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Enhancing the Ilizarov Apparatus: An Overview Prioritizing Mechanical Stiffness

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Abstract

The Ilizarov system is a form of external fixation device utilized by medical professionals to aid patients who have sustained injuries from accidents, bone shortening, or nonunion of the bone. The device is fixed onto the long bone of the patient and is adjusted according to the nature of the injury. Ilizarov's techniques are minimal invasiveness, not aggressive, spare tissues and involve little blood loss. It consists of wires that are secured to a modular circular frame and then tightened. The Ilizarov fixator is a valuable tool for treating acute fractures, especially in cases where there is bone loss and compromised soft tissue. Several studies have aimed to improve the effectiveness of Ilizarov fixation through modifications to its frame components, such as ring diameter, transosseous element diameter, ring separation, transosseous element count in each ring, and number of rings, as well as the type of transosseous element employed, including wires, full-pins, or half-pins. Furthermore, positioning of transosseous elements at the correct crossing angle without damaging the nerves and vessels while considering the intricacy of bone deformities. Recent advancements in Ilizarov fixation will be thoroughly reviewed in this manuscript, with a particular focus on improving the stiffness of the entire frame. The main objective of this review is to pinpoint the optimal configurations, with a particular focus on stiffness, in order to foster stability and ensure a successful recuperation.

Keywords: Ilizarov Fixation, External Fixation, Circular Fixation, Stability, Improving Stability.

تعزيز جهاز إليزاروف: ملخص عن الصلابة الميكانيكية

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الخلاصة:

إليزاروف هو جهاز تثبيت خارجي، يتكون من أسلاك يتم شدها بعد ربطها بإطار دائري خارجي. يساعد الجهاز على إعادة ربط قطع العظام بسبب استخداماته المتزايدة في علاج وإصلاح عيوب العظام وتلفها، بالإضافة إلى تطويل الأطراف. يقوم الجراحون بتثبيت مثبت إليزاروف الخارجي على ساق المريض، ويمكن إجراء العديد من التغيرات على مثبتات إليزاروف، ويعتمد ذلك على إصابة المريض. تتميز تقنيات إليزاروف بالحد الأدنى من التدخل الجراحي، وليست أنسجة عدوانية احتياطية، كما أنها تنطوي على فقدان القليل من الدم. هدفت العديد من الدراسات إلى تحسين فعالية تثبيت إليزاروف من خلال إجراء تعديلات على مكونات إطاره، مثل قطر الحلقة، وقطر العنصر التي تخترق العظم، و التباعد بين الحلقات، وعدد العناصر المخترقة للعظم في كل حلقة، وعدد الحلقات، وكذلك نوع العنصر المخترقة للعظم. المستخدمة، بما في ذلك الأسلاك، أو الدبابيس الكاملة، أو نصف الدبابيس. علاوة على ذلك، يتم وضع العناصر التي تخترق العظم في زاوية التقاطع الصحيحة دون الإضرار بالأعصاب والأوعية الدموية مع الأخذ في الاعتبار مدى تعقيد تشوهات العظام. سيتم مراجعة التطورات الحديثة في تثبيت إليزاروف بدقة في هذه المخطوطة، مع التركيز بشكل خاص على تحسين صلابة الإطار بأكمله. الهدف الرئيسي من هذه المراجعة هو تحديد التكوينات المثالية، مع التركيز بشكل خاص على الصلابة، من أجل تعزيز الاستقرار وضمان التعافي الناجح.

1. Introduction

The principle of the Ilizarov is that bones are supported to the framed rings by thin wires (Kirschner wires) that were tensioned before being fastened to the rings after drilling through the bones as shown in Fig.1. One of the critical characteristics of the Ilizarov fixator is patient movability early in the course of therapy, which influences the best possible bone regeneration through the functional activity of the limb's muscles and joints. Moreover, the weight-bearing causes very minor cyclical axial strain in the fracture space, promoting additional osteogenic processes [1,2].

