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Biomechanical comparison of three-point bending resistance of titanium and stainless steel locking screws in intramedullary nails

İntramedüller çivilerde titanyum ve paslanmaz çelik kilit vidaların üç nokta eğilme dirençlerinin biyomekanik yönden karşılaştırılması

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ABSTRACT

Objectives: This study aims to investigate whether there is any significant difference in bending resistance between titanium and stainless steel locking screws of femur nails and to review deformation of locking screws which is a common problem in interlocking nailing.

Materials and methods: In this study, a total of 60 pieces of 5 mm major diameter titanium and stainless steel locking screws were used as six groups in three different thread depth structures (high threaded, low threaded, and unthreaded). Three-point bending tests were conducted on steel screws placed inside stainless steel tube with 30 mm inner diameter, which imitated the level of lesser trochanter. We used an axial compression testing machine in order to determine the yield points that permanent deformation occurred in the locking screws.

Results: For low threaded locking screws, which are the most frequently used thread type for locking screws, the mean bending yield points were 1413 N on the titanium screws and this level was below 1922 N (2.8 BW) of level walking loading on femur for 70 kg person. On low threaded stainless screws, bending resistance was 2071 N, which was above the value of 1922 N. For high threaded locking screws, the mean bending yield points were 874 N on the titanium screws and 556 N on stainless screws.

Conclusion: In comminuted femur shaft fractures (in full load bearing conditions), using stainless steel locking screws is better instead of titanium screws to avoid locking screw deformation since low threaded stainless steel screws were 46.5% more resistant to bending deformation than titanium ones. Stainless steel or titanium high threaded locking screws may only be carefully used in non-comminuted fractures.

Keywords: Femur fractures; femur nail; locking screw; three-point bending.

ÖZ

Amaç: Bu çalışmada kilitli femur çivilerinde titanyum ve paslanmaz çelik kilit vidaların eğilme dirençleri arasında anlamlı fark olup olmadığı araştırıldı ve kilitli çivilemelerde sık görülen bir sorun olan kilit vida deformasyonu incelendi.

Gereç ve yöntemler: Çalışmada toplam 60 adet 5 mm majör çaplı titanyum ve paslanmaz çelik kilit vida üç farklı yiv yapısında (yüksek yivli, alçak yivli ve yivsiz) altı grup halinde kullanıldı. Küçük trokanter seviyesini temsil eden 30 mm iç çapı olan paslanmaz çelik tüp içine yerleştirilen çelik vidalar üzerinde üç nokta eğilme testleri yapıldı. Kilit vidalarda kalıcı deformasyonun oluştuğu akma noktalarının tespit edilmesi için aksiyel kompresyon test makinası kullanıldı.

Bulgular: Kilit vidalarda en sık kullanılan yiv tipi olan alçak yivli vidalarda ortalama akma noktası titanyum vidalarda 1413 N idi ve bu değer 70 kg bir kişide düz zemin yürümede femura gelen 1922 N (2.8 BW) yüklenmenin altında idi. Eğilme direnci alçak yivli paslanmaz vidalarda 2071 N olarak 1922 N değerinin üzerinde idi. Yüksek yivli vidalarda ortalama eğilme akma noktası titanyum vidalarda 874 N ve paslanmaz çelik vidalarda 556 N idi.

Sonuç: Alçak yivli paslanmaz çelik vidalar titanyumlara göre eğilme deformasyonuna %46.5 daha dirençli olduğundan, parçalı femur cisim kırıklarında (tüm vücut ağırlığının yüklenme durumunda) kilit vida deformasyonu olmaması için titanyum vida yerine paslanmaz çelik kilit vida kullanılması daha uygundur. Paslanmaz çelik veya titanyum yüksek yivli kilit vidalar sadece parçalı olmayan kırıklarda çok dikkatli bir şekilde kullanılabilir.

Anahtar sözcükler: Femur kırıkları; femur çivisi; kilit vida; üç nokta eğilme.

