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Mechanical Effects of Lag Screw Retightening in a Simulated Hindfoot Arthrodesis Model

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Abstract

Background: Nonunion following hindfoot arthrodesis may be caused by failure to maintain compression at the arthrodesis site. The ability of lag screws, commonly used in arthrodesis, to maintain compression in hindfoot bones has not been well characterized. The aim of this work was to quantify the stress relaxation response of hindfoot bone with initial and repeated compression with a lag screw.

Methods: Ten sets of 25-mm-diameter bone cylinders were cut from the talus and calcaneus in fresh-thawed cadaveric feet. A load cell was compressed between cylinders with an 8.0-mm partially threaded cannulated lag screw simulating arthrodesis. For 7 sets, screws were tightened by 3 quarter-turns, rested for 3 minutes, retightened 1 quarter-turn, and rested for 30 minutes. Three sets served as controls in which screws were not retightened.

Results: Maximum compression after initial screw tightening and retightening averaged 275 and 337 N ($P = .07$), respectively. Compression 3 minutes after initial screw tightening and retightening averaged 199 and 278 N ($P = .027$), respectively. The compression recorded 3 minutes after screw retightening was an average of 40% higher than that recorded 3 minutes after initial tightening. The average compression 30 minutes after screw retightening was 255 N, a compression loss of 25% from the average maximum compression after retightening. Eighty percent of this compression loss happened in an average of 5.5 minutes.

Conclusion: Hindfoot bones exhibit compression loss over time during simulated arthrodesis. Compression maintenance in bone is improved with screw retightening. Further work is needed to understand the mechanism of action and determine optimum time for recompression.

Clinical Relevance: Retightening lag screws before wound closure may improve compression at the arthrodesis site and thereby decrease the chance of nonunion.

Level of Evidence: N/A, laboratory experiment.

Keywords: Bone, fusion, subtalar, ankle, nonunion, stress relaxation, viscoelasticity

Introduction

Hindfoot (tibiotalar or talocalcaneal) arthrodesis is used to treat a variety of degenerative and traumatic conditions affecting the hindfoot. Nonunion and delayed union are common complications, occurring in 28% to 48% of cases,[3,8,14] with higher rates in patients with trauma, avascular necrosis, tobacco use, diabetes mellitus, and chronic kidney disease.[3,7-9] Compression across the arthrodesis site stimulates osteocytes and osteoblasts to promote bone growth[12] and thereby decreases the risk of nonunion.[6] Conversely, the failure to obtain and/or maintain compression at

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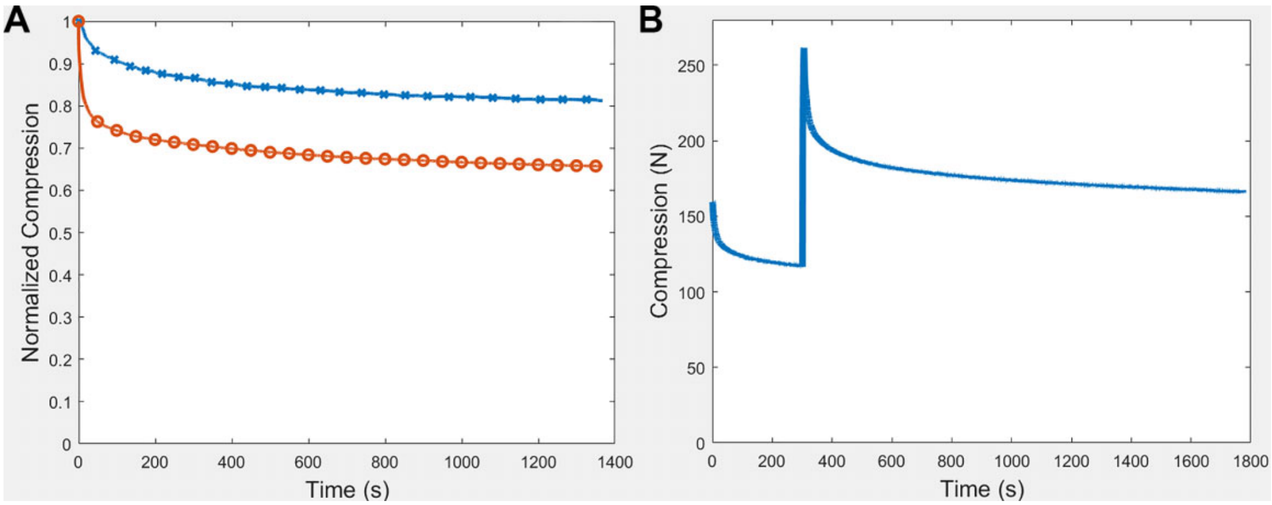

