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Improved wire stiffness with modified connection bolts in Ilizarov external frames: a biomechanical study

JAN GESSMANN[1]*, BIRGER JETTKANT[2], MATTHIAS KÖNIGSHAUSEN[1],
THOMAS ARMIN SCHILDHAUER[1], DOMINIK SEYBOLD[1]

[1] Department of General and Trauma Surgery, BG University Hospital Bergmannsheil, Ruhr University Bochum, Germany.
[2] Department of Surgical Research, BG University Hospital Bergmannsheil, Ruhr University Bochum, Germany.

Frame stability in Ilizarov external fixators is mainly dependent on the tension of the transosseous wires, which are clamped to the ring by connection bolts. It was the purpose of this biomechanical study to investigate the holding capacity of a modified bolt design featuring a ruffled wire–bolt interface (TrueLok^{TM}) and its influence on wire stiffness in comparison with that of classic bolts featuring a smooth, unruffled wire–bolt interface. Six different ring and bolt configurations were tested using a simplified model consisting of a single ring and wire. The holding capacity at two different tightening torques (10 and 14 Nm) of classic cannulated bolts (CB) and slotted bolts (SB) was determined on Ilizarov and Taylor Spatial Frame (TSF^{TM}) rings, whereas the modified TrueLok^{TM} CBs and SBs were used with the TrueLok^{TM} rings. The wire stiffness was calculated via a regression analysis of the load–displacement graphs. The modified TrueLok^{TM} bolts demonstrated significantly better slippage resistance than the classic bolts in all configurations and wire stiffness was significantly higher in the TrueLok^{TM} frame set-ups. After maximum loading, all of the wires showed plastic deformation, including constant wire deflection and dent marks at the clamped wire ends. In conclusion, the decrease in wire stiffness can be explained mainly as a result of wire slippage, but plastic deformation and material yielding also contribute. The relatively simple modification made by roughening the wire–bolt interface results in improved holding capacity and wire stiffness. A frame that contains these modified TrueLok^{TM} bolts should provide improved mechanical stiffness.

Key words: *Ilizarov external fixator, wire slippage, fixator stiffness, connection bolt*

1. Introduction

Ilizarov ring fixators are widely used in fracture care, limb reconstruction and deformity correction. Unlike other external frames, the Ilizarov system uses thin transosseous wires that allow the stable yet dynamic fixation of the bone fragments. To prevent large interfragmentary movements, the wires in the Ilizarov system must be able to withstand the axial load of the bone fragments during weight bearing. Biomechanical parameters such as the wire angle, the amount of wire tension and the wire material have been defined as improving overall frame stiffness [1]–[6]. A very important but often overlooked component is the wire–bolt interface. The bolts clamp the wire to the ring after the tension loading of the wire to improve the initial low bending stiffness [7], [8]. It has been demonstrated that a decrease in wire tension occurs directly after the wire is clamped to the ring, at the moment when the tension loading device is removed and during weight bearing [6], [7], [9]–[14]. Wire slippage has been identified as the main reason for this tension loss [7], [9], [14]. This tension loss results in a decreased overall frame stiffness, the instability of the bone fragments and larger interfragmentary movements, which in turn

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* Corresponding author: Jan Gessmann, Department of General and Trauma Surgery, BG University Hospital Bergmannsheil, Ruhr University Bochum, Bürkle-de-la-Camp-Platz 1, 44789 Bochum, Germany. Tel.: 0049 234 302 0, fax.: 0049 234 302 6542, e-mail: jangessmann@me.com

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cause prolonged bone healing, non-union and secondary deformities [3], [15]. Thereby the connection bolts have been identified as one of the weak elements of the Ilizarov device [6], [7], [10], [11]. Increased holding capacity can be achieved when higher tightening torques are applied to the bolts [6], [14] and when the bolt surface is roughened [7]. In a recent study, LA RUSSA et al. [7] used custom-made bolts with a sandblasted surface. Modifications to the commonly used cannulated and slotted bolts have been introduced. These bolts feature a grooved profile on the side of the wire–bolt interface (TrueLok™, Orthofix; see figure 1(A) and figure 2(A)) and are available for clinical use. The purpose of this study was to investigate the slippage resistance of the riffled bolts and their influence on wire stiffness in comparison with that of bolts featuring the classic design with a smooth profile.

