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Force Relaxation and Sprinback of Novel Elastic Orthopedic Cables

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Abstract: **Cerclage cables have proven to be very useful in the orthopedic field for bones stabilization and plate fixation but the initial enthusiasm for metallic cables has declined with their high complication rates. Metal materials provide limited elastic deformation compromising their ability to maintain compression. This study compares the mechanical properties of new elastic cables with cobalt-chrome and stainless-steel cables.**

Methods: Stainless-steel, cobalt-chrome, nylon and nickel-titanium cables were first loaded up to 356 N, then elongation was maintained for 12 hours, next unloaded and finally reloaded to failure. Initial elongation (%), Relative force relaxation (% loss of initial load after a 12h), elastic springback (%) and force to failure (N) were extracted from force-elongation curves.

Findings: Initial elongation was the highest for nylon cables (9%), followed by the nickel-titanium (4%) and both metallic cables (0.3%). During 12 hours, no relaxation was observed for the nickel-titanium and the cobalt-chrome cables, whereas 28 and 45% of the tension was lost respectively for the stainless-steel and the nylon cables. The elastic springback of the nickel-titanium and nylon cables (4.4 and 4.7% respectively) was 20 times higher than that of the stainless-steel and cobalt-chrome cables (0.12 and 0.16% respectively). The force to failure of the stainless steel and cobalt-chrome cables was twice that of the nickel-titanium cables.

Interpretation: Multi-braided stainless-steel and cobalt-chrome cables have a high-stiffness with limited ability to tolerate displacement, leading to early cable loosening. Novel low-stiffness cables made of nylon or nickel-titanium offer significant elastic springback improving binding stability.

INTRODUCTION

Cerclage techniques are commonly used to obtain osseous fixation in the field of trauma, in arthroplasty as well as in spinal surgery. First generation monofilament wires were used by Charnley for the fixation of trochanteric osteotomies [1]. These wires had a tendency to kink during application which caused weakening [2]. Wire breakage rates of 20% and trochanteric non-union rates of up to 8% were reported [3-5]. These issues led to the development of second generation multi-braided cables, which offer greater compression [3] and less displacement [4], but are still associated with a significant complication rate [5]. Fatigue and fray of multi-braided metal cables causing metallic debris and third-body polyethylene wear have been reported [6-8]. Cable loosening contributes to poor fixation and delayed fracture or osteotomy healing. For adequate stabilization, tension in the cables must be maintained to minimize micro-motion between fragments. The poor springback of multi-braided metallic cables prevents them from adjusting to bone resorption or the micro-motion associated with in-vivo loading.

Novel cables providing greater elastic springback have now been developed; a polyethylene coated nylon (Ny) cable available commercially since 2004 [9], and a braided superelastic nickel-titanium (NiTi) cable [10]. Early clinical experience with the nylon cables is promising [11]. Two of 29 patients developed a non-union at a minimum of 13 months after surgery and there were no breakages or complications directly related to the cables.

These new cables have a different mechanical behavior than that of the metal cables commonly used today, but relatively little information has been published on the subject. The purpose of this study was to compare the mechanical properties of these new cables (Ny and NiTi) with those of cobalt-chrome (CoCr) and stainless-steel (SS) cables in use today.

I. METHODS

Cerclage cables were tested:

a. Cobalt-chrome multi-braided cerclage cable (CoCr), Zimmer (USA);
b. Stainless steel multi-braided cerclage cable (SS), Zimmer (USA);
c. Ultra-high molecular weight polyethylene (Ny) SuperCable^{TM} Iso-Elastic^{TM} cerclage system, Kinamed Inc. (USA); and
d. Tubular superelastic cable made of nickel-titanium shape memory alloy (NiTi) developed and improved for orthopedic applications.

Four specimens of Ny cables and NiTi cable and five specimens of CoCr were utilized, but due to the greater variability of the results obtained with the SS cables, a total of eight SS specimens were tested. The cables were loaded on a Mini Bionix$^{®}$ 858 (MTS, USA) equipped with a cable grip set and a 2500 N axial load cell. Specimens were immersed in 37 °C deoxygenated water (Figure 1). The

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cables' relative elongations were measured with an MTV 1360 CA video-extensometer (Mexxphysik GMBH, Austria).

