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A new intramedullary sustained dynamic compression nail for the treatment of long bone fractures: a biomechanical study

Uzun kemik kırıklarının tedavisi için yeni bir intramedüller sürekli dinamik kompresyon çivisi: Biyomekanik çalışma

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ABSTRACT

Objectives: We developed a new intramedullary interlocking nail (sustained dynamic compressive nail; SDCN) which can sustain a continuous dynamic compressive force on the fracture edges to overcome implant failure, screw loosening and nonunion complications encountered in the traditionally used static intramedullary nailing (SIMN).

Materials and methods: Six pairs of composite femurs were fixed with SIMN and SDCN. The axial compression, bending, torsional stiffness, and strain values were analyzed.

Results: The mean axial compression stiffness values were 427.1 N/mm for the SDCN and 217.8 N/mm for SIMN, indicating a statistically significant difference (p=0.006). The mean stiffness values of rotation were 1.42 Nm/° for the SDCN and 0.89 Nm/° for SIMN. Anteroposterior bending tests were carried out. The mean results of stiffness were measured as 218 N/mm for the SDCN and 182.7 N/mm for the SIMN. The mean strain measurements in compression were 2454.5 μ-strain for the SDCN and 1123.8 μ-strain for the SIMN.

Conclusion: Biomechanically, the intramedullary SDCN is more stable than the SIMN system and it provides good abutment of the nail to the bone. Also, SDCN increases the stability by producing continuous compression and increasing the contact pressure of the fracture ends.

Keywords: Dynamic compression; fracture fixation; fractures; intramedullary.

ÖZ

Amaç: İmplant kırılmaları, vida gevşemeleri ve kaynamama komplikasyonlarını önlemek için geliştirdiğimiz kırık kemik uçlarına sürekli dinamik kompresyon yapabilen (sürekli dinamik kompresyon çivisi SDCN) yeni bir intramedüller çivi, geleneksel kilitli statik intramedüller çivi (SIMN) ile biyomekanik olarak karşılaştırıldı.

Gereç ve yöntemler: Altı çift kompozit sentetik femurun SDCN ve SIMN tespitleri yapıldı. Aksiyel kompresyon, bükülme, torsiyonel sertlik ve gerilme değerleri incelendi.

Bulgular: Ortalama aksiyel kompresyon sertlik değerleri SDCN için 427.1 N/mm ve SIMN için 217.8 N/mm idi; bu farklılık istatistiksel olarak anlamlı idi (p=0.006). Ortalama torsiyonel sertlik değerleri SDCN'de 1.42 Nm/° ve SIMN'de 0.89 Nm/° idi. Arka-ön bükülme testi yapıldı. Ortalama bükülme sertlik değeri SDCN için 218 N/mm, SIMN için 182.7 N/mm olarak ölçüldü. Kompresyonda ölçülen ortalama gerilim değerleri SDCN için 2454.5 μ-strain, SIMN için 1123.8 μ-strain idi.

Sonuç: Biyomekanik olarak SDCN, SIMN'den daha stabildir ve kırık kemik uçlarına daha iyi temas sağlamaktadır. Ayrıca, SDCN sürekli kompresyon yaparak ve kırık uçlarındaki temas basıncını artırarak stabiliteyi artırır.

Anahtar sözcükler: Dinamik kompresyon; kırık sabitlenmesi; kırıklar; intramedüller.

