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Original Article

Biomechanical comparison of the combined partially threaded cancellous lag screw and partially threaded cancellous lag screw

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Abstract: The partially threaded cancellous lag screw (PTLS) is the standard screw for establishing rigid fixation in intra-articular fractures. However, its use in the clinical setting is associated with difficulties in obtaining the optimal compressive force (CF) and screw purchase (pullout strength [POS]) for rigid fixation. In the present study, we investigated whether the combined PTCLS (CPTLS) outperforms the PTLS in creating CF and maintaining POS. The CF and POS were measured after the PTLS and CPTLS were tightened manually for compression by a surgeon using surrogate cancellous blocks of three different densities: 0.12, 0.16, and 0.20 g/cm^3. The CF and POS of the CPTLS were significantly higher than those of the PTLS ($P < 0.001$). The CPTLS outperformed the PTLS in terms of the coefficient of variance of CF. CF and POS were affected by the bone mineral density and screw design ($P < 0.001$), and there was no interaction between these two factors ($P = 0.872$ for CF and $P = 0.909$ for POS). Our results demonstrate that the CPTLS is better than the PTLS for creating compression, as its use improved the compressive ability, resulted in better screw purchase, decreased compression-induced damage to the surrounding cancellous bone, and reduced the possibility of inadvertent incomplete tightening, overtightening, and screw stripping.

Keywords: Combined partially threaded cancellous lag screw, partially threaded cancellous lag screw, compressive force, pullout strength, screw design, bone mineral density

Introduction

Displaced intra-articular fractures are a common type of acute injury. Anatomic reduction and rigid fixation are standard techniques for managing these fractures [1]. The use of the partially threaded cancellous lag screw (PTLS) is the most effective and widespread method of rigid fixation, which requires an optimal choice of compressive force (CF) and screw purchase (pullout strength [POS]) [2]. However, selecting these parameters is still difficult in the clinical setting, and screw stripping is not a rare event when the PTLS is used [3-6]. Screw stripping significantly decreases the CF and POS, which leads to failure of rigid fixation [4, 6]. This problem is exacerbated in patients with osteoporosis, and insufficient CF and POS are becoming major issues [4, 6].

One method to overcome this obstacle is augmentation with bone cement to increase stiffness of the bone [7]. Many biomechanical studies have demonstrated that augmentation improves the CF and POS, providing mechanical advantages and minimizing the negative effect of osteoporosis [8, 9]. This conclusion has been confirmed in the clinical setting [7, 10]. However, the augmentation method is not widely used owing to the limitations imposed by the use of bone cement, including its poor biocompatibility and distribution as well as difficult implant removal [11, 12].

Another approach to the problem is to change the screw design. Several biomechanical studies have shown that a threaded design significantly affects the CF and POS [13, 14]. Therefore, we developed a combined partially threaded cancellous lag screw (CPTLS) featur-

Figure 1. The partially threaded cancellous lag screw (PTLS) and combined partially threaded cancellous lag screw (CPTLS). These screws have identical shank lengths (28.4 mm) and threads (inner diameter: 3.2 mm, outer diameter: 6.5 mm, thread pitch: 2.75 mm, and length: 32 mm). A. PTLS: the shank has a simple structure. B. CPTLS: the shank has a complex structure. C. The CPTLS shank consists of an inner cylinder and outer cylinder. The inner cylinder is contiguous to the thread (outer diameter: 4.5 mm) and contains fine threads on the surface. The outer cylinder is hollow and contiguous to the head (outer diameter: 6.5 mm), and it contains fine threads (thread pitch: 0.85 mm).

ing a novel compound shank design. The CPTLS is tightened by shortening the shank, which pulls the thread to compress the surrounding cancellous bone in a linear manner and thereby generates CF. In contrast, the shank of the PTLS is rotated; therefore, the thread compresses the surrounding cancellous bone in a rotating manner to produce CF when tightened.