Figure 1. Stress relaxation: (A) Compressive force (normalized to peak force) vs time for bone specimen undergoing external compression with a hydraulic press (o) and lag screw compression (x). (B) The impact of external recompression (at 300 seconds) on maintenance of compressive load in cylindrical bone samples.

the arthrodesis site increases the risk of developing nonunion.

Bone, like other biologic materials, is highly viscoelastic.[11] It exhibits material properties characteristic of both solids and liquids. One of these is stress relaxation where the initially compressed material experiences a loss of compressive force over time as the material "flows" into a new configuration. Previous work in our laboratory has demonstrated that 65% of the compressive force applied directly to a sample of bone with a hydraulic press (hereafter referred to as external compression) is lost over 30 minutes[13] (80% of which occurs in the first 6 minutes). Stress relaxation leads to compressive loss both when bone is externally compressed and when compressed by a screw (Figure 1A). Moreover, it was found that in externally compressed hindfoot bone cylinders, this loss of compressive force can be mitigated by repeated external compression (Figure 1B).[13] This viscoelastic behavior of bone may be an important determinant of the amount of compression that can be maintained at an arthrodesis site.

Fixation in hindfoot arthrodesis is commonly achieved with partially threaded cannulated screws used to lag the 2 bones together. To determine the impact of bone viscoelasticity on the development and maintenance of compressive force during arthrodesis, it is necessary to understand not only the material behavior of the bone but also that of the fixation device and that of the interface between the bone and the fixation device. Our prior work, quantifying the loading response of bone cylinders subjected to external compression, provided information about the viscoelastic behavior of bone itself but did not account for that of the screw or the bone-screw interface.

In the present study, we sought to create an experimental model of hindfoot arthrodesis using bone cylinders harvested from talus and calcaneus and to quantify the composite compressive force obtained in these cylinders compressed with a partially threaded lag screw. Retightening of screws after an initial period of stress relaxation, as is commonly performed during internal fixation with plates and screws, has the potential to decrease the compression loss due to viscoelasticity. Although a number of studies have described the performance of these screws in obtaining compression in cancellous bone,[1,2,4,5] none have evaluated the time-dependent loss of screw compression nor assessed the ability of retightening to improve compression maintenance.

The goal of this study was to quantify the stress relaxation response of hindfoot bones compressed with a lag screw during simulated arthrodesis. Specifically, we sought to measure the loss of compressive force over time after placement of lag screws. Additionally, we sought to determine if screw retightening would have a significant impact on the maintenance of compression. We hypothesized that the magnitude of maximum compression would be larger for screw retightening compared with initial tightening; we also hypothesized that screw retightening would result in superior compression maintenance over time compared with initial tightening.

Materials and Methods

The talus and calcaneus were dissected free from 10 thawed fresh-frozen cadaveric feet. Soft tissue was removed and the subtalar joint was prepared for simulated arthrodesis by removing the cartilage from the articular surfaces of the talus and calcaneus. A 3.2-mm guide pin was placed perpendicular to the articular surface and a 5.5-mm cannulated drill was used to prepare the screw hole. Ten sets of bone cylinders 25 mm in diameter were then cut along the axis of the drilled