An interlocking nail system with a stable static fixation technique is the gold standard treatment for the treatment of femoral shaft fractures. This technique has biomechanical superiority thanks to its more stable fixation and less soft tissue stripping than traditional plating techniques.[1-4]

However, fracture nonunion, which may cause an implant failure, is still a problem.[1,5,6] Immediate or subsequent dynamization of an interlocking nail is regarded as an effective treatment for patients with fracture nonunion, particularly of hypertrophic types.[1,7-11] Several studies have demonstrated that

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stress is exceptionally high at the distal interlocking screws or holes of the nail, leading to mechanical failure of the implant and loss of fixation or fracture nonunion.[10,12,13] Interlocking intramedullary rod systems are widely used; however it may produce rotational instability and fixed gap at the fracture site. The stress bypasses the gap from bone to implant, leading to possible implant failures such as screw or rod breakage, therefore, nonunion is the frequent result in many cases.[12,13]

Recently, experimental studies showed that timing of union after intramedullary nailing is influenced by the motion at the fracture gap and demonstrated that relatively rigid constructs lead to earlier fracture healing.[6] Compression at the fracture site enhances fracture healing in terms of mineralization of the fracture gap and mechanical properties at mid-term and at the time of union compared with statically fixed bones.[14-16] According to the Wolff's law, narrow gap, rigid fixation and sustained dynamic compression are essential for bone healing.[17-20]

In the earlier studies, researchers concluded that the dynamization technique should be performed by removing the most distal locking screw from the fracture site. Unfortunately, there is no mechanical evidence to prove the efficacy of such an approach.[1] Therefore, we developed a new intramedullary sustained dynamic compressive nail (SDCN) to provide a continuous sustained compression at the fracture site. In our study, we report an experimental assessment of the implant design and compared it with the statically fixed standard intramedullary nail (SIMN).

MATERIALS AND METHODS

Artificial femur nailing technique, osteotomy

We used six pairs of composite femur models (4th Generation, Sawbones®, #3403, Vashon, Washington, USA, European Department in Sweden) with a length of 400 mm from the piriformis fossa to the intercondylar notch. Artificial femurs were used, as they have more consistent geometry and material properties. This allowed standardization of the materials and structures for the biomechanical comparative studies. The diaphysis portion of the femur had only cortices. At the metaphyseal region, there were cortices and polyurethane foam simulating cancellous bone. The nails were inserted after over-reaming the medulla of intact femurs by 1 mm. The osteotomies, then, were created by using oscillating saw. An osteotomy located at 20 mm above the isthmus representing a situation with short nail-cortical contact. The entry portal of the nails was at the piriformis fossa. After inserting the nails and confirming that they were properly positioned, all locking screws were applied under an external guide attached to the proximal nail end.

Two kinds of intramedullary nails were compared in a randomized pair-match design. One was the commercially available standard 10x340 mm SIMN (Tıpsan Joint Stock Company, Izmir, Turkey) which was locked with screws both proximally and distally. The other one was our newly designed SDCN of the same size which is manufactured and produced by the same company (Tıpsan Joint Stock Company, Izmir, Turkey). The nail has a potential to generate a compression force of 400 N. This compression force and shortening of the bone can be adjusted by the surgeon during surgery. The SDCN, shown schematically in Figure 1, consists of an outer hollow cylinder SDCN shaft. The proximal end houses an adjustment screw and the SDCN is formed by a metal sheath in the form of a tube. The dynamic system is placed inside this hollow cylindrical tube. The distal part of the dynamic system, which is 2 mm smaller in radius, can move inside and outside of the proximal tube. The compression spring is adjusted using the

Figure 1. Schematic drawings of nailing mechanism. **(a)** The view of established system before application. **(b)** The view of the system activated during application. **(c)** Stage of the implantation of the system to the bone. **(d)** The view of the system which was activated after fixation.

proximal screw before the nail is placed into the bone medullary canal. While adjusting the proximal screw, the length of the nail gets longer. Following the placement of the nail inside the intramedullary cavity, the locking screws are placed and a continuous compression is provided on the fractured ends by loosening the proximal adjustment screw. Each nail system was inserted into six femoral bone models and was fixed tow distal and tow proximal locking screws.