The Ilizarov surgical operations are non-aggressive, minimally invasive, and cause little blood loss. The key components of curing are firm circular fixation, fragment position control, bone transmission, and monitoring of bone renewal, allowing for any necessary adjustments to be made as treatment progresses while limb weight bearing and joint motion are maintained [3-5]. For the fixation to function effectively, wires must be tensioned critically and fastened to the frame. In order to bridge the gap between the bones, the tensioning is based on the fundamental biomechanical concept of axial mechanical stress and micro-movements in the osteogenic zone of the fracture area. The Ilizarov apparatus's stiffness depends on the wire pretension used, and when that pretension is lost, the bone fragment's axial displacement grows [6-8].

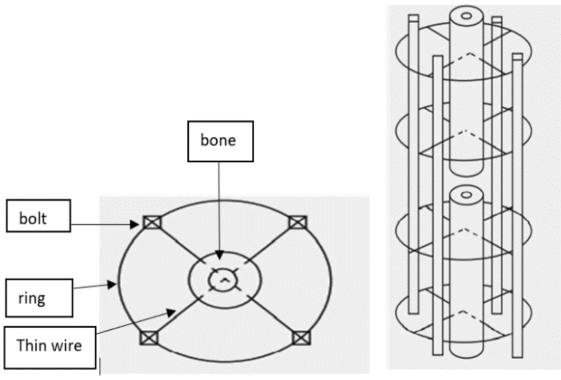

Figure (1): Standard Ilizarov fixation [3].

2. Improvement Made on Ring

The rings' principal function is to distribute stress from the wires or pins to the longitudinal parts as evenly as possible. They also help to maintain wire tension. The improvement included the diameter of rings, number of rings, and suppuration between rings. It has been concluded by Bronson et al. that decreasing the ring diameter makes a noticeable increase in overall frame stiffness, taking into consideration that the size of the limb limits the reductions in ring size, the ring size normally leaves two fingers approximately 3.5 cm between the ring and the skin surface [9,10]. Yilmaz E et al., compared the standard ilizarov with four improved (hybrid) Ilizarov fixators, standard ilizarov have 4 full rings two in the upper bone segment and two in the lower segment with all standard wires and wire fixators. While the first improved model exchanges the upper 2 full rings by one femoral arch and the wires replaced by two half-pins with 90° crossing angle, the second design includes two femoral arches, the first which is attached to the bone by one ½ pin and the second which is attached to the bone by two perpendicular ½ pins. The third model utilizes the same configuration as the second, with the exception that the second arch's crossing angle between the ½ pins is 45 degrees. The fourth and final design includes three femoral arches, with the first two secured to the bone by a single ½ pin and the third by two parallel half-pins as shown in Fig.2. Axial compression, antero-posterior bending, medio-lateral bending, and torsion were all tested on each model. According to the findings, axial and bending rigidity are greater in the typical Ilizarov fixator than in all improved models. So, it has been concluded that to increase hardness in improved fixators, use at least three femoral arches and four ½ pins, with the ½ pins positioned at 90 degrees [11].

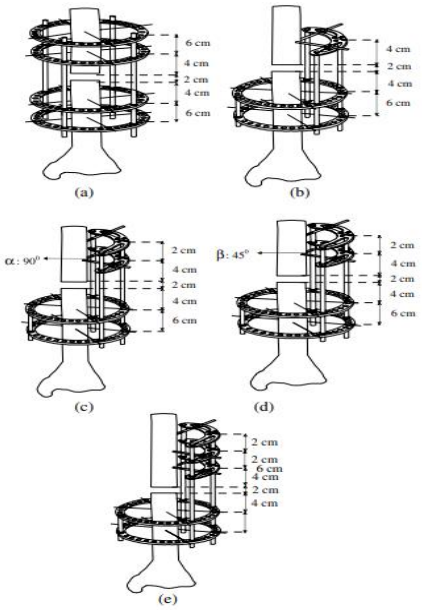

Figure (2): (a) standard ilizarov, (b) first hybrid model, (c) second hybrid model, (d) third hybrid model, (e) fourth hybrid model [11].

