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Mechanical Properties and Comparisons of Cerclage Wires of Various Diameters in Different Knot Methods

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Abstract The aim of this study was to compare the mechanical properties of 0.6 and 0.8 mm cerclage wires with the 1.0 mm cerclage wire in the twist, single-loop, double-loop, double-wrap, and loop/twist knot methods. Six stainless steel cerclage wires of various diameters in different knot methods were tied round a customized jig mounted on a load testing machine. The initial tension, initial stiffness, and yield load were evaluated. The failure mode of each cerclage was observed. For each wire size, the double-loop, double-wrap, and loop/twist knots showed significantly greater initial stiffness, and yield load than those seen with twist and single-loop knots. The single-loop knot showed the least initial stiffness regardless of the diameter. As the cerclage wire diameter increased, the cerclage tended to show significantly greater initial stiffness, and yield load. Failure modes varied depending on the knot configurations. Single-loop knots of smaller-diameter wires less than 1 mm had similar or lower initial tension, initial stiffness, and yield load than a twist knot. Owing to the variance in mechanical properties, the clinical application of the knot type should depend on the diameter of the cerclage wire.

Key words cerclage wire, mechanical property, yield load, failure mode.

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Introduction

An internal plate provides splinting as the major element stabilizing the fracture while the cerclage reduces and fixes the fragments, exerting additional stability via a centripetal force (11). Because the stability provided by cerclage wires is important for healing, understanding how the various configurations generate tension and rest load is necessary (13). Since the degree of wire compression on the bone fragments depends on the knot method, the load that the cerclage wire resists also depends on the knot method. Several studies have assessed the tensile and failure loads of various cerclage wire configurations (6,8,10,15,16,18,19). Previous studies showed that a loop-knot cerclage generated more tension than a twist-knot (TW) cerclage, but it failed at a lower load than a twist-knot cerclage (1,14,20), while Blass et al. (1) revealed that the double-loop (DL) knot generated greater static tension and had a higher yield load than both the twist- and loop-knot configurations. They observed that TW yielded by untwisting and loop-style knots yielded by unbending of the arm or arms. Using cerclage wire with a diameter of 1.0 mm, Roe (13) revealed that the yield loads of DL, double-wrap (DW), and Loop/twist (LT) knots are superior to those of twist and Single-loop (SL) knots. Most of the other previous studies used 1.0 mm or 1.2 mm wires (1-3,5, 6,9,12), but mechanical studies with smaller diameter wires, which are recommended for cats and small-breed dogs, are lacking.

Wire products may be purchased in a spool or as preformed loop wire and are available in sizes ranging from 22 gauge (0.64 mm) to 18 gauge (1.2 mm). The use of 22 or 20 gauge wire is recommended for cats and small dogs, whereas 18 gauge wire is recommended for larger dogs (7). Another recommendation states that 18 gauge wire is appropriate for animals weighing over 20 kg, while 20 gauge (1 mm) wire should be used for animals weighing under 20 kg (4). However, no exact evidence or references were found in any of the papers.

There are studies of mechanical properties of cerclage wire according to the knot method in wires larger than 1 mm, but there is no study using a wire less than 1 mm. This study was undertaken to identify the mechanical properties of cerclage wire in various diameter and knot methods. The study compared initial tension, initial stiffness, yield load and failure mode with wires of three diameters with five existing techniques (13). We hypothesized that 0.6 and 0.8 mm cerclage wires would have different mechanical characteristics depending on the type of knot.

