Rapid pre-tension loss in the Ilizarov external fixator

An in vitro study

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Background and purpose Wire pre-tension in the Ilizarov frame is considered to be important in order to reduce movements that can impair fracture healing. Wires will eventually lose part of their pre-tension, however. In order to gain more insight into the need for wire pre-tension, we investigated: (1) the amount of pre-tension loss, (2) the relationship between pre-tension loss and bolt-tightening torque, (3) the cause of a possible loss of pre-tension, and (4) the effect of pre-tension on cyclic micromotions and total displacement of the bone segments.

Methods 3 Ilizarov configurations, with various wire pre-tensions and bolt-tightening torques, were tested 3 times with an MTS machine. For each wire, slippage and tensions were measured for the duration of the whole experiment.

Results A loss of wire pre-tension (up to 75%) due to slippage was found. Higher bolt-tightening torques significantly reduced the amount of pre-tension loss. Furthermore, a higher wire pre-tension reduced the maximal axial displacement of the bone fragment. There was, however, least cyclic axial micromotion when no wire pre-tension was present—probably due to the lack of wire recoil.

Interpretation Wires in an experimental Ilizarov external fixator lose pre-tension within a limited period of time, and probably also in the clinical setting. This does not seem to lead to increased cyclic axial micromotions of the bone fragements. However, the question remains as to how excessive axial displacement of the bone fragment and other loading configurations will affect the process of fracture healing in a patient.

The Ilizarov system has proven successful for the treatment of complicated fractures and limb-lengthening procedures (Marsh et al. 1997, Arazi et al. 2001, Ramesh et al. 2004, Nikonovas et al. 2005, Sardis et al. 2006).

Inter-fragmental movements play an important role in the complex process of fracture healing. Although the optimal environment for fracture healing is still unknown, large shear forces, bending, and large axial movements have a deleterious effect (Noordeen et al. 1995, Yamaji et al. 2001, Augat et al. 2003, Schell et al. 2005), while small shear and small axial movements are beneficial (Wolf et al. 1998, Bishop et al. 2006).

In order to promote small movements of the bone fragments and to avoid large inter-fragmental movements, the Ilizarov frame requires adequate settings. Wire pre-tensions of 981–1,275 N (100–130 kg) and bolt-tightening torques in the 10–20 Nm range are considered to be suitable for stable fixation (Aronson and Harp 1992, Catagni et al. 1996, Mullins et al. 2003, Renard et al. 2005).

It is known that Ilizarov wires lose their initial pre-tension, but the exact cause is the subject of debate. Some authors believe that slippage is responsible for the loss of pre-tension (Aronson and Harp 1992, Renard et al. 2005), while others have shown that material yield (Hillard et al. 1998) or a combination of material yield and wire slippage (Delprete and Gola 1993, Watson et al. 2003b, Osei et al. 2006) cause the loss of pre-tension in the wires.

According to Ilizarov (1990), proper wire tension should be maintained throughout the entire healing

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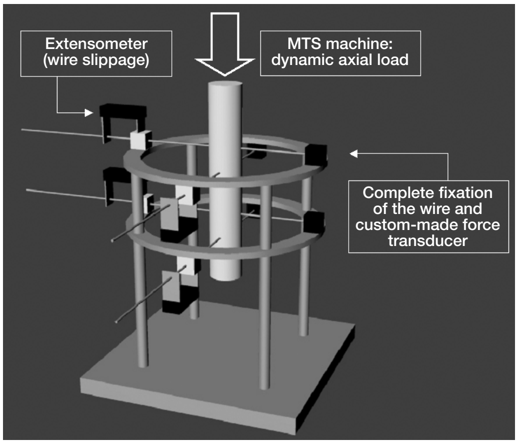

Figure 1. Overview of the experimental set-up. The black and white blocks attached to the rings represent the fixation clamps and the cannulated bolts, respectively.

period. However, loss of wire tension can be as much as 100% after 15 min of dynamic loading, as we have shown in a previous study (Renard et al. 2005). It should be mentioned that these data were obtained using an experimental set-up consisting of only one wire, and it is unknown whether this considerable loss of pre-tension is also found with a more realistic and complex experimental set-up.