Mechanical tests

All the tests were performed with a Shimadzu AG-IS 10 kN model test machine (Shimadzu Corporation, Kyoto, Japan). The femoral bone models were fixed to the load cell of the test machine. The vertical load was applied to the femoral head with a hemi-cylindrical cup which allowed medial translation of the femoral head during loading (Figure 2). Initially, a loading of 100 N was given with a loading rate of 10 mm/min; this was repeated several times until the load deformation relationship was stabilized. Then the femur-nail constructs were loaded up to 750 N.[21-23] In all tests the change in axial, bending and torsional angles were recorded both in loaded and unloaded states. Because of the small sample sizes, the statistical analysis of this study was conducted with the Mann-Whitney U test as well as SPSS for Windows version 15.0 software program (SPSS Inc., Chicago, IL, USA).

Axial compression testing

The nail-bone construct was tested under axial loading with the femoral head in compression and the condyles were seated in physiological position. Prior to the test, a non-contact CCD camera extensometers (Non- contact Video Extensometer DVE-101/201, Shimadzu, Japan) was used. 5 N the axial test, a preload of 5 N and a maximal load of 750 N were applied and, then, reduced to 0 N while simultaneously recording the vertical displacement and the strain. Displacement was detected by the rotary linear variable differential transformer in the testing machine, and strain was detected by an extensometer. The test velocity was 0.1 mm/s. Each side was loaded for three cycles. The weight of one leg is approximately 10-15% of the body weight. The weight of one leg of a person with 80 kg body weight approximately is equal to 8-10 kg.[18,19] The leg is lifted and moved forward in the swing phase of walking. Meanwhile, in a person with femur fracture, the leg is distracted with approximately a force of 80-100 N by the distal part of the fracture during walking.[24] In this study, a distraction force of 100 N was applied for both SIMN and SDCN. During axial loading, the strain was measured by the strain-gauges placed at the fractured ends.

Four-point bending testing

A four-point bending model was used for the anterior posterior (AP), posterior anterior (PA)

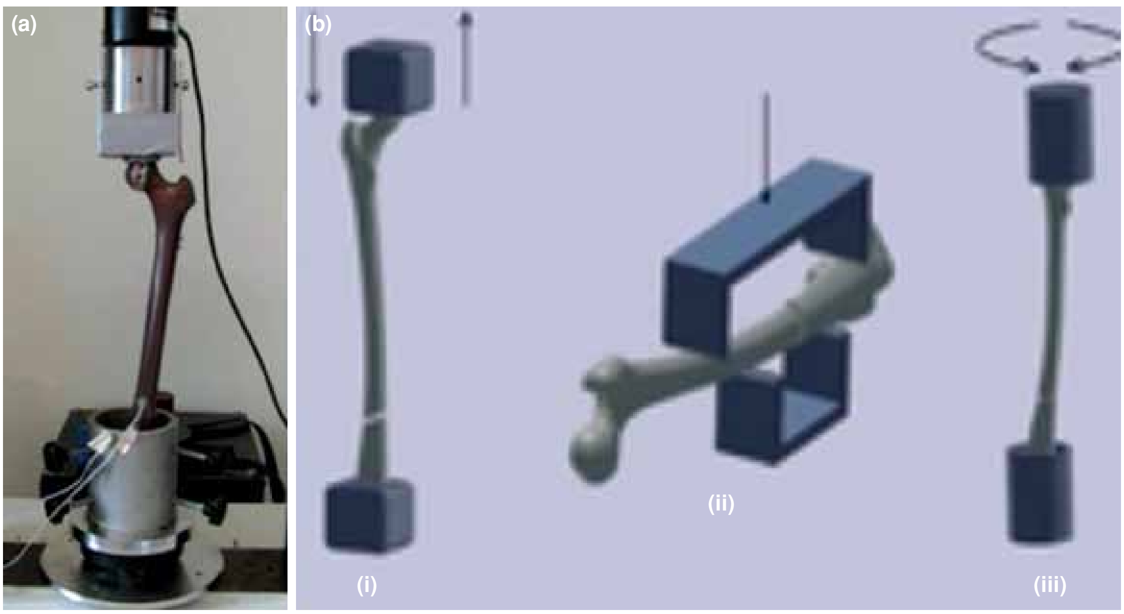

Figure 2. (a) Potted specimen prepared for mechanical tests. Figure showing the specimen placed in the load cell of the testing machine. Strain-gauges are placed on the sawbone femur's fracture contact points. **(b)** Schematic drawings of the tests. ***(i)*** Testing of potted bone-implant axial compression and distraction. ***(ii)*** Testing of A-P, P-A, L-M, M-L four-point bending and ***(iii)*** testing of rotation. The arrows demonstrate the loading directions.