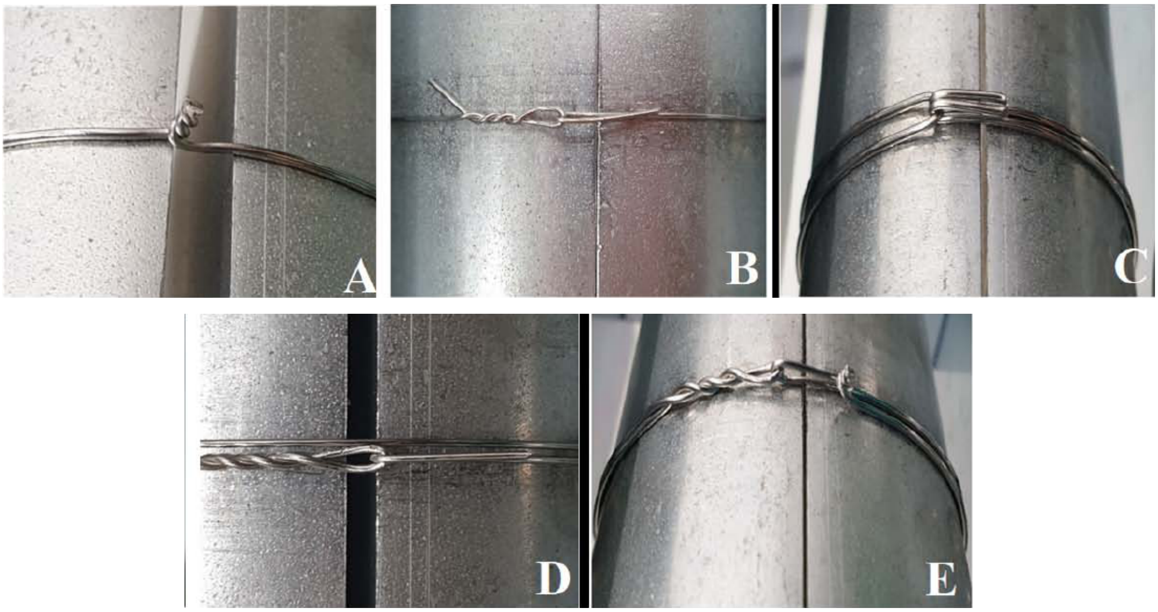

Fig. 1. Pictures of the five cerclage wire knot types compared in this study. (A) TW knot: A wire was twisted while tensioning upwards. (B) SL knot: A small loop, with a diameter less than 2 mm was made at one end of a wire. The other end of the wire was passed through the loop and attached to the crank of a wire tightener and tightened. (C) DL knot: A wire was folded to make a small loop near the middle. Each end of the wire attached to a crank of a wire tightener, tightened and bent over. (D) DW knot: DW knot was similar to SL cerclage knot except that the wire was wrapped around the testing jig twice. (E) LT knot: Only one end of a wire was passed into the loop and attached to a crank of the wire tightener. The wire's other end, which was not passed through the loop, was attached to the second crank. The crank holding the first end was tightened, and the instrument was rotated along its long axis.

Materials and Methods

Cerclage wire configurations

Cerclage wires were formed using 0.6 mm, 0.8 mm, and 1.0 mm orthopedic wires purchased from one supplier (Synthes Ltd, Wayne, PA). Three traditional cerclage knot-tying techniques (Fig. 1A-C) and two techniques (Fig. 1D, E) designed by Roe (13) were applied in the test.

TW knots were formed with a wire twister (Veterinary Instruments, Sheffield, UK). The wire length require to make the twist was 30 cm. The wire was twisted while tensioning upwards with two strands of wire end wrapped around each other. The knot was cut with a wire cutter leaving 2 or 3 twists and was not bent over (Fig. 1A).

A SL knot was made by an operator (AR) such that a small loop, with diameter less than 2 mm, was formed at one end using the wire twister. At least one and a half twists were present at the base of the loop, and the loop was made as small as possible. The wire length used to make the SL configuration was 40 cm. One arm passed through the loop and was attached to the crank of a wire tightener (No. 391.210, Synthes, Ltd, Wayne, PA) and tightened by turning the crank until an operator judged it was tight enough. The arm was bent over maintaining tension, cut with about 1 cm left from the loop, and the end was pressed flat by the tightener (Fig. 1B).

A DL knot was made from a 70 cm length of wire. The wire was folded to make a small loop near the middle of the length. Two ends of the wire were passed through the loop near the middle and tied around the testing jig. They were tightened by the same wire tightener used to make the SL knot, with the only difference being that two cranks were used to make a knot. Both ends of the wire were applied to each crank of the wire tightener. And both cranks were turned until the operator judged they were tight enough. Maintaining the tension of the cranks, the wire tightener was bent over. The cranks were turned in the opposite direction to release the wire and the ends of the wire were cut with 1 to 2 cm left and flattened using the same instrument (Fig. 1C).