In this study, we addressed four questions: (1) What is the extent of pre-tension loss of the wires in an Ilizarov external fixator after 15 min of dynamic loading? (2) How is a possible loss of pre-tension related to the tightening torque of the bolts? (3) Can the loss of pre-tension be solely explained by slippage of the wires? (4) What is the relationship between the pre-tension and the micromotions at the fracture site? To answer these questions, we carried out measurements on an experimental Ilizarov frame, which was dynamically loaded for 15 min. Wire pre-tension and bolt-tightening torque were varied in the various configurations.

Methods

Experimental set-up and measurements

The standard Ilizarov frame (4 rings, 8 wires) is symmetrical with respect to the fracture site. Thus, we concentrated our measurements only on the upper 2 rings (4 wires) of the system. This allowed us to measure slippage of—and pre-tension in—each wire.

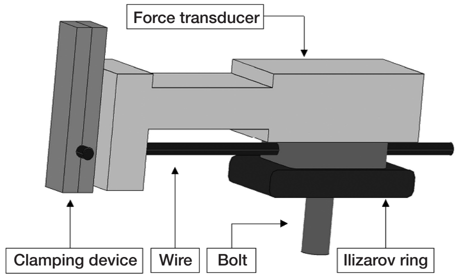

Figure 2. Representation of one force transducer. The wire passes through the outer rim of the transducer and ends up in a clamping device. The wire is bent 90 degrees and clamped between 2 metal plates, to ensure complete fixation of the wire.

The experimental set-up (Figure 1) consisted of a polyethylene bar with a length of 17.6 cm and a diameter of 3 cm, which represented the bone fragment. The polyethylene bar was suspended in an Ilizarov frame that consisted of 2 metal rings (diameter 150 mm) (Smith & Nephew part number 101305; Smith & Nephew Healthcare Ltd., Cambridge, UK). Each ring supported 2 perpendicularly-oriented K-wires with a diameter of 1.8 mm (Smith & Nephew part number 102102) that were drilled through the bar. The distance between the rings was 6 cm.

One side of each wire was clamped to the corresponding ring in such a way that no slippage was possible. These clamping systems were equipped with a custom-made force transducer that was able to monitor the forces in the wire (Figure 2). All force transducers were individually calibrated using an MTS machine (MTS Systems Corp., Eden Prairie, MN). After fixing one end of each wire, the wire was pre-tensioned. When the desired amount of pre-tension was applied, the “free” end of the wire was attached to the ring using a cannulated bolt (Smith & Nephew part number 100600). In order to measure slippage of the 4 wires, 4 calibrated extensometers were used. Each extensometer was attached to the cannulated bolt and the free end of the wire (outside the ring) was clamped by that bolt. In this way, slippage toward the center of the ring was quantified. Hence, pre-tension and slippage were monitored for each individual wire during the experiment.

All experiments were done with this basic set-up; the parameters that were varied were the tightening torque used to tighten the bolts and the initial

Table 1. Overview of the settings for the 3 frame configurations

Configuration number	Wire pre-tension (N)	Tightening torque (Nm)	Axial load (N)
1	0	10	800
2	1,275	10	800
3	1,275	20	800

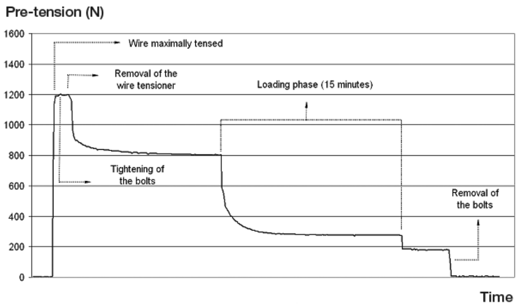

Figure 3. Typical graph of the pre-tension in one wire during one test. This particular wire was tensed to 1,275 N (130 kg) and the bolts were tightened to 10 Nm (configuration 2).

wire pre-tension (Table 1). A tightening torque of 10 Nm was chosen for the first and second configuration, as this amount of torque is used in clinical practice (Mullins et al. 2003, Renard et al. 2005). A higher tightening torque of 20 Nm was chosen for the third configuration, because it represents a safe upper limit for the bolt torque (Aronson and Harp 1992). Each configuration was tested 3 times, and all 9 tests were performed with the same cannulated bolts, nuts, and Ilizarov rings. New wires were used for every test. To minimize the effect of possible material wear and plastic deformation, the tests with the various configurations were performed in random order.