Grivas et al., suggest using a twin ring module instead of a single ring, due to the twin rings' increased thickness (2 times 5.0 Equals 10.0 mm), the spacing between its top and bottom wire levels had also been increased, so it is possible to safely insert up to 5 wires by using twin rings. Axial and shear experiments were done repeatedly on basic construction setups. The single and twin rings each have a 200mm-diameter ring and are attached to artificial bone modules using 1.8mm-diameter wires and typical Ilizarov system accessory parts. Two wires were bored perpendicular to one another and fixated onto the upper ring surface in each of the modules. The system's dynamometric wire tensioner was used to tension all the wires to a level of 130 after drilling two additional wires at a 45-degree angle to the initial two and attaching them to the bottom surface of the ring as shown in Fig.3. It had concluded that the twin ring has properties that support fracture healing while also eliminating the requirement for bridging adjacent joints, but greatly lowering patient morbidity [12].

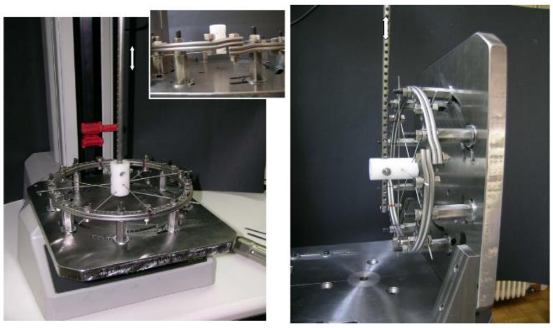

Figure (3): Axial and shear loading applied on single and twin rings [12].

3. Transosseous Element Improvement

The purpose of the wires and pins is to attach the bone segments robustly within the frame, and allow a range of interfragmentary motion (IFM) in the axial direction only. In General ring fixators use tensioned wires, but in some cases of ilizarov fixation, half-pins can be adopted to lessen the transfixion of soft tissues. However, since wires are approximately one-third that of half-pins, the soft tissue and bony reactions are reduced, and long-term damage is also lessened since smaller holes are left on the bone. Two wires are normally required for each full or part ring to achieve three-dimensional control of fracture fragments, and the desired bending, rotational and translational rigidity in a frame [9,13].

Kummer, F.J., found that increasing the tension of the wires also increases the stiffness of the frame. The maximum limit in tensioning for 1.5-millimeter wire is 90 kg and 130 kg for 1.8-millimeter wires because of the yield strength of the stainless steel and slippage at the wire bolts. The test has shown that increasing the tension of a single wire results in a non-linear rise in rigidity. The rate of increase decreases as the tension increases [14]. ORBAY GL et al., investigated the results of altering the number of wires and wire placement orientation. Long bone simulated by rigid polyvinylchloride plastic tubing having a 30 mm diameter, and wall thickness of 4 mm, smooth wires of 1.5-mm and 1.5-mm olive wires were used. The rings used were 180 mm in diameter. The results have shown that the number of wires employed determines the rigidity under axial and torsional loading, and the angle of the wire determines the hardness of bending for a single ring. Using olive wire restores stability for all wire convergence angles. It has been concluded that The Ilizarov fixator's stability is directly proportional to the wire's arrangement. An unstable state arises when the crossing angle is less than 60 degrees, and this design significantly reduces stability in shear and bending. The use of olive wires and a third wire (drop wire) that is placed at least 4 cm from the level of the ring restores stability [14,15].

Wilkes RA et al., have suggested using a parallel wire instead of crossed wires, each wire attached to a separate ring as shown in Fig.4, this configuration is suggested because the crossed wires transfix a bulk of the muscles which causes soreness and swelling, that tie up patient mobilization. Stiffness was tested for parallel and crossed wires with different ring diameters and 1.8 mm wires. In the case of crossed wires, the wires are inserted at 90°. An artificial tibia of 30 mm diameter was used to test the frame structure, each structure was tested by six loadings: axial loading, parallel bending, vertical shear perpendicular bending, parallel shear, and torsion. It has been concluded based on the mechanical tests, that the basic form of parallel wires is not as rigid as the crossed wires in vertical bending and shear loading. However, changing the wires in-between distance to 5 or 6 cm produces an equal bending rigidity, and this distance can be lessened if the angle between the wires varies. By modifying the parallel wires model, it can be made at least as stiff crossed wires [16].