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Interlocking intramedullary nailing is a widely accepted method for the treatment of femoral fractures.[1,2] The locking nails are important treatment elements in comminuted fractures as load-bearing device. On comminuted fractures in particular, failure of locking screws is a union threatening complication. Locking screws bear the stress in full load bearing situations and they transfer the load between fractured fragments. In case of early failure of locking screws in comminuted fractures, we should expect complications such as nonunion, malunion, delayed union, shortening, and nail migration.[3,4] Fatigue fractures of locking screws are also a common complication reported with an incidence up to 50%.[5-10]

Yield point of a material is defined as the value of force at which material starts to deform plastically. It was reported that fatigue life of implanted elements was correlated to the yield point of the screws in the three-point bending tests.[11,12] It was stated that load bearing also depends on the activity; for example, peak axial loading on the femur shaft was 1922 N (2.8 BW) for a 70-kg healthy person while walking and 2128 N (3.1 BW) while walking down the stairs.[13,14] In comminuted femur fractures treated with interlocking nailing; the yield points of the locking screws must be higher than 1922 N (2.8 BW) for level walking so that the locking screws not to deform plastically.

The use of titanium intramedullary nail and locking screw for femur and tibia fractures is becoming more widespread recently, due to the features of titanium such as corrosion resistance, biocompatibility, fatigue strength and fewer artifacts on magnetic resonance imaging and computed tomography. We have sought such studies comparing the yield points of titanium and stainless steel locking screws having the same screw structure; however, we were unable to find any, except for some studies about fatigue strength of different type of screws that were manufactured by many different factories.[11,12,15,16]

We hypothesized that bending resistance of the titanium locking screws are lower than stainless steel locking screws. Therefore, in this study, we investigated whether there is any significant difference in bending resistance between titanium and stainless steel locking screws of femur nails and to review deformation of locking screws which is a common problem in interlocking nailing.

MATERIALS AND METHODS

We investigated bending resistance of six types of screws with two different materials (titanium and 316 L stainless steel) and with three different thread depths (unthreaded, low threaded, and high threaded) by performing three-point bending tests (Figure 1).

When we checked the manufacturers' product catalogues of locking screws of intramedullary nails and the postoperative X-ray of the operated patients from other clinics, we realized that mostly 5 mm low threaded titanium and stainless steel screws were used, but unthreaded and high threaded screws were also used as locking screw. We used 30 custom made titanium (Figure 1) and 30 medical custom made stainless steel (316 L) (produced by Hipokrat Medical Devices, İzmir-Turkey for the study) proximal locking screws for six groups, 10 screws for each group (Table I). Of the titanium screws, 10 were smooth, 10 were low threaded, and 10 were high threaded; likewise, of the stainless steel screws, 10 were smooth, 10 were low threaded, and 10 high threaded (Table I). Major diameter of all screws was 5 mm and length of all screws was 55 mm. Low threaded screws had a low-profile high-pitch thread and their core diameter was 4.2 mm (5 mm major diameter) (Figure 1). High threaded screws had a high-profile low-pitch thread and their core diameter was 3.5 mm (5 mm major diameter) (Figure 1). Titanium and stainless steel smooth screws had no thread in their shaft; whereas high threaded and low threaded screws had thread 27 mm in length only in the middle of the screw. Three-point bending test device that we used in our study was exactly the same with the test device used by the previous researchers.[11,12] In this study, the inner and outer diameters of the stainless steel cylinder representing lesser trochanteric level were 30 mm and 45 mm on the level of lesser trochanter.[17-20] Two centimeters below the tip of the stainless steel cylinder, there were two opposite holes with a diameter of 8 mm. In the three-point bending test, we used an interlocking nail of 380x12 mm, the proximal 90 mm part of which was 13 mm in diameter

Figure 1. Unthreaded, low threaded, and high threaded titanium screws.

TABLE I

Yield point values at three-point bending test comparing titanium and stainless steel screws (5 mm major diameter) with three different thread height (n=60)

Screw groups	Titanium screws (N)		Stainless steel screws (N)			
	Mean±SD	95% CI	Mean±SD	95% CI	%	*p*
Low threaded	1413±109	1334-1491	2071±250	1892-2250	46.5↑	0.000
High threaded	874±94	806-941	556±83	496-616	57 ↓	0.000
Unthreaded	2452±52	2415-2490	3169±248	2991-3346	30 ↑	0.000

N: Newton; SD: Standard deviation; CI: Confidence interval.

(Tıpsan Medical Devices Company, İzmir, Turkey). There was an oblong proximal locking screw hole which was 12 mm long and 6 mm wide 60 mm distal from the interlocking nail proximal edge. In order to prevent the sidewise movement of the interlocking nail within the metal cylinder, two rings supported the nail proximally and distally (Figure 2) and the outer diameter of which was 2 mm smaller than the inner diameter of the cylinder. These two rings were placed on the nail by three screws, and then their free movement within the cylinder was checked, both distally and proximally. The screws to be tested were passed through metal cylinder holes which had an 8 mm diameter and a proximal locking screw hole of the nail (Figure 2). In this experiment assembly, the whole load was transferred through the proximal locking screw, from the proximal to distal.