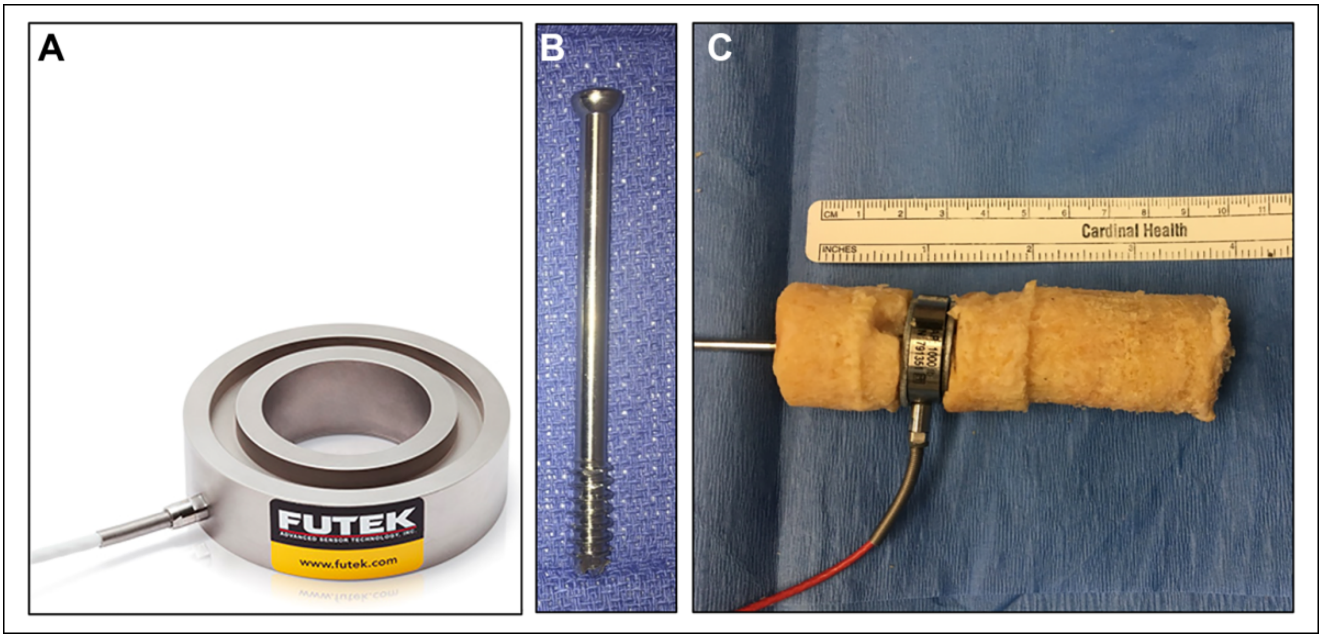

Figure 2. Experimental setup. (A) Load cell, (B) 8.0-mm partially threaded cannulated screw, (C) load cell and washers interposed between talus and calcaneus bone cylinders. The screw was advanced from right (calcaneus) to left (talus) over a guidewire (far left) to simulate subtalar arthrodesis.

holes using a 32-mm hole saw. The subchondral surface of each cylinder was then flattened with an oscillating saw. Bone cylinders with orthogonal arthrodesis surfaces were used rather than whole bone to ensure symmetric axial loading on the donut load cell.

A calibrated FUTEK LTH300 donut load cell (FUTEK Advanced Sensor Technology, Inc, Irvine, CA) and 2 metal washers were sandwiched between the 2 bone cylinders (Figure 2A). If necessary, additional washers were used as spacers to ensure that the threads of the partially threaded cannulated screw were entirely within the talus. The sensor was connected to an Arduino MEGA 2560 board (Arduino, Somerville, MA), FUTEK IAA100 analog load cell amplifier with voltage output (FUTEK Advanced Sensor Technology, Inc), and computer, which recorded the compressive load at 10 Hz through MATLAB (The MathWorks, Inc, Natick, MA). Data were filtered using a sixth-order Butterworth filter with a normalized frequency cutoff of 0.035 Hz.

An 8.0-mm partially threaded cannulated lag screw (Smith & Nephew, Memphis, TN; Figure 2B) was placed from the posterior-inferior aspect of the calcaneus cylinder to the anterior-superior aspect of the talus cylinder to simulate subtalar arthrodesis (Figure 2C). For the first 7 trials, the screw was tightened until the head made contact with the bone, then 3 more quarter-turns, left untouched for 3 minutes, retightened by 1 quarter-turn, and then left untouched for 30 minutes. This time point was chosen based on previous experiments with external compression in which compression had approximately reached steady state after 30 minutes had passed. Compressive force in newtons (N) was recorded continuously throughout each trial. The final 3 trials were conducted identically to the first 7 except the screws were not retightened; these trials served as a control.