The present study tested the hypothesis that the CPTLS is superior to the PTLS in generating CF and maintaining POS after screw compression when the effect of inter-surgeon variation is excluded. The objectives of this study were (i) to compare the PTLS and CPTLS in terms of CF and POS after screw compression in synthetic specimens, and (ii) to determine whether bone mineral density (BMD) and screw design affect the CF and POS after screw compression.

Materials and methods

Experimental design overview

The PTLS and CPTLS were tested using surrogate cancellous blocks of three different BMDs. The CF and POS were measured after screw compression. The operator was an experienced orthopedic surgeon who manipulated screw compression to eliminate the effect of inter-surgeon variation. Before the experiments were performed, the operator was instructed to tighten the PTLS and CPTLS in the cancellous blocks for optimal compression, based on the operator's perception. Optimal compression required optimal CF, and screw stripping needed to be avoided during the procedure. The operator was blinded to the CF and POS values to prevent secondary bias in the visual feedback.

Screws

The PTLS and CPTLS used in this study were custom manufactured by a company specializing in producing orthopedic implants (Weihai Wego Medical Systems, Weihai, China) (**Figure 1**). The PTLS is a standard cancellous lag screw with a 4.5-mm core diameter (**Figure 1A**). The CPTLS has a novel compound shank consisting of an inner cylinder and an outer cylinder that interact through fine threads (thread pitch, 0.85 mm) (**Figure 1B**). The inner cylinder has a

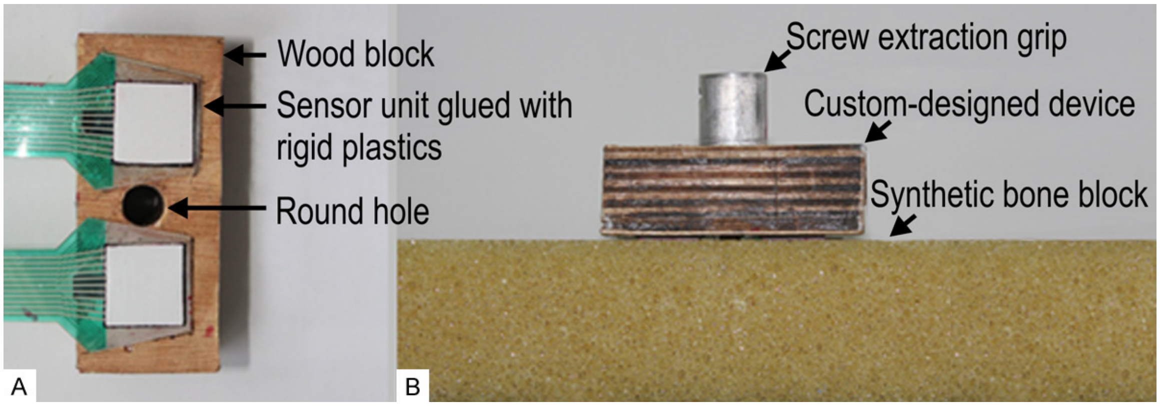

Figure 2. The mechanism for producing and measuring compressive force (CF). A. The custom-designed device for measuring CF consists of a wooden block with a round hole and two sensors attached to the block with rigid plastic. B. The mechanism can generate and measure CF. It consists of a screw extraction grip, custom-designed device, and synthetic bone block.

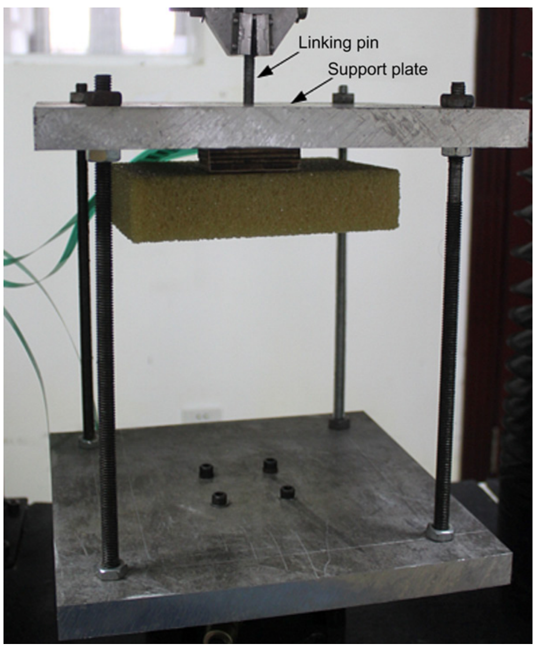

Figure 3. The device used to measure pullout strength. This device consists of a custom-designed linking pin for connecting the screw extraction grip to the testing machine and an aluminum support plate.