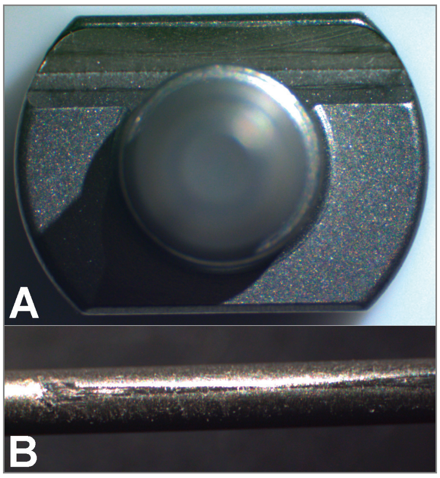

Fig. 1. A photograph of a classic Ilizarov slotted bolt (A) and a wire at the clamped wire end (B) (tightening torque of 14 Nm)

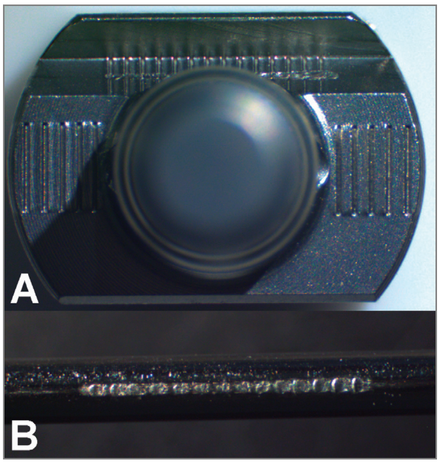

Fig. 2. A photograph of a TrueLok™-bolt (A) and a wire at the clamped wire end (B) (tightening torque of 14 Nm); the slotted part of the bolt was used in the test run

2. Materials and Methods

Three different ring designs with a diameter of 180 mm were used: a classic Ilizarov ring comprised of two stainless steel half rings (Smith and Nephew, USA), and two aluminium full rings (Taylor Spatial Frame™ (Smith and Nephew) and TrueLok™ (Orthofix, USA)). The rings were mounted rigidly on the base plate of a universal test machine (UTS, Germany) with four steel blocks (figure 3). A polyethylene bar that was 3 cm in diameter was fastened to the actuator of the test machine, which represented a bone fragment. Stainless steel (1.8 mm) wires were inserted through the bar through a 1.8 mm hole that was predrilled perpendicular to its axis. The wires were tension loaded using a standard wire tensioner (Smith and Nephew) to the 110 kg mark (1,080 N) and secured to the ring with slotted or cannulated bolts and a DIN-certified torque wrench (Dremometer AM 6-30 N, Gedore, Germany). In the assembly process used with the Ilizarov/TSF™ rings, Smith and Nephew wires and bolts were used, and for the TrueLok™ assembly process, Orthofix wires and bolts were used. After the tension loading of the wire, an inductive displacement transducer (W2ATK, HBM, Germany) was placed at each free end of the wire outside the ring and on the connection bolts to determine the degree of wire slippage. The core unit and the plunger were fixed in a custom-made mounting device: the core unit was attached to the ring at the level of the connection bolt, and the plunger was attached parallel to the wire (figure 3). This configuration allowed the wire slippage to be measured towards the centre of the ring at each end of the wire using a measurement unit of 0.1 μm. The polyethylene bar was pushed perpendicularly towards the wire at its centre of length, and the following parameters were recorded: the displacement of the polyethylene bar (in mm), the applied load (in N) and the wire slippage (in mm). This basic experimental design was used with the three different ring designs, the different slotted and cannulated bolts and the tightening torques of 10 Nm and 14 Nm. Each configuration was tested 10 times with new bolts and wires, and the rings were rotated so that each bolt and wire was secured at a previously unused hole. The different torques were chosen based on the literature and our own clinical tests; RENARD et al. [14] found torques ranging from 8 Nm to 14 Nm (median: 10 Nm,) and MULLINS et al. [5] used a median torque of 8 Nm. OSEI et al. [6] determined that a torque of at least 10 Nm should be used and suggested the optimal torque to be 14 Nm.