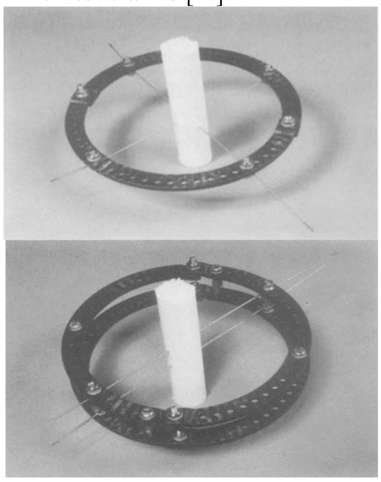

Figure (4): (abov0e) crossed wires configuration, (below) parallel wire configuration [16].

Hillard PJ et al., determined whether thin wires distorted plastically under load-bearing, tensile tests have been carried out to verify the results of the finite element analysis that have been utilized to create a number of finite element models that mimic typical frame structures. The effect of changing the frame factors (wire length (ring diameter), wire diameter, wire pre-tensioning) on the load-displacement relationship has been collected.

To reduce the degree of detensioning (loss in wire tension) which occurs while weight bearing, the diameter of the wires should be increased and the pretension decreased, and the minor effect is due to wire length but it also should be minimized (reducing the ring diameter). The effect of wire diameter on the load and displacement relationship over a single load cycle has been tested. It observed that increasing wire diameter will increase the wire's ability to withstand high loads with less deflection (displacement). It had been concluded that tensioned wires used in the fixation of lower limbs undergo noticeable plastic distortion when subjected to slow walking. Plastic distortion causes a lessening in wire tension, and as a consequence, a reduction in overall frame rigidity occurs and lessens its capacity to prevent large axial and shear movements at the injured area that are harmful to bone therapy [9,17]. Calhoun et al. determined if adding a drop wire boosts the frame's strength by a similar amount as adding another ring. drop wire only produces very low tensions because they are not on the ring's plane, thus only very small tensions are permitted [18]. Rocchio TM et al., measured the impact of the parameter's olive wire cross-angle, ½ pin cross-angle, and ½ pin diameter, on foot stabilization. A variety of external fixation setups employing either calcaneal tensioned olive wires or ½ pin were tried on a simulated foot model. The test findings demonstrated that the type and location of loading had an impact on how these parameters affected stability. Two crosses ½ pin are necessary for foot fixation, two cross ½ -pins improve axial and medial-lateral bending toughness, widening the ½ pin cross angle improves medial lateral bending rigidity to lateral loading of the foot, and ½ pin diameter has an impact on foot stabilization. The increase in olive wire crossing angle improves the axial and anterior posterior bending rigidity [19]. Roberts CS et al., Wire crossing angle's impact on fixation rigidity was examined. Fiberglass composite tibias have been fixed into a standard fixator. Loads were applied using a servo-hydraulic load frame, five loads were used: central, medial, posterior, posteromedial compression, and torsion. Using the same stress conditions, load distortion behavior was examined at the various angles of wire crossing. It has been concluded that using the widest wire crossing angle, and placing wires as close to the loading level as possible increase the rigidity. Thin wire with diameters of 1.5 or 1.8 mm is used because they tend to withstand failure under expected loads, and have a low rigidity to allow some micromotion at the fracture site axially. In the lower extremity the wire is performed with 1.5–2 mm in diameter, in clinical practice, transosseous elements (wires, pins) of 1.5–6 mm diameters are most used. Growing the transosseous components' thickness causes the fixation of the bone segments to become stiffer. Increasing the number of transosseous elements per ring increases the frame stiffness [9,20,21].