4.5-mm outer diameter and fine threads on the surface, contiguous to the thread (**Figure 1C**). The outer cylinder is a hollow cylinder with a 6.5-mm outer diameter and identical fine threads inside, contiguous to the head (**Figure 1C**). The custom-designed screwdriver for the CPTLS is composed of two components: an inner screwdriver that matches the inner cylinder and an outer screwdriver that matches the outer cylinder. Furthermore, this screwdriver has two modes: a locked mode in which the inner screwdriver and outer screwdriver are interlocked by a bolt (for screw insertion without compression), and an unlocked mode set by loosening the bolt (for screw compression).

The two screws had identical thread parameters (inner diameter: 3.2 mm, outer diameter: 6.5 mm, thread pitch: 2.75 mm, length: 32 mm, and shank length: 28.4 mm) (**Figure 1**).

Surrogate bone model

The screws were evaluated in surrogate cancellous bone blocks (Pacific Research Laboratories, Vashon, WA, USA) to minimize intra-specimen variability [15]. A density of 0.16 g/cm^3 is considered the most representative value of osteoporotic human cancellous bone [16, 17]. Thus, three surrogate bone models were used: specimen I (#1522-09, 0.12 g/cm^3), specimen II (#1522-10, 0.16 g/cm^3), and specimen III (#1522-11, 0.20 g/cm^3). All specimens had dimensions of 180 × 130 × 40 mm.

The specimens were drilled perpendicularly at equal intervals by using a drill press, and 24 pilot holes (3.2-mm diameter, 40-mm depth) were created in each specimen. The depth of these pilot holes was greater than the length of the thread of the PTLS or CPTLS (32 mm). Therefore, these pilot holes could accommodate the entire thread. In total, 72 pilot holes were prepared for this study.

Compression force testing

A custom-designed device was used to measure the CF. This device consisted of a 62 × 25

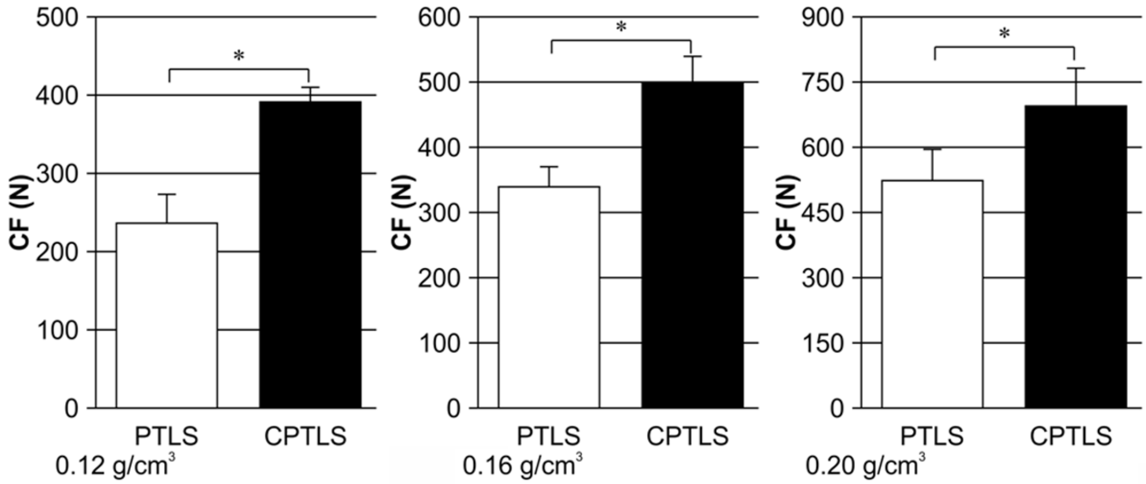

Figure 4. The compressive force (CF) of the combined partially threaded cancellous lag screw (CPTLS) is higher than that of the partially threaded cancellous lag screw (PTLS) in all three specimens. *Significant difference ($P < 0.001$).