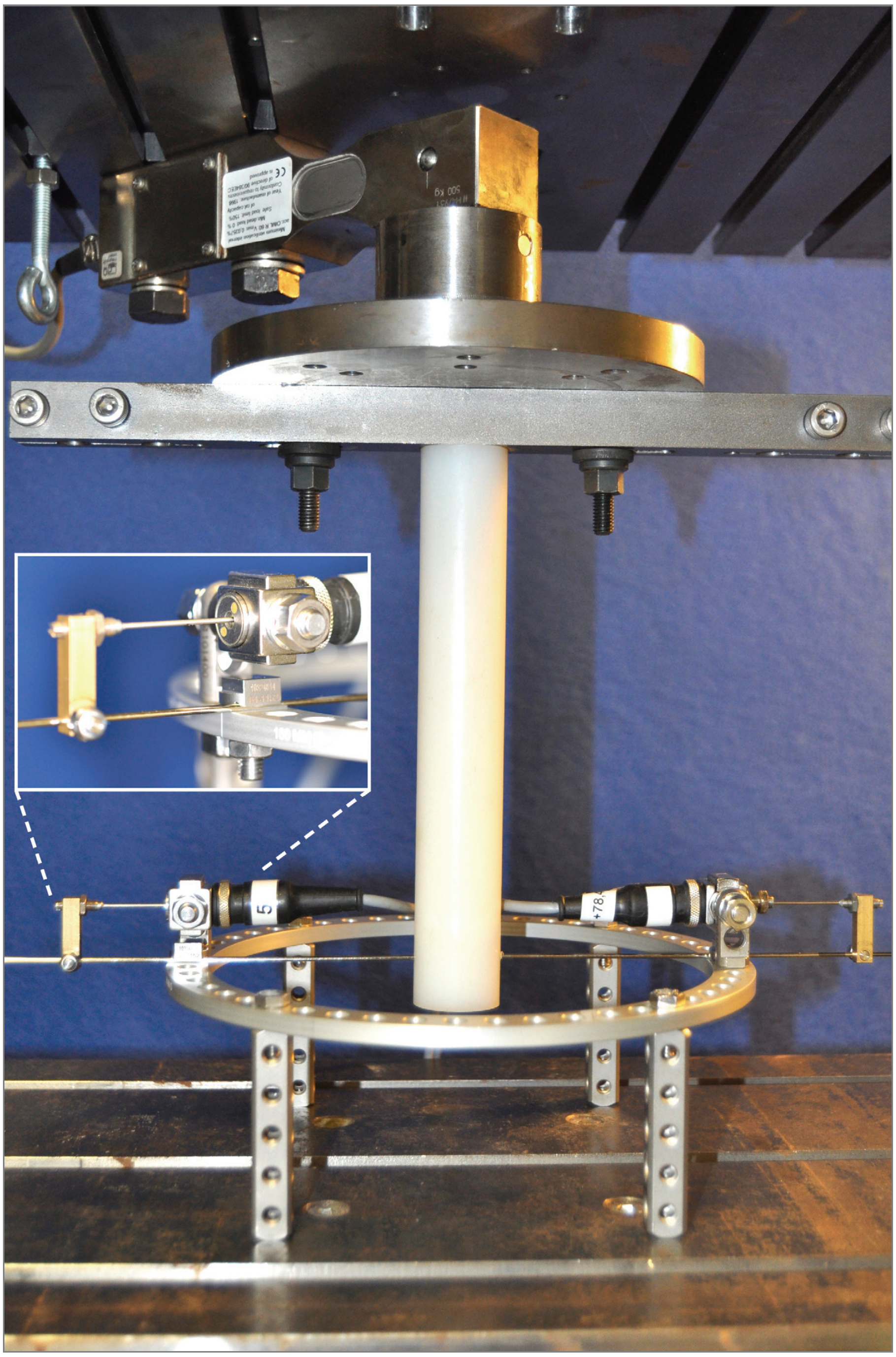

Fig. 3. A photograph showing the experimental set-up (example with a TrueLok^{TM} ring and connection bolts). The picture detail displays a close-up view of one of the two displacement transducers used to measure slippage

Our own tests of the clinical applications of the Ilizarov frames led us to identification of the torques between 10 Nm and 14 Nm.

In most studies which analyse a single wire, a maximum load of 200 N is applied because an equal load distribution in a double 4-wire Ilizarov configuration is theoretically assumed in an 80 kg patient. Although excessive loads on the wires should be minimised, much higher loads may be transmitted by a single wire under weight bearing [5]. Therefore, slippage was analysed at 200 N and at higher loads of 650 N. The results for the two displacement transducers for each experiment are summarised to indicate the total amount of slippage. Additionally, the axial load that induced 0.5 mm slippage was evaluated. The axial stiffness (in N/mm) was calculated based on the load–displacement curves via a regression analysis of the graphs, as previously described [16], [17]. All wires were examined under a light microscope (MVX 10, Olympus, Germany) for friction and plastic deformation caused by clamping and axial loading.

The data acquisition was performed using the VEE Pro software version 7 (Agilent Technologies, USA). All statistical analyses were performed using Excel (Microsoft, USA) and commercial statistical software (Graph Pad Prism, version 5.0; Graph Pad Software, USA). The data were analysed using an