TABLE I

Mean values of displacements

	SIMN	SDCN
	Mean	Mean
Axial compression (mm)	3.68	1.83
Distraction (mm)	1.78	0.178
Rotation (+8) (°)	9.28	5.68
Rotation (-8) (°)	9.15	5.73
Bending AP (mm)	1.73	1.46
Bending PA (mm)	1.28	1.32
Bending lateral (mm)	1.01	1.25
Bending medial (mm)	1.23	1.7

SIMN: Static intramedullary nailing; SDCN: Sustained Dynamic Compressive Nail; AP: Anterior posterior; PA: Posterior anterior.

(sagittal plane), medial-lateral (ML), and lateral-medial (LM) (coronal plane) testing. In each bending test, a maximal load of 300 N was applied at 0.1 mm/s. Centering the device with reference to the center of the fracture zone, all the time was ensured that the bending moment was applied to the same location in each specimen as close as possible. The test was repeated three times to ensure the reproducibility of the results. The load versus displacement values were recorded to calculate the bending stiffness and flexibility and displacement was measured.

Torsional testing

Torsion test was carried out with servo sync torque machine (SQM132, ELSIM Elektroteknik A.S, Istanbul, Turkey). The torsion tests were conducted in the displacement control mode with a constant axial load of 10 N to simulate resting muscle tension and a maximum moment of 8 Nm in both directions; the premoment was 0 Nm and the test velocity was 0.3 °/s. The testing cycle went from 0-8 Nm and all the way through 8 Nm in the other direction back to 0 Nm. Torque versus the degree of angle deformation values were recorded.

RESULTS

Axial compression test

The mean values of stiffness results are shown in Table I. Axial compression tests were carried out for SDCN and the SIMN. Under axial load, the mean stiffness value was 427.1 N/mm for the SDCN (Table II). In addition, axial compression mean values of displacement were 1.83 mm for the SDCN, 3.68 mm for the SIMN, respectively (Table I). However, the mean value of stiffness was 217.8 N/mm for SIMN, respectively (Figure 3). These results showed that the SDCN was more rigid than the SIMN under axial load. It indicated a statistically significant difference between the groups (p=0.006).

Distraction test

For comparison, distraction tests were performed on both nails. In the distraction tests for the SDCN the mean stiffness was measured as 677.7 N/mm (Table II). Also, the distraction mean values of displacement were 0.178 mm for the SDCN, 1.78 mm for the SIMN (Table I). The mean stiffness values for the SIMN were 75.9 N/mm (Figure 3). The results showed that the SDCN was more rigid than SIMN, suggesting a statistically significant difference between the groups (p=0.004).

Rotation test

Rotation tests were carried out for SDCN and SIMN. First a torsional force of +8 N/m was applied.

TABLE II

Mean values of stiffness

	SIMN	SDCN
	Mean±SD	Mean±SD
Axial compression (N/mm)	217.8±68.2	427.1±98.6
Distraction (N/mm)	-75.9±61.6	-677.7±317
Rotation (+8) (Nm/°)	0.89±0.1	1.42±0.1
Rotation (-8) (Nm/°)	0.92±0.2	1.41±0.1
Bending AP (N/mm)	182.7±46.5	218±57.4
Bending PA (N/mm)	239.3±38.3	269.7±120.8
Bending lateral (N/mm)	303.4±57.8	250.1±59
Bending medial (N/mm)	272.3±103.2	194.3±60.6
Strain maximum (μ-strain)	1123.8±66.6	2454.5±45.1
Strain minimum (μ-strain)	0	400.83

SIMN: Static intramedullary nailing; SDCN: Sustained Dynamic Compressive Nail; SD: Standard deviation; AP: Anterior posterior; PA: Posterior anterior.