× 21-mm wood block with a 7-mm round hole and a Tekscan type 6900 pressure transducer (Tekscan Inc., South Boston, MA, USA) (**Figure 2A**). Two sensors of the pressure transducer were attached with rigid plastic to each surface, and then they were glued to the two sides of the hole symmetrically to measure CF. A custom-designed screw extraction grip was used to prevent the head from sinking into the hole and to measure the POS. The PTLS or CPTLS was manually inserted into the pilot hole first through the screw extraction grip and then through the round hole in the wood block (**Figure 2B**). Sensors on the wood block were sandwiched between the wood block and synthetic specimen. The total thickness of the device and screw extraction grip (24 mm) were smaller than the PTLS or CPTLS shank length (28.4 mm), which eliminated the possibility of the thread entering the hole.

The CPTLS compression consisted of two consecutive steps. First, the screw was inserted without compression. The custom-designed screwdriver was used in the locked mode to drive the CPTLS as a single unit until the space between the wood and specimen was approximately 1 mm. The second step was to perform screw compression. The locking bolt was loosened, and the outer screwdriver was rotated while the inner screwdriver was kept still. As a result, the outer cylinder was rotated around the inner cylinder, thereby shortening the shank and pulling the thread linearly to compress the surrounding cancellous bone and produce CF. In contrast, the PTLS was rotated clockwise in the pilot hole, and the thread compressed the surrounding cancellous bone in a rotating manner, generating CF. The procedure ended when the operator felt that optimal compression was achieved. CF was recorded by the transducer at 10 Hz (72 times in total, 24 times for each specimen).

POS testing

An aluminum test jig was designed and constructed to measure the POS. It consisted of an aluminum support plate and a custom-designed linking pin that connected the screw extraction grip to the testing machine (**Figure 3**).

After the CPTLS was tightened and the CF was measured, the CF was reduced to 0 N by rotating the outer screwdriver counterclockwise, with the inner screwdriver immobilized in the transducer monitor. Then the CPTLS was pulled out using a BOSE3510-AT testing machine (Bose Corporation, ElectroForce Systems Group, Eden Prairie, MN, USA) at a rate of 0.02 mm/s. The test was repeated 12 times per specimen, and the POS was recorded 36 times.

After the PTLS was tightened and the CF was measured, the PTLS was rotated counterclockwise until the CF decreased to 0 N, as measured with the transducer monitor. Next, the POS of the PTLS was measured in the same manner as the POS of the CPTLS. The test was repeated 12 times per specimen, and the POS was recorded 36 times.

The POS values were determined simultaneously using the BOSE3510-AT testing machine

Table 1. CF and CV of CF in each group

BMD (g/cm^3)	CF (N)		*P*-value	CV	
	PTLS	CPTLS		PTLS	CPTLS
0.12	235.93 ± 38.67	390.36 ± 22.40	< 0.001	0.163	0.057
0.16	339.63 ± 33.82	500.06 ± 42.86	< 0.001	0.100	0.086
0.20	521.42 ± 80.78	692.68 ± 79.07	< 0.001	0.155	0.114

n = 12 for each testing group. CF, compressive force; CV, coefficient of variance; BMD, bone mineral density; PTLS, partially threaded cancellous lag screw; CPTLS, combined partially threaded cancellous lag screw.

and Tekscan pressure transducer; this allowed us to calculate the proportional relationship between the two readings. Tests for measuring the CF and POS were performed in succession. Therefore, CF values could be converted to Newtons according to the proportional relationship [18, 19].