analysis of variance (ANOVA) followed by a post hoc test determining the individual differences. The Student's *t*-test was applied to compare the slippage and stiffness values between two specific configurations. The level of significance was considered to be $p < 0.05$.

3. Results

The mean results of wire slippage at 200 N and 650 N are presented in table 1 for each of the ring/bolt configurations tested. Slippage occurred in all of the configurations. Thereby the TrueLok$^{\text{TM}}$ configurations demonstrated a higher slippage resistance in comparison to the Ilizarov and TSF$^{\text{TM}}$ configurations. At 200 N, the differences of the SB-configurations were found to be statistically significant (SB 10: $p = 0.034$; SB 14: $p = 0.0031$) whereas the slippage differences for the CBs were not significant (CB 10: $p = 0.053$; CB 14: $p = 0.1061$). At the higher axial load of 650 N, slippage values of both slotted and cannulated TrueLok$^{\text{TM}}$ bolts demonstrated significant differences of slippage resistance (SB 10: $p = 0.0004$; SB 14: $p = 0.0011$;

Table 1. Wire slippage at 200 and 650 N axial load

Rings/Screws/Torques		Slippage at 200 N in mm	Slippage at 650 N in mm
Ilizarov	SB 10	0.27 (0.17)	1.74 (0.28)
	SB 14	0.21 (0.14)	1.46 (0.26)
	CB 10	0.25 (0.31)	2.48 (0.28)
	CB 14	0.1 (0.12)	1.90 (0.69)
TSF$^{\text{TM}}$	SB 10	0.23 (0.09)	2.29 (0.38)
	SB 14	0.01 (0.01)	1.63 (0.33)
	CB 10	0.03 (0.02)	1.94 (0.36)
	CB 14	0.01 (0.01)	1.66 (0.51)
TrueLok$^{\text{TM}}$	SB 10	0.06 (0.03)	1.18 (0.13)
	SB 14	0.02 (0.01)	0.86 (0.11)
	CB 10	0.06 (0.01)	1.15 (0.35)
	CB 14	0.02 (0.02)	0.32 (0.05)