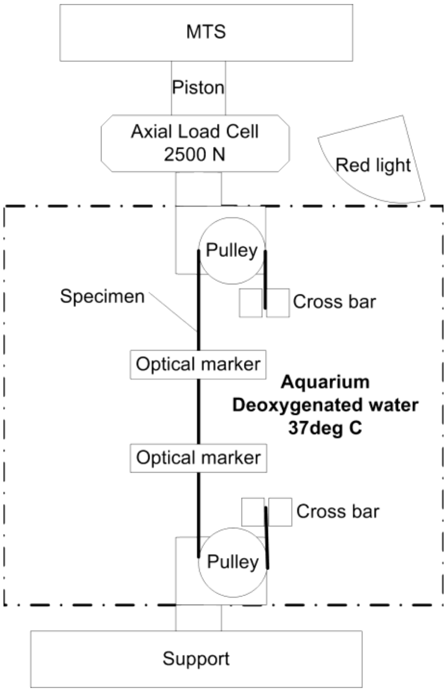

Figure 1: Setup: Samples are clamped in two cross-bars and rolled on two pulleys. The setup is immerged in water at 37° C.

Each cable specimen was installed on the pulleys and clamped in the cross-bars before the optical markers were installed. The reference length for the video-extensometer measurement was set at the beginning of each test, under a 10 N preload. The testing sequence is illustrated in Figure 2.

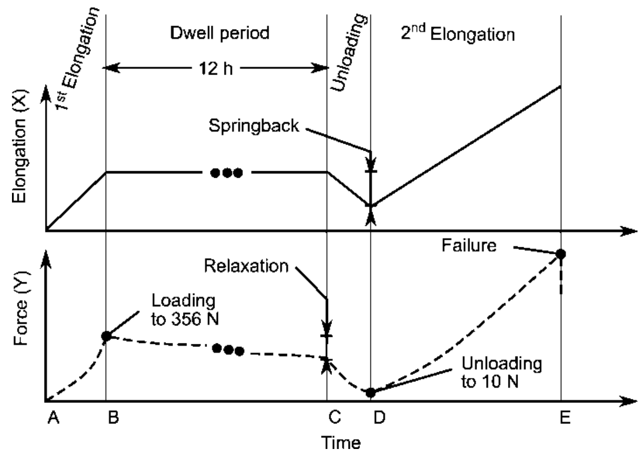

Figure 2: Four-step Loading procedure: Primary elongation (A to B); 12-hour constant-elongation dwell (B to C); Unloading (C to D); Secondary elongation to failure (D to E).

Cables were first loaded to the manufacturer's recommended tensions (points A to B). For the SS, CoCr and NiTi cables, 356 N were applied. Since only one of the two strands of the Ny cables was used, half the recommended load was applied (178 N). The loading rate was 10 % of the coaxial distance between pulleys per minute for the Ny and NiTi cables, and 1 % of the coaxial distance between pulleys per minute for the SS and CoCr cables. The rate is slower for the SS and CoCr cables compared to the Ny and NiTi cables because of their high rigidity. The force relaxation was recorded for 12 hours (points B to C) while maintaining elongation. Preliminary tests showed no major difference of mechanical behavior after this period of time. The cables were then unloaded (points C to D) to 10 N at the same rate as they were initially loaded, and reloaded to failure (points D to E). If either the load cell limit (2500 N) or the setup displacement limit (60 mm) was reached without failure, the test was interrupted. Video-extensometer recording was carried out every 0.05 s except during the 12-hours dwell period, where it was carried out every 10 s.

Force-elongation plots were obtained for each cable and the following mechanical properties were measured:

- Initial elongation during first tensioning at the recommended load (%): $\delta_{RL}=X_B-X_A$.
- Relative force relaxation in percent of the recommended installation force (%): $R=(Y_B-Y_C)/Y_B$
- Springback (available elastic recovery), during unloading (%): $\delta_{SB}= X_C-X_D$.
- Force to failure (N): $L_F=Y_E$.

Statistical analyses were performed in two stages. First, variance analyses (ANOVA) were carried out to determine if there is a significant difference between the mechanical properties of the four cables. Secondly, the Games-Howell formula, recommended for comparing results obtained with an unequal number of samples, was applied to compare each type of cable with another one in terms of their initial elongation, relative force relaxation, springback and force to failure.

II. RESULTS

Figure 3 displays the force-elongation curves for the four types of cerclage cables tested. The mechanical properties of the four cerclage cables are summarized in Table 1.