Statistical analysis

The significance was set at α < 0.05 for all analyses. Two independent-sample t-tests were used to evaluate differences between the CF and POS in each specimen. Two-factor three-level factorial analysis was used to determine whether the BMD and screw design affected the CF and POS after screw compression.

Results

The CPTLS outperformed the PTLS in generating CF, and the CF values of the CPTLS were higher in each specimen (P < 0.001) (**Figure 4**). The average CF values of the PTLS and CPTLS were 235.93 and 390.36 N in specimen I, 339.63 and 500.06 N in specimen II, and 521.42 and 692.68 N in specimen III, respectively (**Table 1**).

The CF values of the CPTLS had a lower coefficient of variance (CV) than those of the PTLS in each specimen. The CV values of the CF generated by the PTLS and CPTLS were 0.163 and 0.057 in specimen I, 0.100 and 0.086 in specimen II, and 0.155 and 0.114 in specimen III, respectively (**Table 1**).

The CPTLS was superior to the PTLS in maintaining the POS after screw compression, and the POS values of the CPTLS were higher than those of the PTLS (P < 0.001) (**Figure 5**). The average POS values of the PTLS and CPTLS were 364.70 and 443.82 N in specimen I, 533.01 and 606.31 N in specimen II, and 857.15 and 937.49 N in specimen III, respectively (**Table 2**).

The BMD and screw design affected the CF and POS after screw compression (P < 0.001). These two factors did not interact with each other (P = 0.872 for CF, P = 0.909 for POS).

Discussion

In the present study, the CPTLS outperformed the PTLS when the effect of inter-surgeon variation was excluded. Three important findings emerged. First, the use of the CPTLS decreased the CV of CF compared with the use of the PTLS. Second, the CF and POS were higher for the CPTLS than for the PTLS. Third, the BMD and screw design were factors that affected the CF and POS after screw compression.

We were surprised to find that the use of the CPTLS decreased the variance of CF. This may be caused by differences in the screw design. It was difficult to achieve a balance between CF and POS during PTLS compression. First, the CF could be adjusted according to the surgeon's perception, whereas the POS could not be adjusted in the same manner directly and promptly [20]. Second, the CF and POS changed asynchronously, and the POS decreased before the maximum CF was achieved [2, 6]. Therefore, the change in CF did not predict the change in POS. Finally, the CF and POS changed abruptly when the CF was near the maximum, and the range of the rotational angle within which changes in the CF and POS could be adjusted was extremely limited for assessing and adjusting the change in the CF and POS. The use of the CPTLS relatively reduced the difficulty of finding the delicate balance between the CF and POS. First, the POS did not decrease until the CF reached the maximum value [18, 19]. Since the POS remained constant, the change in the CF was the only crucial factor in this process. Second, the rate of change in the CF varied with the insertion angle during CPTLS compression [19]. This enabled us to determine the optimal tightness. Finally, the range of the rotational angle within which the change in the CF could be adjusted was wider because of the fine pitch of the thread connecting the inner cyl-