SB: slotted bolts, CB: cannulated bolts; standard deviations in brackets; *p*-values are presented for Ilizarov vs. TrueLok$^{\text{TM}}$ (A) and TSF$^{\text{TM}}$ vs. TrueLok$^{\text{TM}}$ (B): SB 10 (A): $p = 0.0119$; (B): $p = 0.0272$; SB 14 (A): $p = 0.0035$; (B): $p = 0.0431$; CB 10 (A): $p = 0.0017$; (B): $p = 0.0221$; CB 14 (A): $p = 0.0030$; (B): $p = 0.0016$

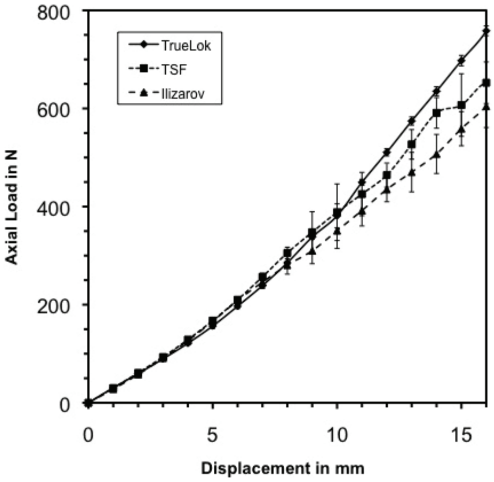

Fig. 4. A load–displacement graph of CB at a tightening torque of 14 Nm

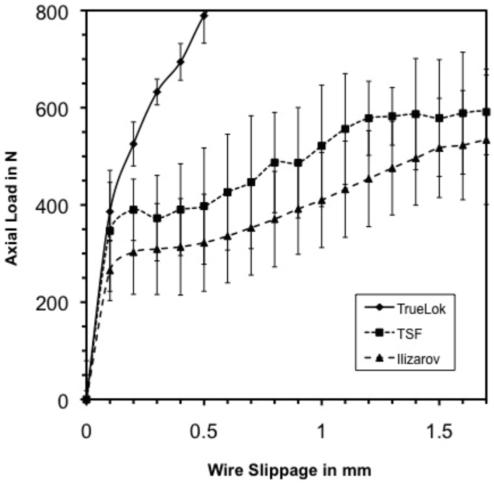

Fig. 5. A load–slippage graph of CB at a tightening torque of 14 Nm

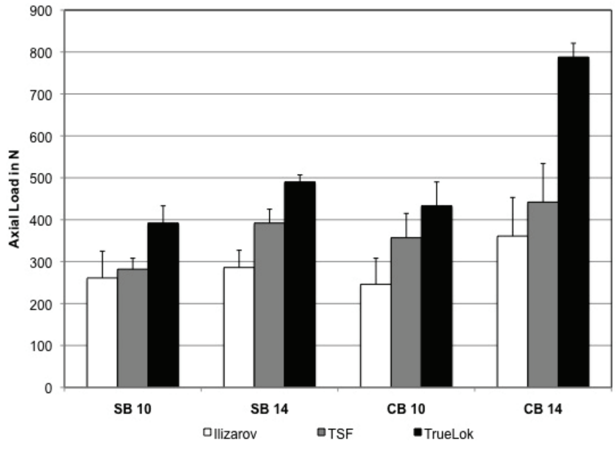

Fig. 6. A diagram showing the axial load inducing a 0.5 mm wire slippage. P-values are presented for Ilizarov- vs. TrueLok$^{\text{TM}}$-configurations (A) and TSF$^{\text{TM}}$- vs. TrueLok$^{\text{TM}}$-configurations (B): SB 10 A: $p = 0.0048$; B: $p = 0.001$; SB 14 A: $p < 0.0001$; B: $p = 0.0004$; CB 10 A: $p = 0.0011$; B: $p = 0.696$; CB 14 A: $p < 0.0001$; B: $p = 0.0001$

CB 10: $p = 0.0003$; CB 14: $p = 0.0008$). The greatest slippage resistance was associated with the TrueLok^{TM}-CB tensioned to 14 Nm. Figures 4 and 5 display the exemplary load–displacement diagram and the corresponding load–slippage diagram for the CB tightened to 14 Nm. The higher slippage resistibility of the TrueLok^{TM}-configurations is also reflected in the evaluation of the axial load that induced 0.5 mm of wire slippage (figure 6).