A DW knot was similar to the SL knot in that it had a small loop at one end but was different in that the wire wrapped around the testing jig twice. All wires were tightened with the wire tightener until an operator judged they were tight enough. Holding the tightener and maintaining the tension, the arm was bent over. Then cut with about 1 cm left from the loop, and the end was pressed flat by the tightener (Fig. 1D).

The LT knot was made from a 70 cm length of wire. The wire was folded to make a small loop near the middle of the length, similar to the DL knot. However, for this configuration, only one end was passed into the loop and applied to the crank of the wire tightener. The other end, which was not passed into the loop, was applied to the second crank. The crank holding the first end was tightened like a SL knot, but the wire was not cut after bending over. Instead, the instrument was rotated to its long axis for the wire to be twisted while tensioning upwards and for two strands of wire ends to be wrapped around each other. The knot was cut with the wire cutter (Model 001246, Vet Instrumentation, Sheffield, UK).

Mechanical evaluation methods

A customized testing jig was used in this study. The jig consisted of a 50 mm diameter steel rod that was cut into two hemi-cylinders. The static testing machine (Model 5582, Instron Corp Inc, Canton, MA, USA) was used to evaluate the mechanical characteristics of the cerclage types. The bottom half was rigidly held by a stand mounted to the base of the machine. The top half was held by an armature that was attached to a 100 kN load cell (Instron Corp Inc, Canton, MA, USA) mounted on the crosshead. At the starting position, there was a 1.0 mm gap between the two portions of the cylinder. The output from the load cell was recorded on a strip chart recorder which produces a plot of an input signal, usually load or strain, against time, while each cerclage was being tied.

Five assessments were performed for each completed cerclage wire: initial tension, initial stiffness, yield load, and failure mode. Six specimens from each knot method and diameter were tested. After the wires encircled the testing jig, the initial tension was recorded. The initial tension was measured twice: before and after wire cutting. The load was measured by the testing machine via an Instron proprietary software program (Bulehill universal software, Instron Corp Inc, Canton, MA, USA).

The distraction was applied at 0.5 mm/min and continued until plastic deformation occurred and the cerclage wire finally failed. The failure modes were noted after the force resulted in the following conditions: (i) the wires unwinding of wires and (ii) breaking of the wires. The Load and displacement were recorded on the chart digitally. The yield load was estimated by visual inspection of the load versus displacement response and selection of the point on the curve where the slope first changed. The initial stiffness of the cerclage wire was determined from the slope. The slope was calculated by linear regression from the initial portion to the estimated yield load on the load-versus-displacement curve.

To identify yield load, the distraction was continued until the wire was broken or failed. Failure modes for each knot type and diameter were also observed.

All tests were conducted at room temperature, and all cerclage knots were formed by one operator.

Statistical analysis

The initial tension, initial stiffness, yield load, and ultimate tensile load were compared for 15 groups using the Kruskal-Wallis test with a Mann-Whitney correction test of the significance level. A level of 5% was used as the criterion for statistical significance (IBM SPSS Statistics version 25, Chicago, IL, USA). Data are reported as mean ± standard deviation.

Results

Initial tension

Initial tension values for all the diameters and tying methods are displayed in Table 1. The initial tension knot before cutting of the 0.6 mm SL was less than those of the other knots. The initial tension of the 0.6 mm DL was greater tension than the TW and LT. For the 0.8 mm cerclage, the initial tension of TW, SL, and LT were significantly lower than those of DL and DW whereas the values for DL and DW showed no differences. For the 1.0 mm cerclage, TW generated the lowest tension. SL and LT were lower than DW.

Initial tension after cutting of the DW knot generated the greatest for all the diameters, followed by the DL knot, whereas the SL knot generated the lowest initial tension for the 0.6 mm (17.8 ± 3.3 N) and 0.8 mm (53.8 ± 14.1 N) wires and the TW knot generated the lowest initial tension for the 1.0 mm wire (70.7 ± 31.9 N).