Sarpel Y et al., compared eight modified ilizarov frame systems with standard ilizarov frame. The modification done by replacing the second upper ring by drop wires and screws, and adding a third wire in the first upper ring. A different mechanical test was done on the nine-frame configuration. A wooden model of 35 cm in length and 3 cm in diameter was used to simulate the bone. Based on the mechanical tests it has been concluded that the standard system with double upper rings was the most successful configuration. The Schanz screw and drop wire models that were at least two centimeters apart from and at a 45° angle to the first ring's wires showed the best mechanical performances. Because there is a lot of cancellous bone in the metaphysis, Schanz screws potentially loosen early or late. Drop wires in the metaphysis and half-pin Schanz screws in the diaphysis are advised for this [22]. Antoci V et al., examined the effects of wire design, placement of the olive wire, and clamping options on the constancy of ring fixation. A simulated tibia bone has been made from a fiberglass composite, and positioned in the center of the standard ilizarov frame. The fiberglass tibia fixed to the frame rings using two smooth wires and two olive wires all of 1.8 mm in diameter, with a crossing angle of 60° as shown in Fig.5. The olives were tested in different positions and tensioned in two modes. First, it tensioned the opposite end to the olive while the wire fixed to the ring, the other mode tensioned from both ends, also while the wire's olive ends were unfastened and tensioned, the tensioner was applied to those ends before they were secured once more in the ring. It has been determined when compare that olive wires that are tightened from both ends offer superior bending stiffness than smooth wires and olive wires that are tightened just on the end opposite the olive. Due to these conclusions' olive preferred to use in fin wire external fixation [14].

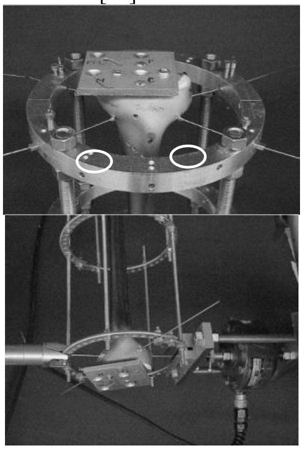

Figure (5): The model used to test olive wire [14].

Renard AJ et al., determined how wire slippage and tension are affected by torque and long-term loading. The torque applied on the fastening bolts is insignificant in clinical practice the average is 10 Nm. stainless steel ring with a 150 mm diameter and four 10 cm bars set on a metal plate. A solid polyethylene bar was punched with 1.8 wire, which then joined to the ring after being tightened. The abovementioned arrangement has produced data on axial load, polyethylene bar movement, wire slippage (at both ends), and ring distortion. According to the findings, the wire tension has decreased to a stable level. After loading with 200 N, 50% of the initial wire pretension was still present in the stable condition (the initial loading cycles resulted in a significant reduction in wire tension to a steady state condition). In the less stable configuration wire slippage occurred without loading and no tension existed after loading. Moreover, no plastic wire distortion was seen as a result of the wires slipping, and the wire tension was lost [23]. Gessmann J et al., analyzed the effect of a weight-bearing platform on the typical four-ring with two 1.8wires in a single ring, with a 60° crossing angle, in comparison to a two-ring frame with three 6 mm half pins, and the ring connected by four threaded rods. A direct loading and an indirect loading were both examined. Displacement transducers were used to capture interfragmentary movements, or the relative motions of bone segments, as well as movements of the rings. Loading cells were used to capture information on the compressive loads at the osteotomy site. Half-pins are discovered to enhance the stiffness of the Ilizarov and permit the use of one ring per bone fragment, but pure unidirectional axial loading leads to shear stress at the fracture site and angular displacements in the frame. The half-pin frame experiences noticeable angular and translational displacements as a result of repeated weight loading [24]. Henderson DJ et al., Examine the interfragmentary strain that results from the frame's stress as well as the impact of using half-pins in place of fine wires. An acrylic tube that is used to represent bone. The standard ilizarov compared with four configurations as shown in Fig.6. The results showed that replacing wires by ½ pins increased the overall rigidity of the frame and reduced planar interfragmentary motion. With rational usage of ½ pins, the degree of shear strain on loading of the frames lowered without altering the mechanical situation of the fracture site. [14].