The values for peak compression and compression 3 minutes after peak compression was reached were calculated for both the initial tightening and retightening for each specimen in the experimental trials. From each of these values, the percentage of compression loss 3 minutes following screw tightening and retightening (ie, the percentage change in compressive force which took place over a period of 3 minutes after each peak compression was reached) and the average rate of compression loss during those 3 minutes were calculated. Comparison between initial tightening and retightening was made using paired Student 1-tailed *t* tests; statistical significance was defined at the 5% ($P \leq .05$) level. The 3-minute time point was chosen based on previous experiments in which the majority of compression loss happened within a few minutes; we felt it would be most informative to focus on this period of rapid initial change. Descriptive statistics were used to characterize the increase in peak compression with retightening, the improvement in compression at 3 minutes after tightening, the magnitude of compression and the percentage of compression loss at 30 minutes as well as the time to reach 80% of the lost compression. These last 2 values were also calculated for the control trials.

Results

Maximum compression after initial screw tightening and retightening averaged 275 and 337 N ($P = .07$; Figure 3 and Table 1), respectively. Maximum compression obtained after

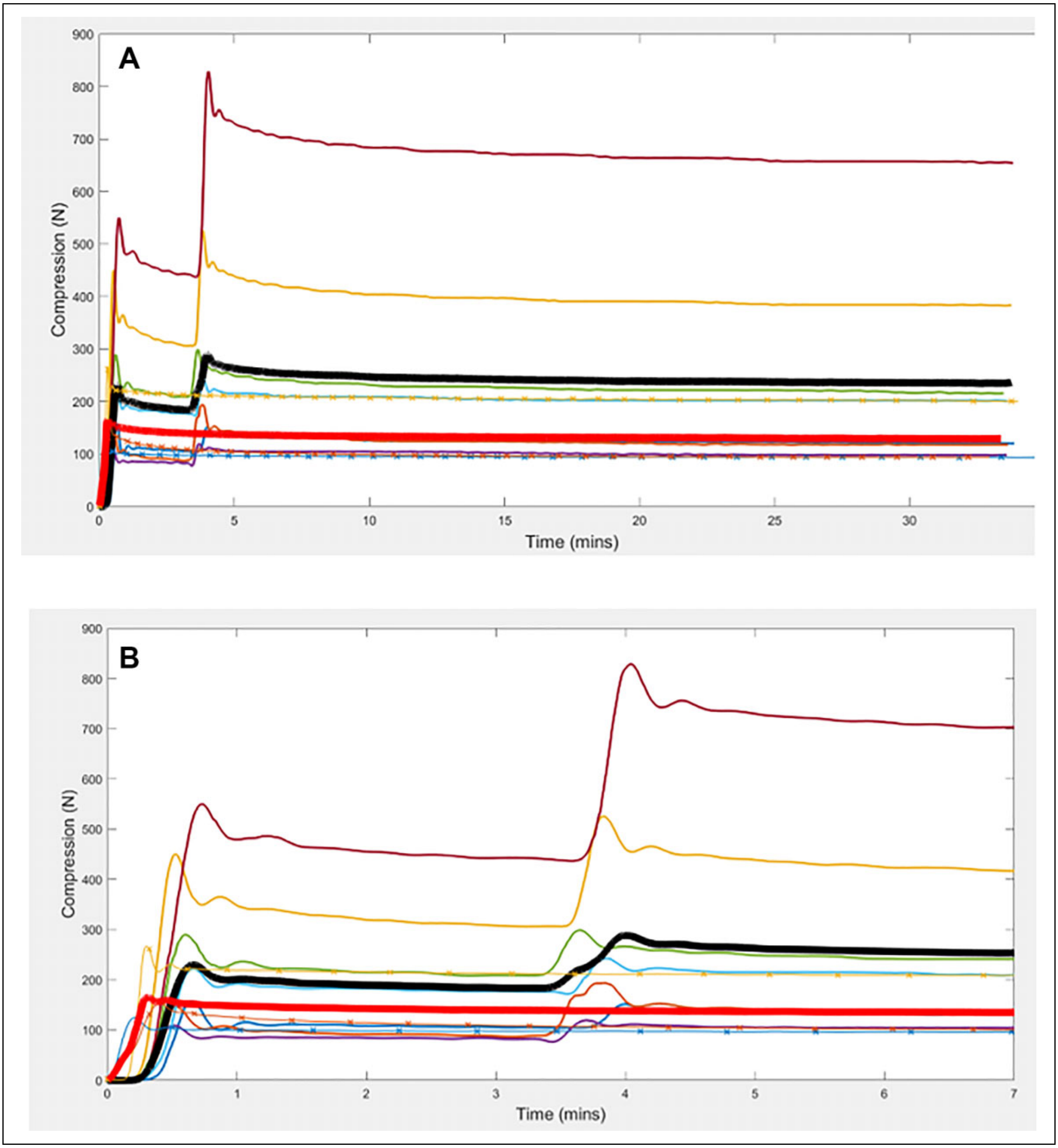

Figure 3. Individual and averaged stress relaxation response of hindfoot bones upon initial and subsequent compression with an 8.0 mm cannulated lag screw over (A) 30 minutes and (B) the first 3 minutes after tightening and retightening. Each thin solid line represents a single experimental trial and each dotted line represents a control trial. Average experimental data are represented by the broad black line and average control data are represented by the broad red line.