This study was conducted in biomechanics Laboratory of Institute of Health Science, at Dokuz Eylül University. The axial compression testing machine (AG-I 10 kN, Shimadzu Corporation, Kyoto, Japan) was used to perform the biomechanical tests. The loading rate we used was 1 mm/minute in displacement control mode.[11,12,15] The loading force was exerted on the head of the nail (Figure 2). 100 N preload was initially applied to the locking screws. In the experimental design of this study, the yield points of the titanium and the stainless steel screws were investigated. Force-displacement graphs were given by computer monitor of the testing machine as output. Force-strain graph revealed the bending in the elastic-plastic deformation point, during the biomechanical test process. The yield point was detected in the graphs, as the point where the straight line turned into a curve. We checked all screws and nails visually

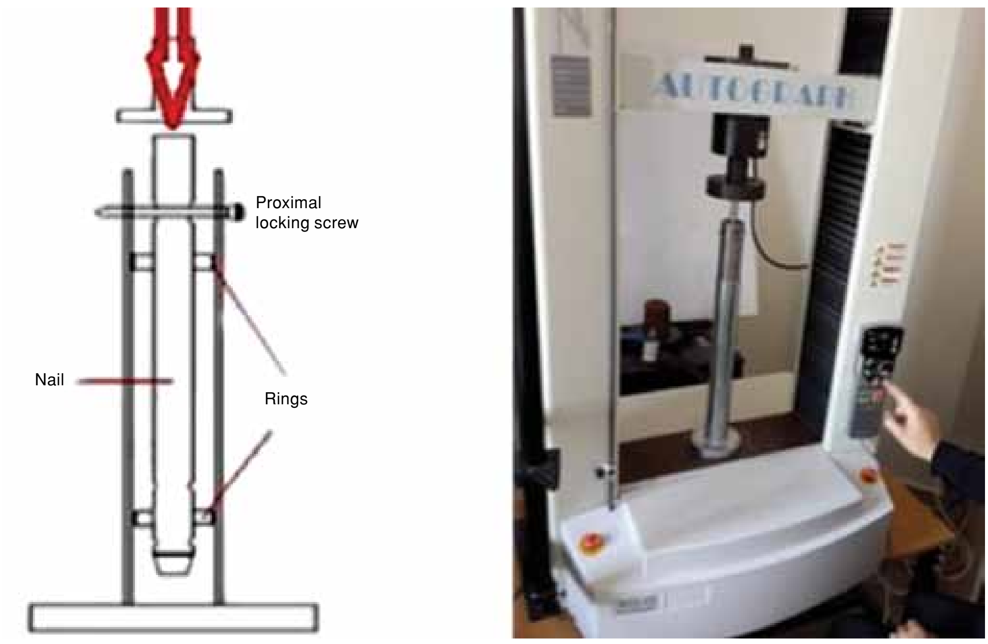

Figure 2. Illustration and photography of three-point bending test of locking screws.

TABLE II

Deformation values (mm) at yield point at three-point bending test comparing titanium and stainless steel screws (5 mm major diameter) with three different thread height (n=60)

Screw groups	Titanium screws (mm)		Stainless steel screws (mm)		
	Mean±SD	95% CI	Mean±SD	95% CI	*p*
Low threaded	0.71±0.03	0.69-0.74	1±0.05	0.96-1.05	0.000
High threaded	0.62±0.05	0.58-0.66	0.4±0.04	0.37-0.43	0.000
Unthreaded	0.77±0.03	0.74-0.8	1±0.08	0.94-1.06	0.000

SD: Standard deviation; CI: Confidence interval.

after every test and saw that all the screws were bent in the middle.

We used the Mann-Whitney test to evaluate the data of the yield point values, the deformation on the yield point and stiffness at the three-point bending test. We accepted p<0.05 for statistical significance.

RESULTS

We found that bending yield point values of the stainless steel screws (5 mm major diameter) were 46.5% more than the titanium ones for low threaded screws which is the most frequently used tread type as locking screw (p=0.000) (Table I). At three-point bending test, we determined that the yield points of titanium low threaded locking screws were mean 1413 N (below 1922 N (2.8 BW) for 70 kg person level walking) (Table I). We determined the yield points of low threaded stainless screws to be 2071 (above 1922 N) (Table I). We detected that the bending resistance of high threaded titanium (874 N) and stainless steel locking screws (556 N) decreased extremely below 1922 N (Table I).