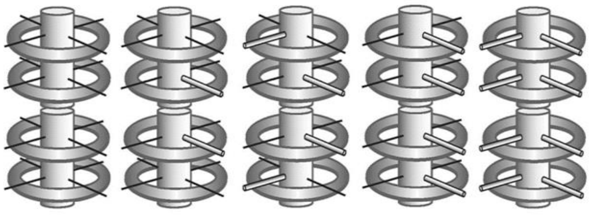

Figure (6): The standard ilizarov compared with four different configurations [14].

4. Transosseous element fixators improvement

Fixation bolts link the wires to the rings to stabilize the frame. The bolts' effects on the wire tension can therefore have an impact on the fixator's functionality. If slippage occurs in the wire-bolt interface a loss in wire tension will occur directly. Buckles, cannulated bolts, slotted bolts, and slotted washers are the clamps used in wire fixation [9,14,24]. Aronson and Harp, revealed that slotted bolts are the best for fastening the wire because they have a greater wire-bolt area of contact. The wire slippage is greater at higher wire tensions, the slippage can be reduced by enlarging the tightening torque of the bolt, but this is restricted by the bolt failure due to high torque applied. It has been determined that slotted bolts can sustain a 34 Nm torque, whereas cannulated bolts can sustain a 28 Nm torque. And 20 Nm torque is enough to prevent wire slippage, since rings and bolts are often reused, the load history must be considered with subsequent use [25]. Davidson AW et al., investigated and compared three designs of wire holding bolts in Ilizarov: cannulated, slotted, and Russian, to determine which bolt should be used. 1.8 mm wires were used and tensions were created at 45, 90, and 135°. The bolts were initially all tightened to 10 Nm before twisting to tension the wires. To prevent the wire from being broken, the bolt is turned by putting a spanner on both the nut and the bolt head and spinning them together. It has been concluded that the most effective bolts in tensioning the wire were the Russian bolts. And bolt twisting technique has advantages over the mechanical tensioner, which is an easier method to create an equivalent tension and the ability to produce greater wire tension [14,24]. La Russa V et al., evaluated three fixators and their capacity to uphold wire tension while bearing weight. Additionally, the study pinpointed the cause of tension loss. The testing apparatus consisted of a straightforward frame, comprising of a 160-millimetre stainless steel ring, fastened with a 15 Nm bolt torque, and secured by 1.8 mm wire as shown in Fig.7. Wires were concatenated with 200 N for 450 times, and the tension of each wire was recorded. Fixators with a larger and rougher contact surface tend to experience less tension loss. The fixator of a cannulated bolt with the washer is considered the best option for reducing tension loss. Conversely, fixators with a smaller and softer contact area are more prone to rapid loss of pretension. Tension loss is typically caused by plastic deformation of the wire and slippage, with slippage being the primary factor. It has been determined that enhancing wire fixators by increasing the wire-bolt contact area would effectively reinforce the wire tension even after repeated loading [26].

Figure (7): The models of bolt fixing suggested [26].

Gessmann J et al., determine the holding capacities of different fixation bolts and to analyze the impact of slippage on the overall stiffness of wire. A comparison between the improved bolt design which is a ruffled wire-bolt area (TrueLok™) and a classic Ilizarov slotted bolt of a smooth wire-bolt interface has been done. Three different ring designs with a diameter of 180 mm were used: a classic stainless steel Ilizarov ring of combined two half rings, two aluminum full rings, and TrueLok™. Stainless steel wires, of 1.8mm diameter, were inserted through a polyethylene bar, of 3 cm in diameter, then the wires tensioned using a standard wire tensioner to the 110 kg mark and fixed to the ring with bolts. wire slippage recorded with an extensometer for all frames and bolt types under the axial loading of the wires. It has been observed that wires slippage and the loss of tension in wires occur directly after attaching the wires to the ring, at the moment when the tensioning device is removed, and during weight bearing. Also, it has been found that the riffled TrueLok™ bolts improve the holding capacity and increase wire stiffness. So, it can be concluded that roughening the wire-bolt interface will result in an improvement in wire stiffness [27].