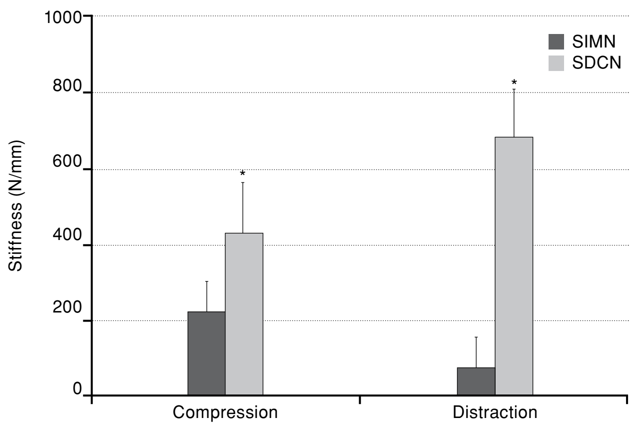

Figure 3. The mean stiffness of Sustained Dynamic Compressive Nail (SDCN) and static intramedullary nailing (SIMN) in axial compression-distraction, and different types of nailing techniques.

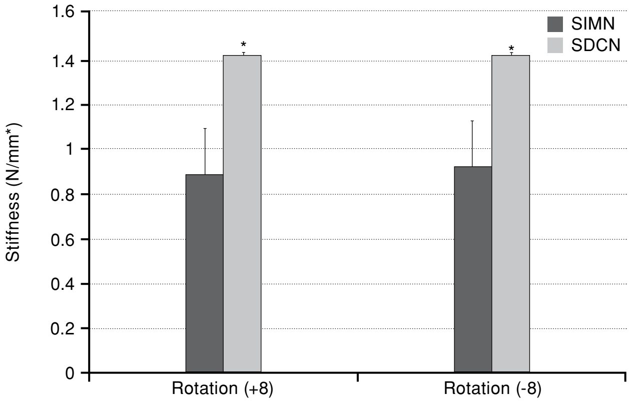

Figure 4. Torsional stiffness during rotational loading in clockwise and counter-clockwise of femur-nail constructs. SDCN: Sustained dynamic compressive nail; SIMN: Static intramedullary nailing.

According to these test results, the mean stiffness values of rotation was 1.42 Nm/° for the SDCN and 0.89 Nm/° for SIMN (Table II). For SDCN, the mean degree was measured as 5.68° and 9.28° for SIMN (Table I). The results have shown us that SDCN has a more rigid rotational stability than SIMN. This difference was statistically significant between the groups (p=0.004). The results obtained after applying -8 Nm rotational mean stiffness values were 1.41 Nm/° for SDCN and 0.92 Nm/° for SIMN (Figure 4). In addition to this, the mean degree was measured 5.73° for SDCN and 9.15° for SIMN. The rotational rigidity for SDCN was more than that of SIMN, indicating a statistically significant difference (p=0.01).

Bending tests

Anteroposterior bending tests were carried out. The mean results of stiffness were measured as 218 N/mm for SDCN and 182.7 N/mm for SIMN. The mean stiffness results of the posterior-anterior bending tests were measured as 269.7 N/mm for SDCN and 139.3 N/mm for SIMN. In the lateral bending tests the results of mean stiffness were 250.1 N/mm for SDCN and 303.4 N/mm for SIMN (Figure 5). In the medial bending tests the results of mean stiffness were maximum 194.3 N/mm for SDCN and 272.3 N/mm for SIMN. All bending test results of SDCN and SIMN are shown in Table II. In addition, there was no significant difference between SIMN and SDCN nails in all bending directions in the displacement measurements (Table I). The compression values of SDCN and SIMN were measured by using strain gauge. Under axial loading, the results of mean strain measurements were 2454.5 μ-strain for the SDCN and 1123.8 μ-strain for the SIMN (Figure 6). In addition, the value of SDCN mean strain was 400.83 μ-strain without axial compression loading. The tension value of the SDCN was higher than that of SIMN, suggesting a statistically significant difference (p=0.004).