retightening was an average of 23% higher than that obtained with initial screw tightening and 67% higher than the compression recorded 3 minutes after initial screw tightening.

The compression recorded 3 minutes after initial screw tightening and retightening averaged 199 and 278 N (P = .027; Figure 3 and Table 1), respectively. Percentage compression loss 3 minutes after initial tightening and retightening averaged 29.5% and 17.7% (P = .0004; Table 1), respectively. The average rate of compression loss over 3 minutes was significantly less after retightening than

Table 1. Peak Compression and Compression Loss Comparison Between Initial Tightening and Retightening.

	Peak Compression (N)		Compression After 3 min (N)		% Compression Loss in 3 min		Average Rate of Compression Loss Over 3 min (N/s)	
Value	Initial	Retightened	Initial	Retightened	Initial	Retightened	Initial	Retightened
Mean	274.8	337.2	198.8	278.2	29.5	17.7	0.47	0.15
SD	166.7	254.9	132.4	215.8	6.8	6.5	0.25	0.10
P value	.074		.027		.0004		.001	

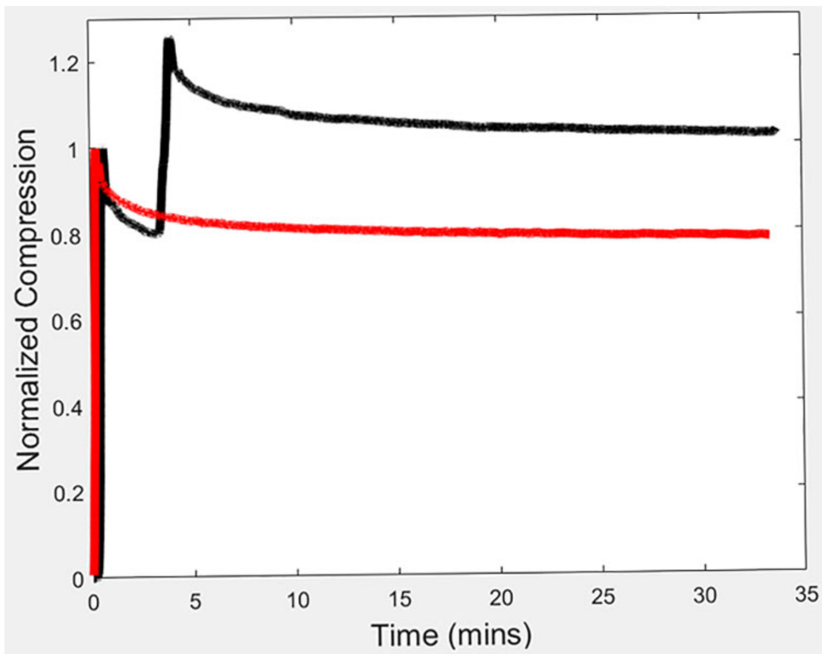

Figure 4. Normalized average stress relaxation response with repeated compression (black line) and control group with single compression (red line).

Table 2. Comparison of Compression Loss at 30 Minutes and Time to Lose 80% of the 30-Minute Compression Loss Between Retightening and Control.

	% Compression Loss in 30 min			Time to Lose 80% of the Total Compression Loss (s)		
Value	I	R	C	I	R	C
Mean	N/A	24.6	29.2	N/A	331.9	152.0
SD	N/A	7.7	8.1	N/A	172.2	75.9

Abbreviations: C, control; I, initial; R, retightened.

after initial tightening (Table 1; $P = .001$). The compression recorded 3 minutes after screw retightening was an average of 40% higher than that recorded 3 minutes after initial tightening (Figure 4).

