures [3, 4, 12, 15-17, 24 -26]. Many years of experience in the use of this type of external fixation devices in adults and children has revealed such their drawbacks as bulkiness, relatively large weight and limitation to use them for working with "short segments", i.e. when the distance between the base and mobile supports does not exceed 10-12 cm [16, 17, 19, 22]. The "problem of weight and size" is especially important in correcting deformities of the mid- and hind foot, because the external supports specially designed for this location are even more cumbersome in comparison with circular ones [17, 19, 26].

Two minimized modifications of standard orthopaedic hexapods are known: Small Bone System and OSFm. The first of these was based on the Orthex-frame and differs from its counterpart (Orthex-frame, Large Bone System) in the reduced size of the components [14, 27]. According to the results of the study, Orthex-frame demonstrated clinical efficacy in correcting deformities in children and was better the Taylor Spatial Frame (TSF) orthopaedic hexapod in terms of the number of re-arrangements, strut exchanges, software residuals or reprogramming, regenerate density, as well as the number and nature of complications [28]. Targeted comparative studies to determine the reduction capabilities of this minimized version of the hexapod have not been conducted.

In a previous study, the superior reduction capabilities of OSF were demonstrated in comparison with other orthopaedic hexapods: TSF and Ilizarov Hexapod Apparatus (IHA) [2]. However, it was not known how the minimization of the OSF affected its reduction capabilities.

The results of the study of the reduction capabilities of OSF and its minimized version OSFm demonstrated significant differences in most simulated bone fragment displacements. These differences were observed in all methods of fixing the struts to the rings: directly to the rings, using straight and Z-shaped plates.

The execution of "distraction" and planar parallel movement stopped when any of the struts reached the maximum possible length. According to these indicators, OSFm outperforms OSF for all types of planar parallel displacements both in the sagittal plane and in the frontal one. The superiority of OSFm is maintained for all three methods of strut fixation. This is because the maximum possible OSFm strut length is 12 mm longer than the maximum possible OSF strut length. This advantage also makes OSFm superior to OSF in rotational displacements.

However, there were no significant differences between OSFm and OSF in "distraction" indicators during fixation of the struts directly and with the help of strait plates. This is because the length of the OSF universal joint is 5 mm longer than the length of the OSFm universal joint. While performing "distraction", the length of the universal joint coincides in direction with the longitudinal axis of the displacement of the bone fragment. This condition compensates for the superiority of OSFm in the maximum possible length of the strut. By using Z-plates, OSFm outperforms OSF in performing "distraction". The simultaneous use of all six OSF Z-plates increases the width distance more than the OSFm Z-plates, since the OSF Z-plate is 18 mm larger than the OSFm Z-plate. Thus, a greater distance in width reduces the possibility of maximum displacement of the bone fragment along the longitudinal axis.

For angular displacements, the main limitation was the minimum possible length of any of the struts. According to these indicators, OSFm outperforms OSF for all types of angular displacements both in the sagittal plane and in the frontal one. The superiority of OSFm is maintained for all three methods of strut fixation. This is because the minimum possible length of the OSFm strut is less than the minimum possible length of the OSF strut by 12 mm.

It should be specifically emphasized that the purpose of this study was not to determine the maximum possible reduction capabilities that could be provided by OSFm and OSF. The results obtained depend only on the assemblies of the studied devices used. Each indicator under study can be increased by changing the distance between the supports, the angle of their inclination, changing the positions of struts fixation, the angle of their inclination, a combination of straight and Z-shaped plates, as well as the use of additional "dummy" rings [1, 3, 4, 29].

The limitation of this study was the exclusion of the sof-tissue effect on the reduction capabilities. Obviously, if at least one of the struts touches the skin, further movement of the mobile fragment becomes impossible. However, such a study is relevant for the development of "optimal" arrangements for the correction in specific anatomical locations: especially for the humerus, forearm, thigh, lower leg, large joints, and foot [3, 4, 24].

Formally, the conclusion is that since OSFm is generally superior in the reduction capabilities provided by standard OSF, the latter (at least equipped with short struts) can be completely replaced by OSFm. However, only a study aimed at determining the osteosynthesis rigidity provided by OSFm can confirm or refute such a statement.

CONCLUSION

Our findings confirm that OSFm, when compared with OSF, possesses better capabilities for deformity correction. Further studies should focus on bone fragment rigidity assessment that can be ensured with OSFm and with designing of optimal assemblies for long bone, large joint and foot deformities.

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