The 0.6 mm SL was the lowest initial tension after cutting of the five knot configurations, and differences among the other knots were not significant. For 0.8 mm, DW generated greater tension than TW, SL, and LT, whereas the tension in DW was not different from that in DL. For 1.0 mm, TW showed significantly lower tension than the other knots. DW showed greater initial tension after handling than SL and LT, but the value was not different from that of DL.

Loss of initial tension after cutting for the 0.6 and 0.8 mm cerclage wires was the greatest in the DL cerclage but for the 1.0 mm wire, TW showed the maximal loss of tension after wire cutting. The tension loss increased for the twist knot and decreased for the loop-type cerclage as the diameter increased.

Initial stiffness

The initial stiffness of the SL knot was the least, with significant differences for all the wire diameters. For 0.6 and 0.8 mm, the initial stiffness values of the other knot methods did not differ. Depending on the diameter, the group that generated the greatest initial stiffness was different. The LT showed the greatest initial stiffness in the 0.6 mm group (391.2 ± 90.6 N/mm), while the TW showed the greatest initial stiffness in the 0.8 mm group (827.5 ± 141.3 N/mm). For 1.0 mm, DL generated significantly greatest initial stiffness (2600.2 ± 214.0 N/mm), followed by the DW, which generated the second greatest initial stiffness (1607.6 ± 679.1 N/mm), while the other knots showed no differences.

For the DL, DW, and LT knots, the initial stiffness increased with the wire diameter. However, for the TW knot, the initial stiffness of the 0.6 mm cerclage was significantly lower than those of the others. For the SL knot, the initial stiffness of the 1.0 mm cerclage was significantly higher than that of 0.6 and 0.8 mm cerclage. These data are presented in Fig. 2.

Yield load

The yield load comparison depending the knot methods and wire diameter is reported in Fig. 3. These yield loads for the DL, DW, and LT knots were greater than those for

Table 1. **Initial tension subdividing before and after wire cutting, depending on diameter of wire and knot methods and loss percentage of the load (Mean ± SD)**

	0.6 mm			0.8 mm			1.0 mm		
	Before (N)	After (N)	Loss (%)	Before (N)	After (N)	Loss (%)	Before (N)	After (N)	Loss (%)
TW	44.2 ± 7.9	40.7 ± 9.5	7.9	76.2 ± 14.6	66.5 ± 13.5	12.7	92.5 ± 37.8	70.7 ± 31.9	23.6
SL	26.0 ± 8.4	17.8 ± 3.3	31.5	58.7 ± 17.4	53.8 ± 14.1	8.3	181.8 ± 19.7	167.0 ± 23.8	8.1
DL	89.2 ± 16.7	41.5 ± 10.4	53.5	190.0 ± 30.3	79.0 ± 32.0	58.4	331.2 ± 159.2	268.0 ± 141.8	19.1
DW	62.5 ± 15.8	41.7 ± 10.5	33.3	140.7 ± 23.3	104.0 ± 18.5	26.1	349.5 ± 33.5	313.8 ± 28.5	10.2
LT	50.2 ± 4.8	32.4 ± 8.7	35.5	73.0 ± 14.9	66.0 ± 11.6	9.6	176.7 ± 23.7	151.2 ± 17.0	14.4

N, newton; TW, twist-knot; SL, single-loop; DL, double-loop; DW, double-wrap; LT, Loop/twist.

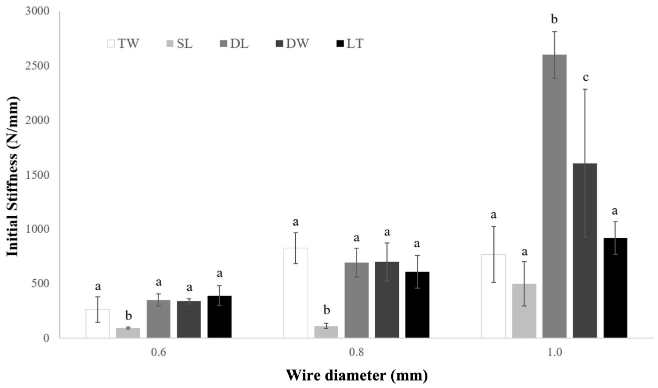

Fig. 2. Comparison of the initial stiffness depending on diameter of wire. For same knot technique, means with different letter above the columns are significantly different from each other (p-value < 0.05). N means newton.