We found that yielding occurs on unthreaded and low threaded stainless steel screws (5 mm major diameter) by 1 mm bending, but on titanium screws with the same structure yielding occurs by 0.77 and 0.71 mm bending, respectively (Table II). The stiffness of stainless steel screws was higher than titanium ones in all groups (Table III).

DISCUSSION

In this study, our objective was to investigate the difference in bending resistance between titanium and stainless steel locking screws. For low threaded screws (the most frequently used thread type as locking screw), we have determined that stainless steel screws (5 mm major diameter) have 46.5% more bending resistance than titanium ones. In comminuted femur fracture, using stainless steel screws as locking screws on stainless steel nails is better in order to allow weight bearing. High threaded titanium or stainless steel locking screws may only be carefully used in non-comminuted fractures (load sharing conditions).

In the test with the polyethylene cylinder, the pull-out and holding power of the locking screw has a major role, and this makes the yield point determination impossible. Instead of yield point determination, mostly the locking screw bending fatigue life tests were performed,[16,21] where the holes of the cylinders were not bigger than the screw diameter. The researchers in the previous studies measured the force around the point of 1 mm deformation and defined it as the "yielding strength" instead of the "true yield point".[11,12,15] The holding power of

TABLE III

Stiffness values (N/mm) at three-point bending test comparing titanium and stainless steel screws (5 mm major diameter) with three different thread height (n=60)

Screw groups	Titanium screws (N/mm)		Stainless steel screws (N/mm)		
	Mean±SD	95% CI	Mean±SD	95% CI	*p*
Low threaded	2180±128	2088-2272	2398±249	2219-2576	0.015
High threaded	1547±141	1446-1649	1963±482	1618-2308	0.043
Unthreaded	3348±117	3264-3432	3662±170	3541-3784	0.000

N: Newton; SD: Standard deviation; CI: Confidence interval.

locking screws (resistance to pull out from cortex) is different in osteoporotic bone (the least resistance), non-osteoporotic bone, and polyethylene cylinder.

Researchers have reported that the fatigue strength of the stainless steel screws is longer than titanium screws of similar size.[16]

In comminuted femur fractures and high-energy fractures where bone resorption on the fracture site is common, interlocking nails serve as full load-bearing implants and locking screws must resist to body weight loading for early weight bearing. In their study, Hou et al.[12] and Taylor et al.[13] have reported that peak axial load on femur while going down the stairs was 2128 N (3.1 BW) for a 70 kg individual and that during level walking peak axial load on femur was 1922 N (2.8 BW). We have determined that the yield points of low threaded titanium screws were below 1922 N. Failure of low threaded titanium screws may be in level walking for full load bearing conditions. We showed that low threaded stainless steel locking screws and unthreaded locking screws (titanium or stainless steel) could endure up to 1922 N of axial loading for level walking.

We detected the most commonly used length of femur and tibia proximal and distal locking screws from a questionnaire which we conducted to production firms and orthopedic surgeons. Working lengths of proximal and distal locking screws of tibia were roughly similar in length with working length of proximal locking screw of femur. We can assume that the bending resistance of femur proximal locking screws would be valid for bending resistance of proximal and distal locking screws of tibia.

In an experimental assembly simulating physiological non vertical or angled forces, it would not be possible to determine the true yield points of locking screws due to slipping between locking screw and nail. With composite femurs, it is impossible to find out which locking screw deformation (one proximal and two distal locking screws) is responsible for the sudden deformation that appears on the force-deformation graph. We found out that even a slight deformation of 0.1 mm can make it impossible to determine the true yield point and affect the test seriously. In polyethylene cylinder or cadaveric femur locking screw holes can also be deformed and it's impossible to differ screw deformation from the cylindrical material deformation or its holes. Therefore, we used stainless steel cylinders holes which are not prone to deformation.

To conclude, in load bearing conditions (in comminuted femur shaft fractures), using stainless steel screws is better instead of titanium locking screws to avoid locking screw failure since stainless steel screws were 46.5% more resistant to bending deformation than titanium ones for low threaded screws. Stainless steel or titanium high threaded locking screws may only be carefully used in non-comminuted fractures.

Declaration of conflicting interests

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