5. Longitudinal elements improvement

Longitudinal element provides longitudinal support, and could also be articulated for angular distortion correction or to facilitate alignment post-assembly, the series of rings are interconnected through the utilization of rods [28]. Two primary sorts of longitudinal rods are used which are: simple threaded rods, and complex articulating distraction assemblies. Bronson et al. determined that compared to six-millimeter threaded rods, telescopic rods increased the bending and torsion strength of a frame [9]. Three connecting rods link the closed complete ring supports; adding a fourth does not enhance the stiffness of the osteosynthetic material. Using a fourth connecting rod enhances osteosynthetic stiffness when one ring of the open type [21]. Jawad et al., compared wearing the Ilizarov frame to not wearing it while analyzing the spatiotemporal gait variables during the Ilizarov method. There was no noticeable contrast found between the Ilizarov and control groups, but the patients required a longer time to walk while using the apparatus, in addition to the Ilizarov effect on the times (stance, swing, and double support) for the unoperated limb [29].

6. Discussion and Conclusion

The stiffness of external ring fixators is influenced by the biomechanics of every individual component that comprises them. In summary rings increasing stiffness by decreasing diameter but the ring has to leave two finger breadths between the ring and the patient skin. Open-end segments have less rigidity than full rings, which are more rigid. On the bone portion, the rings are spaced as widely apart as possible from one another to stiffen the frame. While increasing ring thickness increases overall frame rigidity, it also reduces patient movement. To improve rigidity, a frame's outer ring alignment has to be parallel to one another.

Higher stiffness is achieved by increasing the diameter of the Transosseous element, whereas decreasing it leads to increased soft tissue and bony tolerance as smaller holes are left on the bone. By introducing additional transosseous elements to each ring, the stiffness of the frame can be enhanced. It's essential to ensure that the wires are not tensioned too tightly to increase the rigidity of the frame since high tensions can cause wire slippage and plastic deformation at high loads. Another technique to increase the frame's stiffness is to place the wires at a 90° crossing angle, with a cross-over point as close to the ring's center as possible. However, this approach may not be feasible in certain cases due to anatomical constraints. To increase stability, it is recommended to use olive wires and a third wire (known as drop wire) placed below the ring level. Olive wires offer better bending stiffness than smooth wires and should be tightened only at the end opposite the olive. Slotted bolts can withstand higher torque and have a greater wire-bolt area of contact, giving them superior capacity to endure elevated loads compared to cannulated bolts. In conclusion, the utilization of external fixation for bone lengthening and reconstruction has been deemed as a groundbreaking approach. Nevertheless, orthopaedic surgeons must meticulously weigh the advantages and disadvantages of each available system, while taking into account the level of soft tissue damage and the particular fracture or realignment that requires attention. By doing so, the affected limb can be treated efficiently, leading to positive outcomes for the patient [30-32].

In conclusion, Table 1 provides the influence of each component variation on the stiffness of the frame. Ongoing clinical research is still being conducted on the principles of external fixation and Ilizarov's discoveries.

Table (1): The effect of component variation on the stiffness of the circular external fixation.

Component	Parameter that changes	Effect on the frame stiffness
Ring	Diameter ↓	Increase
	Number ↑	Increase
	Complete ring	Increase
	Open ring	Decrease
	Thickness ↑	Increase
	Rings separation ↑	Increase
Transosseous elements	Diameter ↑	Increase
	Number ↑	Increase
	Wire tension ↑	Increase
	Wires crossing angle ≈ 90°	Increase bending stiffness
	Using olive wires	Increase bending stiffness
Fixation bolts	Using slotted bolts	Increase
	Tightening torque ↑	Increase
	wire-bolt contact area ↑	Increase
	roughening the wire-bolt interface	Increase
Longitudinal Elements	Number ↑	Increase
	Using a fourth rod	Increase stiffness when one ring is of the open type

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