In the second and third configuration, all wires had a pre-tension of 1,275 N (130 kg) according to the scaling on the dynamometric tensioners that were used (Smith & Nephew part number 103101). Calibration of these tensioners showed that the actual wire tension, when the dynamometric tensioner indicated 130 kg, was 1,200 N (122 kg). We will use 1,275 N or 130 kg whenever we refer to this pre-tension, even though it was actually less. This overestimation of 6% is in accordance with the data of Watson et al. (2005). Wires attached to the same ring were tensed simultaneously in order to distribute the tension to the wires evenly, and to prevent deformation of the rings. To make sure that the bolts were tightening with the correct torque, an instrumented torque wrench (Stahlwille part number 73; Stahlwille B.V., Raamdonksveer, the Netherlands) was used.

The complete frame was placed under an MTS machine and tested with an axial dynamic load of 0–800 N for 15 min. The chosen axial load of 800 N was in line with our previous work (Renard et al. 2005), and it was also in accordance with in vivo data from Duda et al. (2002). The loading time of 15 min was chosen based on the work of Renard et al. (2005), who found a substantial loss of wire tension within this time.

Statistics

The average loss in pre-tension between configuration 2 (10 Nm) and configuration 3 (20 Nm) was analyzed at 2 time points: (1) after tightening the bolts, and (2) after the complete loading phase. This was done using Student's t-test. The relationship between loss in wire pre-tension and wire slippage was determined by calculating Pearson's correlation coefficient (r) for every test done with the second configuration (10 Nm) and the third configuration (20 Nm). The average cyclic axial motion and maximal axial displacement of the polyethylene bar of all three configurations were analyzed with ANOVA for statistical differences. A post-hoc Tukey HSD test was performed to determine which groups differed significantly. All statistical analyses were performed with SPSS version 12.01 (SPSS Inc., Chicago, USA).

Results

Pre-tension

In order to show an example of our experiment, a typical graph of the pre-tension of 1 wire is shown in Figure 3. The various stages of the experiment can be seen in this graph: tensioning of the wire, tightening of the bolts, and loading of the frame. Each test provided us with similar data from all 4 wires. Every wire in all the tests with configurations

Table 2. Average loss of pre-tension after tightening of the bolts and after the loading phase

Configuration [a]	Pre-tension loss (SD), N after tightening the bolts	after loading phase
2	277 (92)	829 (146)
3	277 (92)	363 (76)

[a] See Table 1

Table 3. Correlation between wire slippage and pre-tension loss for configurations 2 and 3

Configuration [a]	Test	r [b]	99% CI for r [c]
2	1	–0.997	–0.996 to –0.998
	2	–0.998	–0.997 to –0.999
	3	–0.984	–0.976 to –0.989
3	1	–0.638	–0.502 to –0.743
	2	–0.882	–0.827 to –0.920
	3	–0.808	–0.724 to –0.869

[a] See Table 1
[b] r = Pearson correlation coefficient
[c] 99% confidence interval

2 and 3 showed a loss of pre-tension after tightening of the bolts to fix the wires to the rings (Table 2). The average loss in pre-tension of all wires in all tests performed with configuration 2 (tightening torque 10 Nm) was 277 (SD 92) N. For configuration 3 (tightening torque 20 Nm), the average pre-tension loss was the same: 277 (SD 92) N.

Pre-tensions were further reduced after 15 min of dynamic loading (Table 2). The tests performed with configuration 2 showed an average pre-tension loss of 829 (SD 146) N. The average total loss of pre-tension in configuration 3 was limited to 363 (SD 76) N after 15 min of loading. Student's t-test revealed that configuration 2 lost significantly more pre-tension than configuration 3 ($p < 0.001$), indicating that greater loss of pre-tension was found with a lower tightening torque of the bolts.

Wire slippage

All wires in configurations 2 and 3 showed some amount of wire slippage after tightening of the bolts. The wires of the second configuration (tightening torque 10 Nm) showed an average wire slippage at the end of the loading phase of 0.37 (SD 0.067) mm for all tests. An average slippage value of 0.018 (SD 0.003) mm was recorded in the third configuration (tightening torque 20 Nm). There was a high correlation between the slippage that occurred during the loading phase of the experiment and the loss of pre-tension (Table 3).