The average compression 30 minutes after screw retightening was 255 N, which is a compression loss of 25% from the average maximum compression after retightening. Eighty percent of this compression loss happened in an average of 332 seconds (5.5 minutes). The control group experienced an average compression loss of 29% over 30 minutes; 80% of this compression loss occurred in 152 seconds (2.5 minutes) on average (Table 2).

Discussion

The goal of this study was to quantify the stress relaxation response of hindfoot bones when compressed with a lag screw during simulated arthrodesis by measuring the loss of compressive force over time after initial tightening and then after retightening of the lag screw. We found that stress relaxation occurred after both the initial compression and after recompression; however, the average rate of compressive force loss over 3 minutes was significantly lower after retightening. Such that, although the second peak compression was only increased by 23% with retightening compared with the first peak compression, the second peak compression was increased by 67% compared with the compression recorded 3 minutes after the first peak compression. In addition, the compression maintained at 3 minutes was increased by 40%. The difference in peak compression measured with screw retightening vs initial tightening was not found to be statistically significant, which may have been related to the small sample size.

Retightening screws resulted in a smaller average percent compression loss over 30 minutes compared with the control trials, and average time for 80% of that compression loss to occur was noticeably longer with retightening compared with control. These results agree with our findings that screw retightening slows the rate of compression loss and decreases the total amount of compression loss over 30 minutes. The normalized average experimental and control data curves in Figure 4 also suggest that the steady-state compression reached after screw retightening is noticeably higher than that reached after only initial tightening. However, statistical tests were not used to determine whether these differences are statistically significant because of the small sample sizes, which limits the conclusions we can draw from these data.

The principal finding of this study was that screw retightening leads to a significant decrease in compression loss. The impact of screw retightening on maintenance of compression has not been previously quantified and the underlying mechanism is not understood. However, it is known that trabecular deformation caused by screw tightening only occurs over a very small distance (less than 1 mm from the threads).[10] The resultant high local stresses caused by this concentrated deformation might exceed the yield point of the bone and create plastic (irreversible) deformation within and adjacent to the threads. Although widespread plastic deformation (stripping of the threads) leads to a decrease in holding power, it is possible that more localized deformation leads to increased local bone density and decreased stress relaxation.

As a precursor to the current study of screw tightening and compression loss, we had performed an investigation of compression loss during externally applied compression of cancellous hindfoot bones. In that study, we found that approximately 66% of the initial applied load was lost to stress relaxation over 30 minutes and that most (80%) of this happened in the first 6½ minutes. Recompressing after 5 minutes lead to a 33% improvement in retained compression.[13] In the present study, we found much less stress relaxation in compression with a screw as compared to external compression of a bone specimen. This may be related to the very limited area over which trabecular deformation occurs with screw tightening.[10]

There were a number of limitations in this study. First, the cadaveric simulated arthrodesis used in this study only models the behavior of bone at the time of surgery. Successful arthrodesis requires a minimum of 6 weeks for bone-to-bone healing, during which time there are likely changes in compression due to bone resorption that occurs during the healing process. Additionally, the fresh-thawed cadaveric bone used in this experiment may not adequately model the living bone in vivo, in which both blood and synovial fluid are under pressure within the bone. This likely changes the viscoelastic or poro-viscoelastic properties of the composite material. Another limitation is that the screws were not tightened to a preset torque, nor was the applied torque measured during tightening. Finally, the creation of a flat arthrodesis surface, which was needed to allow the load cell to sit flat, necessitated the removal of more subchondral bone than would be done routinely during arthrodesis.

In conclusion, the hindfoot bones exhibit viscoelastic behavior during simulated arthrodesis with loss of compression over time. The average rate of compression loss and the amount of retained compression were improved by retightening the screws after 3 minutes. The use of retightening during hindfoot arthrodesis could improve the amount of compression retained at the arthrodesis site. Further work is needed to understand the mechanism of action of retightening, determine the optimum time for recompression, and compare devices that are commonly used in hindfoot arthrodesis.

Ethics Approval

Ethical approval was not sought for the present study because no human subjects were involved.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. ICMJE forms for all authors are available online.

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