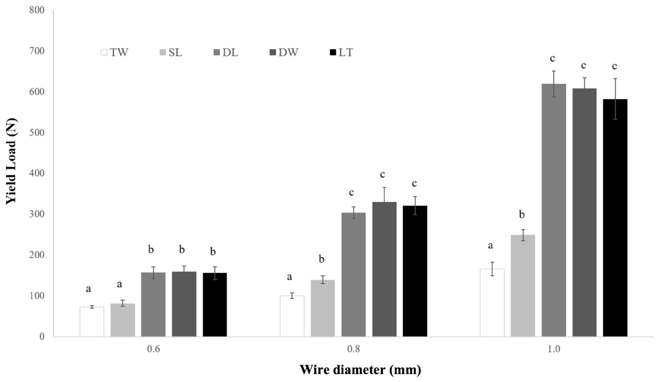

Fig. 3. Comparison of the mean yield load depending on diameter of wire. For same diameter, means with different letter above the columns are significantly different from each other. As the diameter of wire increased, all the cerclage configuration generated significantly greater yield load (p-value < 0.05). N means newton.

the TW and SL, and showed no significant differences among DL, DW, and LT for all wire sizes. The load resisted by 0.6 mm cerclage wires did not significantly differ between the TW and SL, whereas for the 0.8 mm and 1.0 mm wires, the SL generated significantly greater tension than that of TW knots. The yield load that was generated by 0.8 mm DL, DW, or LT was greater than that by 1.0 mm TW or SL. Similarly, the yield load generated by 0.6 mm DL, DW, or LT was higher than those generated by 0.8 mm TW or SL.

Failure mode

The TW knots for 0.8 mm and 1.0 mm wires failed by unwinding of the twist. For the 0.6 mm TW, however, failure occurred in 33% of the knots as a result of breakage of the innermost part of the twist and for 67% by breakage of the counterpart of the twist. The failures for all the loop-type knots, regardless of diameter, occurred by unbending of an arm or arms interacting with the loop. One LT knot made of 0.8 mm wire failed with breakage of the innermost part of the twist and a 1.0 mm cerclage failed with breakage of the folded part of the arm passing through the loop. Except for the two specimens, all others failed with unraveling of the twist part.

Discussion

The mechanical properties of wires with diameters of 0.6, 0.8, and 1.0 mm were compared on the basis of initial tension, initial stiffness, yield load and failure mode. The cerclage wires of 0.6 and 0.8 mm diameters showed reduced bending strength compared to that of 1.0 mm due to their different area moment of inertia.

Previous studies (14,17) have revealed that cerclage lost 12% to 44% tension during wire cutting. The present study showed an 8% to 58% tension loss after handling of the cerclage. The amount of initial tension loss after handling differed depending on the knot method and wire diameter. The percentage of tension loss in the 0.6 and 0.8 mm cerclages was greatest for DL while the percentage of tension loss in the 1.0 mm cerclage was greatest for TW. For 0.6 mm, the TW knot showed the smallest decrease in initial tension after wire cutting while the SL cerclage showed the smallest decrease for 0.8 and 1.0 mm.

Different tendencies of initial tension loss were observed between the TW knot and loop-type knots (SL, DL, and DW). The TW knot is formed at the same time as the tension is generated in the cerclage (13). Due to this mechanical property, the tension of the knot was affected greatly by cutting the knots. As a result, the percentage of initial tension loss of the TW knot increased as the diameter of the wire increased. In contrast to the TW knot, as the wire diameter increased, the initial tension loss of the loop-type cerclage decreased. This could be explained by the fact that when the loop-type cerclage was formed, the tension was generated first and the knot is secured subsequently (13). In this study, the greatest reduction was observed after cutting of the DL type. It may be affected by the fact that there are two parts where the wire is cut. However, in this study, only the tendency of initial tension could be confirmed according to the diameter and knot type. Further studies are needed to confirm this relationship.