In general, the configurations with better holding capacity showed a greater ability to sustain the axial load and less axial displacement of the polyethylene bar. Consistent with the results of the load–displacement and slippage experiments, the TrueLok^{TM}-CB and SB bolts demonstrated significantly greater stiffness at both of the tightening torques than was found for the Ilizarov and TSF^{TM} configurations. The mean axial stiffness results for all of the configurations are presented in table 2. The highest stiffness was found for the TrueLok^{TM}-CB tightened to 14 Nm with 45.2 (SD 0.53) N/mm compared to 39.71 (SD 2.88) N/mm (Ilizarov, $p = 0.003$) and 41.35 (SD 1.65) N/mm (TSF^{TM}, $p = 0.0016$).

Table 2. Axial stiffness (N/mm) at tightening torque of 10 and 14 Nm

	SB 10	SB 14	CB 10	CB 14
Ilizarov	38.94 (1.76)	39.4 (0.84)	36.0 (1.26)	39.7 (2.88)
TSF^{TM}	39.0 (1.35)	41.4 (0.31)	38.5 (0.88)	41.4 (1.65)
TrueLok^{TM}	40.8 (0.68)	42.3 (0.54)	41.1 (1.60)	45.2 (0.53)

SB: slotted bolts, CB: cannulated bolts; standard deviations in brackets; p-values are given for Ilizarov vs. TrueLok^{TM} (A) and TSF^{TM} vs. TrueLok^{TM} (B): SB 10 A: $p = 0.0119$; B: $p = 0.0272$; SB 14 A: $p = 0.0035$; B: $p = 0.0431$; CB 10 A: $p = 0.0017$; B: $p = 0.0221$; CB 14 A: $p = 0.0030$; B: $p = 0.0016$

Plastic deformation was observed in all of the wires, both at the clamped ends of the wire and as permanent mid-point-deflections. The light microscopy analyses of the clamped wire ends showed that the riffled surface of the TrueLok^{TM}-bolts was moulded into the wire, whereas a plain impression was left by the classic Ilizarov bolts (figure 1(B) and figure 2(B)).

4. Discussion

This study was designed to determine the holding capacities of different connection bolts and to analyse the influence of slippage on the overall amount of wire stiffness.

It has been shown that wire slippage and a loss of wire tension occur directly after clamping the wire to the ring at the moment when the tensioning device is removed and during weight bearing [6], [7], [9]–[14]. Consistently wire slippage was recorded for all configurations under the axial loading of the wires in the present study. Different methods of determining wire slippage in the Ilizarov system have been described in the literature. OSEI et al. [6] marked the wires with tape attachments and measured the slippage by recording any separation of the tape from the side of the ring of at least 1 mm, suggesting that this was the smallest gap that could be observed "by the naked eye". However, other authors have demonstrated that slippage occurs on smaller scales than 1 mm and that such small amounts of slippage have a significant influence on wire tension [7], [9]. To precisely detect these small changes, an electrical measurement technique must be used. AQUARIUS et al. [9] recorded wire slippage with an extensometer on one end of the wire while slippage on the other end of the wire was eliminated with a custom-made fixation device. Like RENARD et al. [14] and LA RUSSA et al. [7], who both measured slippage with extensometers on both sides of the wire, we used two inductive displacement transducers that recorded the total amount of wire slippage. The bolts used in the first study were not mentioned by RENARD et al. [14], while LA RUSSA et al. [7] used cannulated bolts and washers that were modified with a custom-made sandblasted surface to roughen the wire–bolt contact interface and optimise the frictional force of the bolts. The researchers found significantly lower amounts of wire slippage in all of the loading conditions tested. Similarly, the TrueLok^{TM} configurations demonstrated significantly lower amounts of slippage than did the classic bolts tightened on both standard Ilizarov and TSF rings under the tightening torques tested.