Table 4. The average cyclical movements and the maximal axial displacement of the polyethylene bar, measured in all configurations

Configuration	Test	Axial cyclical movements (mm)	Maximal displacement (mm)
1	1	3.45	6.1
	2	3.42	5.9
	3	3.37	6.2
	average	3.44 [a]	6.1 [b]
2	1	3.90	5.8
	2	3.97	5.4
	3	4.15	5.3
	average	3.93	5.5 [c]
3	1	4.18	– [d]
	2	3.81	4.5
	3	3.81	4.3
	average	3.99	4.4

[a] $p = 0.006$ vs. config. 2 and $p = 0.01$ vs. config. 3.
[b] $p = 0.04$ vs. config. 2 and $p = 0.001$ vs. config. 3.
[c] $p = 0.04$ vs. config. 1 and $p = 0.005$ vs. config. 3.
[d] Value missing due to technical error.

Cyclic axial movements

Significant differences in the cyclic axial motions were found amongst the test groups. The mean cyclic axial motion of the last 50 measurements during the loading phase are shown in Table 4. The mean cyclic motion of the polyethylene bar in configuration 1 (no pre-tension) was 3.44 (SD 0.018) mm. This was lower than the cyclic axial motions observed in configuration 2 (10 Nm) ($p = 0.006$, Tukey HSD test), with a mean of 3.93 (SD 0.05) mm, and configuration 3 (20 Nm) ($p = 0.01$, Tukey HSD test), with a mean of 3.99 (SD 0.26) mm. Thus, a complete lack of pre-tension resulted in lower amounts of cyclic axial micromotion of the polyethylene bar. No significant differences were found between configurations 2 and 3 ($p = 0.8$, Tukey HSD test). Hence, cyclic axial movement of the polyethylene bar was not affected by the tightening torque of the bolts.

Maximal axial displacement

The axial displacement of the polyethylene bar increased with decreasing pre-tension of the wire. The mean maximal axial displacement of the polyethylene bar for the last 50 measurements of the loading phase (Table 4) in configuration 1 (no pre-tension) was 6.07 (SD 0.15) mm. In configuration 2 (10 Nm), the mean maximal axial displacement was 5.5 (SD 0.27) mm. In the third configuration (20 Nm), the mean maximal axial displacement was 4.4 (SD 0.14) mm.

Configuration 1 showed more axial displacement than configuration 2 ($p = 0.04$, Tukey HSD test) and 3 ($p = 0.001$, Tukey HSD test). The maximal axial displacement between configurations 2 and 3 was also different ($p = 0.005$, Tukey HSD test). Hence, the displacements were higher in configurations that had no pre-tension or that showed a high amount of pre-tension loss.

Discussion

This study was performed to determine whether rapid loss of wire pre-tension would occur in a more realistic experimental set-up of an Ilizarov external fixator, and how possible pre-tension loss would be related to wire slippage and bolt-tightening torque, and how it could influence (cyclic) axial motion of the bone fragment.

The results were obtained using an experimental set-up rather than being measured under in vivo conditions. This leads to some limitations, which should be realized when interpreting the results. First of all, only axial loads were applied to the model in the current experiment, whereas more complex loading conditions would be present under clinical circumstances. Clinically, probably similar phenomena to those found in this study would occur under these more complex loading conditions, but additional studies are required to confirm this assumption.

Furthermore, we only used standard wire angles (perpendicular orientation). It is known that wire angles can influence frame stiffness, although the effect is greater on bending stiffness than on the axial stiffness of the frame (Bronson et al. 1998). Thus, we believe that these standard angles provided us with a good idea of the axial movements of the “bone fragment”.

All Ilizarov wires in configuration 2 (10 Nm) and 3 (20 Nm) showed a loss in pre-tension, which occurred in two stages: immediately after tightening of the bolts, and during the loading period. The average pre-tension loss that occurred immediately after tightening of the bolts was almost identical for both configurations: around 277 N, and in both this represents a loss of around 24% of the initial pre-tension. These data are in accordance with the data of Watson et al. (2003a), who demonstrated an average loss in wire pretension of 22% after tightening of the bolts. It seems, however, that the cause of their loss in wire pre-tension was different than ours. Watson et al. (2003a) demonstrated that the initial loss was due to plastic deformation of the wire; the wires were squeezed outwards and increased in length (like toothpaste squeezed out of a tube), thus losing pre-tension. Our set-up was similar; we tightened the bolts while the dynamometric tensioners remained attached to the ring, but we only measured a loss in pre-tension when we removed the tensioners—and not during the tightening of the bolts (Figure 3). This suggests that it was not plastic deformation of the wires, but rather wire slippage, that caused the pre-tension loss. In addition, we found that both configuration 2 and 3 showed the same amount of pre-tension loss—a phenomenon that would be unlikely to occur if the pre-tension was lost due to wire deformation, as one would expect more deformation (and thus more pre-tension loss) in the 20-Nm torque configuration than in the 10-Nm torque configuration.