Initial stiffness was different from the values reported in a previous study (13), although the same diameter and knot configurations were used. In comparison with the results of a study by Roe (13), our results were generally lower. The application of polymethyl methacrylate to the testing jig in the previous study caused an additional friction force between the jig and the wire, resulting in high initial stiffness values.

The initial stiffness showed a different tendency regardless of the knot type and the diameter of the wire. The stiffness of various wires was not influenced by initial tension before and after cutting. Each type showing a significant difference in initial tension has resulted in similar stiffness. This finding means stiffness was affected by the combination of the material properties of the wire, type of knot, and the number of wires bearing the load. A greater initial stiffness that relates to less displacement would indicate more stable fixation (21). However, how the superior initial stiffness of a cerclage might influence the stability and healing of a fracture is still unknown (13).

The yield point is the load after which cerclages are permanently deformed. Before this point, the cerclage returns to its original configuration if the applied force was removed. In other words, because the cerclage can maintain its function without deformation of the structure up to this point, the yield load is clinically significant. The yield load of the 1.0-mm cerclage in a previous study was associated with the knot types (13), and the present study has similar result. The yield load of the SL cerclage was superior to that of the TW knot for 0.8 and 1.0 mm wires while the yield load of the SL cerclage was as low as that of the TW knot for 0.6-mm wires without significance. The yield loads of DL, DW, and LT knots were two or three times higher than those of TW and SL, while there were no significant differences among DL, DW, and LT knots regardless of the diameter of the wire. Therefore, the SL knot is not recommended, and DL, DW, and LT knots might be better able to resist load.

Failure modes varied depending on the knot configurations. Previous studies have demonstrated that most TW knots failed with untwisting of the knot, and some twist knots failed with breakage of the base of the twist (2,3,19). In our study, the failure modes of twist knots were similar to those reported previously (2,3,19), except for the knots generated using 0.6 mm wires. The 0.6 mm cerclage failed in a unique pattern, wherein 67% of the cerclage wires yielded with breakage of the counterpart of the twist. This could be attributed to the fact that the tensile load of the wire itself was less than the load that the knot generated because of its thin diameter.

The LT knot is a modified knot from a hairpin loop designed in a previous study (3). The difference between the hairpin loop and LT was that the LT configuration was formed by cutting the twist instead of bending. Cheng et al. (3) showed that failure of the hairpin loop knot occurred at the loop part, the base of the twist, or in midsubstance of the wire. In our results, one of the six 0.8 mm LT knots was broken at the base of the twist and one of the six 1.0 mm cerclages was broken at the loop part that an arm passed through and folded. The other LT knot for wires of all diameters did not yield by unraveling of the twist, unlike the findings of the previous study. Thus, bending the twist of the LT knot could make the tension-generating parts weak and work as a stress point. However, we applied a single load to failure, and the LT resisted loads that exceeded the tensile strength of the wire, so wire breakage was observed. Therefore, there may be differences between failure due to fatigue that may actually occur in clinical setting and the results of the current research.

The present study had two limitations. The true yield load of a cerclage, which is the load that causes it to be loose, could not be accurately determined from a single load to failure protocol. In addition, a single strong load was determined to wire failure as cause of failure in this study. However, the goal of cerclage wire is not only to achieve the strongest fixation in a single load, but also to maintain wire tension despite fatigue by low-load cyclic loading. Further studies can examine the fatigue properties under low-load cyclic loading with various diameters and in knot methods and the loads that actual fractured bone experiences may provide insight into the in vivo performance of these constructs.

Conclusions

The mechanical properties of 0.6 and 0.8 mm cerclage wires depending on the knot techniques were generally similar to those of the 1.0 mm cerclage, except for the initial stiffness and yield load of the 0.6 mm SL knot. The yield loads of DL, DW, and LT knots with the 0.6 and 0.8 mm wires were superior to those of the TW or SL knots, similar to the findings obtained with 1.0 mm cerclages in previous studies. For rigid fixation, DL, DW, and LT knots are strongly recommended when using 0.6 mm wire. Cerclage made of 0.6 and 0.8-mm wires is easy to manipulate due to their lower bending strength compared with that of 1.0-mm cerclage. The surgeon must decide between knot security and malleability in small patients.

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Conflicts of Interest

The authors have no conflicting interests.

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