DISCUSSION

In the present study, we aimed to evaluate the biomechanical properties of a newly designed intramedullary interlocking nail which sustains a dynamic compression on fracture edges for long bone fracture fixation. The design of the nail was intended to overcome the most commonly encountered complications of the well-known static interlocking nails. Therefore, we performed a comparative biomechanical assessment between the SDCN and a commercially available static interlocking nail device.

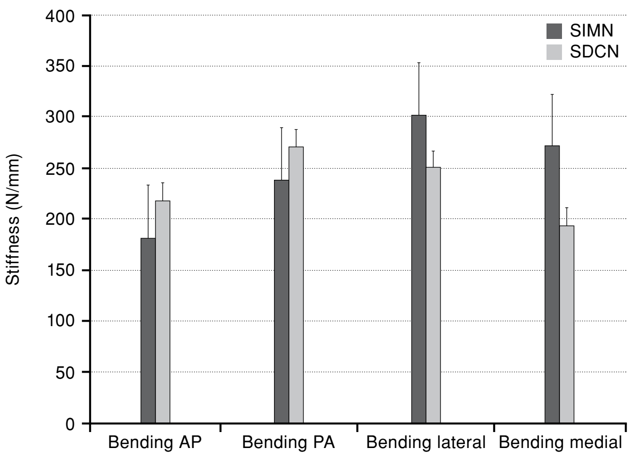

Figure 5. Bending stiffness in different positions of femur-nail constructs. Bending stiffness measurements for all femur models showed no statistically significant differences between the measured data. SDCN: Sustained dynamic compressive nail; SIMN: Static intramedullary nailing.

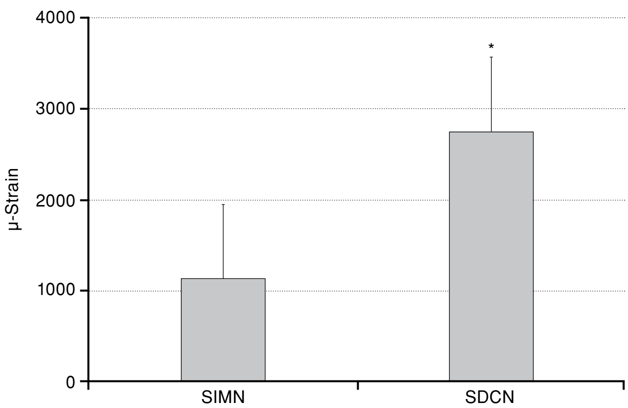

Figure 6. Sustained dynamic compressive nail (SDCN) and static intramedullary nailing (SIMN) strain during loading between two groups of femur-nail constructs. The space under the strain of SDCN bar is 400.83 μ-strain which represents sustained compression on the system without any external force.

The new sustained dynamic compression device fixation technique resulted in significantly smaller fracture gaps and generated better contact pressure than the static fixation technique. Thus, the body weight can be transferred from the proximal fragment to the distal fragment and the fractured femur can share the stress with the interlocking nail system via the fracture site. From a clinical point of view, a smaller fracture gap and sufficient contact pressure are key factors in improving the healing rate.