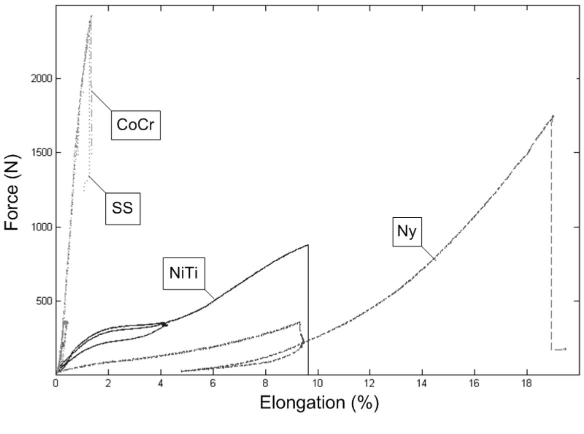

Figure 3: Typical Force/elongation curves of the tested cables.

TABLE I
MECHANICAL PROPERTIES OF COCR, SS, NY AND NITI CERCLAGE CABLES.

	Initial elongation (%)	Relative force relaxation (%)	Springback (%)	Force to failure (N)
CoCr (n=5)	0.29±0.12	2.31±4.52	0.16±0.04	2408±40*
SS (n=8)	0.29±0.20	28.25±25.46	0.12±0.04	2196±240
Ny (n=4)	9.42± 0.23	45.65±6.64	4.70±0.19	N/A**
NiTi (n=4)	4.37±0.24	6.73±1.92	4.40±0.27	899±17
	P<0.01***	P<0.01***	P<0.01***	P<0.01***

* Failure was reached for 3 CoCr cables only
** Ny cables never reached failure
*** From ANOVA test

A. Initial elongation

Their initial elongation was significantly different: low for CoCr and SS, high for the NiTi and very high for the Ny. The Games-Howell test showed no significant difference (*P*=0.99) between the SS and CoCr cables.

B. Relative force relaxation

Relative force relaxation was significantly greater for the Ny cables than for the SS, NiTi and CoCr cables (Figure 4). Surprisingly high and strongly variable relaxation was measured for the SS cables, even when four additional SS cables were tested to extend our sampling. Actually, of the eight SS cable specimens, three had no load loss over the dwell period (0.8 SD 1.3) whereas five lost half of the installation force (44.7 SD 15.2). The results obtained from all eight SS cables were used for the statistical analyses.

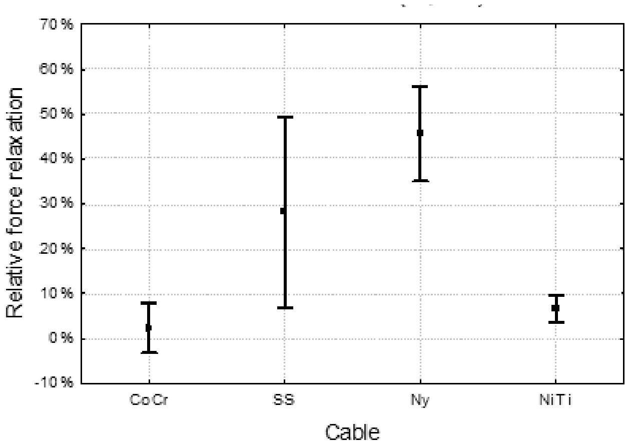

Figure 4: Relative force relaxation in percent of the installation force for the CoCr, SS, Ny and NiTi cables. Squares represent the mean and bars represent the confidence interval (95%).

C. Springback

As of springback, all of the tested cables apparently belong to one of two groups as shown of the Figure 5: high-stiffness cables with conventional linear elasticity (SS and CoCr), or low-stiffness cables with extended non-linear elasticity (so-called iso-elastic Ny and superelastic NiTi cables). Games-Howell analyses did not show significant difference in relaxation between CoCr and SS cables (*P*=0.98), nor between NiTi and Ny cables (*P*=0.81).

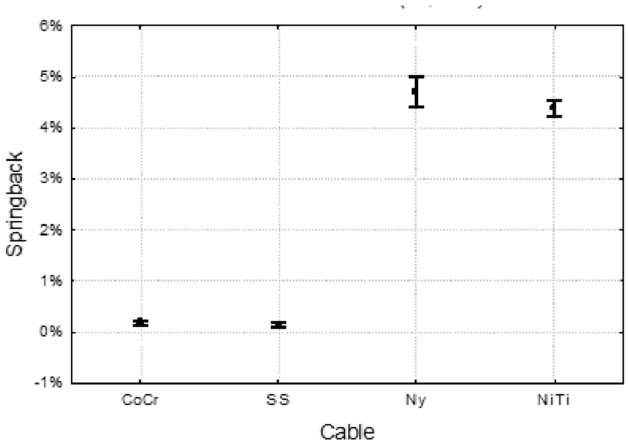

Figure 5: Springback for the CoCr, SS, Ny and NiTi cables. Squares represent the mean and bars represent the confidence interval (95%).