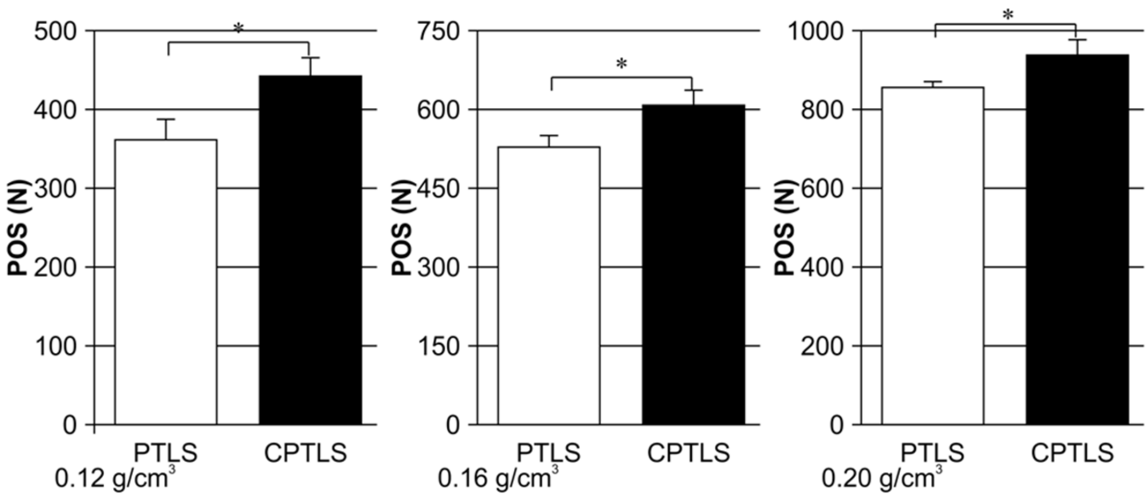

Figure 5. The pullout strength (POS) of the combined partially threaded cancellous lag screw (CPTLS) is higher than that of the partially threaded cancellous lag screw (PTLS) in all three specimens. *Significant difference ($P < 0.001$).

Table 2. POS in each group

BMD (g/cm^3)	POS (N)		*P*-value
	PTLS	CPTLS	
0.12	364.70 ± 25.77	443.82 ± 28.57	< 0.001
0.16	533.01 ± 23.32	606.31 ± 29.95	< 0.001
0.20	857.15 ± 24.75	937.49 ± 42.28	< 0.001

n = 12 for each testing group. POS, pullout strength; BMD, bone mineral density; PTLS, partially threaded cancellous lag screw; CPTLS, combined partially threaded cancellous lag screw.

inder and outer cylinder (0.85 mm). These advantages are very important since the improved ability to control compression variation in the case of the CPTLS decreases the possibility of inadvertent errors, including incomplete tightening, overtightening, and screw stripping.

According to our results, the CPTLS provided a higher CF and maintained a higher POS after screw compression in a uniform specimen. This may be due to two reasons related to differences in the screw design. First, the maximum CF of the CPTLS was higher than that of the PTLS [21]. Moreover, the maximum CF of the CPTLS could be achieved [18], unlike that of the PTLS [2]. Second, the use of the CPTLS resulted in more consistent outcomes of screw manipulation. This may decrease the incidence of inadvertent errors that reduce CF and POS.

The BMD was another independent factor that affected the compression outcomes. The CF and POS of the two screws increased as the BMD increased. Therefore, increasing the stiffness of the specimen by cement augmentation is an effective way to improve the compressive ability and screw purchase of the PTLS and CPTLS. This may be important when treating fractures in patients with severe osteoporosis.

Our results demonstrate that the CPTLS may be a preferable alternative to the PTLS for treating intra-articular fractures. Thus, the use of the CPTLS improved the compressive capacity and screw purchase while reducing compression-induced damage to the surrounding cancellous bone and possibility of inadvertent errors. The importance of these advantages becomes more apparent in patients with osteoporosis, which exacerbates problems such as the insufficient compressive ability and screw purchase when using the PTLS [3, 8, 10].

This study has some limitations. First, inter-surgeon variation is an important factor that affected CF and POS when the PTLS was used for compression [3, 6]. Further studies will be required to analyze how inter-surgeon variation affects CPTLS compression. Second, synthetic cancellous blocks were selected in this study. Although there were no significant differences in the CF and POS between human and artificial cancellous bone materials [2], the specific numeric values obtained from this study cannot be directly applied in the clinical setting; in vivo studies will be required to compare the two screws more precisely.

In conclusion, the CPTLS outperformed the PTLS. In particular, the CF and POS of the CPTLS were significantly higher after compression, which improved the compressive ability; maintained better screw purchase; decreased compression-induced damage to the surrounding cancellous bone; and reduced the possibility of inadvertent incomplete tightening, overtightening, and stripping. Therefore, the CPTLS may be an attractive alternative to the PTLS for treating displaced intra-articular fractures. Additional studies will be needed to investigate other effects of the use of the CPTLS and to optimize the fixation strength of this lag screw for treating intra-articular fractures.

Disclosure of conflict of interest

None.

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