A static interlocking nail system is often selected to treat fractured femurs, since this system can provide sufficient fixation stability and can prevent limb shortening.[1,25] However, the static fixation technique can result in a gap between fracture fragments which is a serious disadvantage of this technique.[1] Compressive loading for bone healing is still controversial in the literature. In previous experimental studies 300 N, 500 N, 700 N and one and half times of body weight compressive loading have been suggested for bone healing.[26-30]

In our study, it was possible to use 400 N compressive loading. In addition to this, 750 N loading was used to represent body weight and total load was equal to approximately one and half times of body weight. Gardner et al.[26] showed that increased load magnitude was coupled with higher strain rates to maintain a constant loading. Higher strain rates would be expected to increase bone healing. Meanwhile, the distal part of the femur fracture induced a distraction of approximately 100 N.[24] This distraction force might increase the gap. In our study, a distraction force equal to 100 N was applied to both SDCN and SIMN. The gap increases were 0.18 mm for SDCN and 1.78 mm for SIMN, indicating a statistically significant difference (p=0.004). Maintained compressive force during the first six weeks produced a higher amount of new bone formation. Higher amount of periosteal new bone formation was observed.[31-33] Shortening of fracture gaps by compression can improve the healing process. Thus the main effect of this procedure is the reduction of the fracture gap distance, which is known to improve the bone healing.[34-36] In the axial compression loading, a slight micro movement was recorded at the fracture site with SDCN. However, the movement recorded at the fracture site was more with SIMN compared to SDCN. The reason for the little micro motion in SDCN is sustained compression of 400 N at the fracture ends. This compression narrows the gap considerably. The contact pressure increases and the gap narrows at the fracture site. Thus, the micromotions with SDCN (1.83 mm) are much less than those of SIMN (3.68 mm). This difference in micromotions was statistically significant between the groups (p=0.006). It also supports increased stability and load sharing between the nail and the bone. As a result, the nail and screw failure rate may decrease. The problem of locking screw failure and nail breakage has been described after using intramedullary nails. In a large series, 13.8% failure rate of nails and screws was reported, which was treated with small diameter nails and large gaps.[34,37] Better rotational stability was also observed for SDCN, indicating a statistically significant difference (p=0.004). Continuous compression increases the contact pressure of the fracture ends which in term increases rotational stability. Drosos et al.[38] showed that fractures reduced with a bony contact area of 50% or more of the diaphyseal diameter, irrespective of the presence of comminution or not, showed significantly higher torsional stability than fractures with a contact area of less than 50%.

Furthermore, mechanical strain should be in the range of 100-2,000 μ-strain for bone healing.[39-41] Under compressive loading 400 to 2,465 μ-strain was recorded at the synthetic bone fracture site with SDCN. This value is consistent with the literature data. The strain ranges between 0 to 600 μ-strain with SIMN. Strain falls to zero may cause delayed unions or non-union. In a traditional perspective, dynamization is provided by removing proximal or distal interlocking screws in SIMN. In the absence of sufficient callus tissue formed or in the presence of multi-fragmented fractures, a rotational instability or shortening may result. With over shortening, the nail penetrates the knee joint.[1]

However, a dynamic compression is provided without removing the interlocking screws with SDCN. Thus, similar displacement values were recorded in four-point bending tests with both nails. There was not any statistically significant difference. With SDCN the distal part can move in the proximal part in axial direction and the distal part is 2 mm thinner than the proximal part. Although SDCN provides continued axial compression, the results of four point tests were similar to that of SIMN.

Despite its biomechanical advantages of SDCN, its biological and clinical behaviors are still to be elucidated. It is necessary to conduct animal studies with SDCN to learn its biological behavior and *in vivo* stability.

Conclusion

We conclude that the SDCN is an effective femoral fracture fixation device. The technique displays mechanical stability which is superior to that of the standard SIMN in axial compression and torsion in the laboratory setting. Furthermore, little micro-movement was recorded at the fracture site with SDCN in the axial compression loading. The compression is sustained in SDCN, even in lying or sitting positions. Continuous dynamic compression provides μ-strain for bone healing without removing the interlocking screws for dynamization with SDCN. Thus, the formation of axial and rotational instability is prevented. Continuous compression increases the contact pressure of the fracture ends which in term may increase the stability.

Declaration of conflicting interests

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