The influence of the different tightening torques on the holding capacity of the classic bolts has been evaluated [4]–[6]. A torque of 10 Nm is suggested by MULLINS et al. [5] to prevent wire slippage, whereas OSEI et al. [6] found a torque of 14 Nm to be optimal for withstanding higher loads without loss of pre-tension and suggested that higher torques resulted in the mechanical failure of the bolts [4]–[6]. In this study, the higher tightening torques of 14 Nm resulted in greater holding capacities in all of the wire–bolt–ring configurations. Interestingly, only tightening torques between 5 Nm and 10 Nm have been reported in clinical tests with experienced Ilizarov surgeons [5], [14]. In all of the classic configurations (with exception of the TSF^{TM} with CB at 10 Nm) we found comparatively large amounts of slippage at already 200 N axial loading (see table 1).

As in earlier studies, lower amounts of wire slippage corresponded to greater wire stiffness [1], [7], [9], [14], indicating the influence of wire slippage on the overall frame stiffness. This relationship has been the subject of debate in the literature: a decrease in frame stiffness has been attributed to wire slippage [1], [14], to a combination of wire slippage through the connection bolts and material yielding [6], [10], [18] and to material yielding alone [13]. For example, AQUARIUS et al. [9] identified a 24% loss of wire tension directly after tension loading due to slippage, whereas WATSON et al. [12] recorded a similar tensioning loss of 22% but explained the loss as having been due to the plastic deformation of the wire: tightening squeezed the wire and increased the wire length, resulting in pre-tension loss. Visible plastic deformation has been observed in all wires in this study, both at the clamped ends of the wire and as permanent deflections at the loading site as described similarly in previous studies [6], [7], [10], [13], [18]. It has been hypothesised that the effect of material yield and plastic deformation increases when slippage is nearly eliminated [1]. Our results support this hypothesis; the overall wire slippage and the wire stiffness of the different configurations were not directly proportional. For example, the total slippage of the TrueLok$^{\text{TM}}$-CB (14 Nm) was more than five times less than that of the CB tightened on a TSF$^{\text{TM}}$ ring, yet the TrueLok$^{\text{TM}}$ bolts resulted in only an eight percent increase in overall wire stiffness. The load–displacement relationship in all of the configurations tested showed the typical non-linear behaviour that has been attributed to the self-stiffening effect of the wires under increasing loads [2], [19], [20]. ZHANG [20] demonstrated that higher wire tensions cause the wire to harden at lower loads, resulting in the constant plastic deformation of the wire, which could result in earlier material failure and wire breakage even when the slippage is nearly prevented [1], [18]. We did not detect any wire breakage even at the maximum induced loads; however, these results may be different under clinical conditions including residual and dynamic stresses. Clinical trials and biomechanical studies involving the dynamic loading of more realistic frame constructs must be conducted to answer these questions.

In conclusion, we agree with the conclusion presented in other recent studies [7], [9]: decreases in wire stiffness and wire tension are affected both by wire slippage and by wire yielding, with slippage as the major influencing factor. More complex loading conditions and interactions between other ring parameters are not taken into account in the present study and need to be considered when interpreting the results for clinical practice. Despite these limitations, it can be demonstrated that the riffled TrueLok$^{\text{TM}}$ bolts generate improved holding capacity and increased wire stiffness. A frame constructed with these bolts should provide better mechanical stability. To our knowledge, this is the first biomechanical study of the TrueLok$^{\text{TM}}$ fixator. The high slippage results observed for the classic bolts, especially under lower but often clinically relevant [5], [14] tightening torques, underline the importance of the surgeon's tightening the bolts to at least 14 Nm.

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