The pre-tension loss that could be seen after the loading phase was very different for configurations 2 and 3. This indicates that a high bolt-tightening torque (20 Nm) is better able to maintain a higher wire pre-tension than a low bolt-tightening torque (10 Nm). This is in accordance with the results of other studies (Aronson and Harp 1992, Renard et al. 2005). This finding poses questions about the clinical reality of why surgeons do not use a much higher tightening torque (of at least 20 Nm) on the bolts.

The loss of pre-tension during the dynamic loading phase as seen in the 3 tests with configuration 2 (130 kg; 10 Nm), could be explained almost completely by wire slippage. There was almost a perfect linear relationship between these two parameters, according to the correlation coefficients between –0.984 and –0.998 for the various tests. This linear relationship between pre-tension loss and wire slippage was lower in the tests performed with the third configuration (20 Nm). This is most probably caused by the small amount of wire slippage and pre-tension loss during the dynamic loading phase seen in these tests. Obviously, a small amount of wire slippage is unfavorable for the signal-to-noise ratio. In this experiment, the noise was predominantly caused by the elastic response of the frame to the dynamic loading regime. As a consequence, a small cyclic extensometer signal is generated, which is not related to the wire slippage. This erroneous signal will be relatively high if the actual slippage of the wire is very small. The extremely high correlation between slippage and loss of pre-tension clearly shows that the main reason for pre-tension loss is wire slippage, and this finding is in line with the results of our previous study (Renard et al. 2005).

Our most remarkable finding was the low amount of cyclic axial movements of the polyethylene bar in the configuration without wire pre-tension, when compared to the other configurations. Although these differences were significant, they were also very small (the greatest difference was 0.60 mm). In the clinical setting, when soft tissues increase the axial stiffness of the Ilizarov frame even further (Duda et al. 2000), these differences in cyclic axial movements will probably be reduced even further. Even so, the surgical aim of maintaining wire pre-tension can be questioned; not only is a rapid loss in pre-tension apparent, but also cyclic axial motions are smaller when no pre-tension is applied. This is contrary to the philosophy that wires must keep their pre-tension in order to ensure stable fixation (Ilizarov 1990). The fact that wires without pre-tension show less cyclic axial motion than pre-tensed wires can be explained by the fact that when an axial load is put on the bone, the pre-tensed wires are pushed downwards—but also recoil to their initial position (assuming there is no plastic deformation in the wire or frame). When the wires have no pre-tension, however, they are pushed downward as the load is applied and do not return to their initial position after unloading. This hypothesis is supported by the maximal axial displacement of the polyethylene bar. Configuration 1 (no pre-tension) showed significantly more displacement than the other 2 configurations.

We found that a quick loss of pre-tension of the wires can be expected, but that this is not accompanied by an increase in the cyclic micromotions of the bone fragments under axial loading conditions. Hence, the microenvironment for fracture healing is not necessarily jeopardized by the loss of pre-tension. However, this does not mean that pre-tension in the wires is not an important factor. We found that the bony segment shows more displacement under conditions of low pre-tension, which could lead to (dynamic) contact of the bony segements. Extremely slack wires might even facilitate large, cyclic bending or shearing motion under transverse in vivo loading conditions, leading to delayed bone healing, pain, and discomfort for the patient.

We conclude that: (1) the wires in an Ilizarov frame show a rapid reduction of their initial wire pre-tension due to wire slippage, (2) higher bolt-tightening torques can be used to maintain more of the wire pre-tension, (3) loss of initial pre-tension leads to more total axial displacement of the bone fragment, and (4) micromotions are smaller when no pre-tension is applied to the wires. As discussed above, this last conclusion does not mean that pre-tensioning of the wires should be neglected. Stability of the bone fragments might be jeopardized in cases of overly slack wires.

Contributions of authors

RA: planned and performed the experiment, analyzed the data, and wrote most of the manuscript. AvK: gathered the materials used in the experiment, gave advice during the execution of the tests, and helped in writing the manuscript. NV: supervised the project and helped in planning and execution of the experiment, and in writing the manuscript.

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No competing interests declared.

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