D. Force to failure

At failure, force was significantly different for each type of cable. All of the SS cables failed at a mean force of 2196 N. Three CoCr cables failed at a mean force of 2408 N. Two CoCr cables did not fail, reaching the load cell limit (2450 N). The NiTi cables' force to failure averaged 899 N. Failure was not achieved and the experimental setup maximal displacement of 60 mm was reached for all Ny cables. The maximum mean force reached was 1616 N.

III. DISCUSSION

The initial enthusiasm for multi-braided metallic cables has declined as the associated high complication rate has become apparent [12-14]. Many factors influence cerclage cable tension loss during surgery and postoperatively. During this period, cables are subject to micro-motion and displacement created by soft-tissue interposition and bone resorption. To maintain a continuous compression across bone fragments of an osteotomy or fracture, the cables need to be able to tolerate movements with minimal loss of tension, ie have a high elasticity and stability of its mechanical properties over time (low stress relaxation).

The Ny and NiTi cables exhibit plateau behavior significantly different from linear behavior of multi-braided metallic cables (Figure 3). A greater elongation range at the installation force increases the tightening precision.

SS cables presented an important and unexpected scatter in relaxation. A hypothesis was put forward, which is that micro-movement of the cable's filament could explain the large variation in the results. In fact, given the high stiffness of SS, a movement of 0.1 mm (5 % of the cable diameter) could result in almost 30 % loss of tension. An uneven distribution of the filaments in the cable cross-section could also result in a severe tension loss. Early cable loosening of cerclage cables has also been reported by Haddad et al with multi-braided metal cable, in association with clamp fixation [15]. They concluded that technique, implant and instrumentation were responsible for the tension losses, which were greater than 50 %.

However, even more relaxation occurred in Ny cables than in the SS, CoCr and NiTi cable: the Ny cable loses nearly half the initial force during the first 12 hours followed fixation. The mean relaxation recorded here (46 %) is close to that found by Sarin, who reported 40 % relaxation after eight days ,with 99 % of the relaxation occurring during the first day [16].

High elastic springback is a mechanical behavior that provides a margin of displacement where compression between bony fragments can be maintained. Low-stiffness Ny and NiTi cables have similar elastic springbacks of 4.4 and 4.7 %, respectively, which is 20 times superior to that of SS and CoCr cables (0.12 and 0.16 %, respectively). This suggests that, in the clinical setting after the 12-hours dwell period, a 10 cm cerclage subjected to 1 mm loosening due to cable sliding or soft-tissue resorption, Ny cables could maintain a tension of 98 N. In the same setup, the high-stiffness and low-springback SS and CoCr cables would have lost all tension. For NiTi cables, the same situation would result in a 253 N load of residual tension. This characteristic of maintaining tension shown by Ny and NiTi cables could be a significant clinical advantage in maintaining bone fixation stability.

Force to failure testing showed that the SS and CoCr cables shared similar results, with more than 2000 N required to reach failure. The high elongation potential of the Ny cable prevented rupture from occurring, but it accepted mean loads of 1616 N. The NiTi force to failure averaged less than 1000 N, about half of the strength of the multi-braided metal cables. As with nylon cables, adding a second strand to the NiTi cable would easily compensate for the difference in strength performance.

IV. CONCLUSION

Knowledge about the intrinsic mechanical properties of cable could explain in-vivo behavior of the cerclage fixation. For example, a cable with very low springback could induce primary loosening when micro-movements occur. On the other hand, a high relaxation could explain possible loosening of the cable in time.

Currently available multi-braided SS and CoCr cables have high-stiffness with limited ability to tolerate displacement, leading to early cable loosening. Ny cables demonstrate a notable stress relaxation, but they offer a significant springback, which could prevent cable loosening. NiTi cables combine high springback of Ny cables with zero stress relaxation of SS and CoCr cables. Further clinical testing is needed to determine the field of use for elastic cables in orthopedic surgery.

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