A Biomechanical Comparison of Unlocked or Locked Reamed Intramedullary Nails in the Treatment of Mid-third Simple Transverse Femoral Shaft Fractures

Chi-Chuan Wu, MD; Ching-Lung Tai, PhD

Background: Despite that a mid-third simple transverse femoral shaft fracture has been traditionally treated with an unlocked reamed intramedullary nail, recently a static locked reamed intramedullary nail has been favored by some orthopedists to avoid missing extended fracture lines. A prospective comparison of both nails was conducted to investigate the superiority between the nails from biomechanical viewpoints.

Methods: Seven pairs of fresh healthy cadaver femora underwent mid-third transverse osteotomy. Consequently, all seven left femora were stabilized using Kuntscher nails and all seven right femora, static Russell-Taylor locked nails. Finally, all 14 femora were tested using a Material Testing System (MTS) machine to investigate the sustained mechanical loads, the maximal failure load, and the relative fragment displacement.

Results: The locked nails produced the larger mechanical loads ($p = 0.02$). The unlocked nails had the larger fragment displacement ($p = 0.02$) and the higher maximal failure load (6090 verse 5590 newtons, $p = 0.02$). All tests ended due to basal neck oblique fractures.

Conclusions: Biomechanically, an unlocked nail, being a load-sharing device, is superior to a static locked nail, being a load-bearing device, in the treatment of a mid-third simple transverse femoral shaft fracture. Clinically, careful investigation of the fracture types and adequate selection of the nail type should be performed in treating these types of fractures.
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Key words: biomechanical comparison, unlocked nail, locked nail, femoral shaft fracture.

Closed reamed intramedullary nailing has been the treatment of choice for closed or mild open femoral shaft fractures.[1-3] The invention of locked nails further extends the indications for the treatment of femoral fractures.[4,5] However, an unlocked reamed intramedullary nail is usually suitable for mid-third simple transverse or short oblique fractures.[6,7]

Although an unlocked nail possesses a low torsional stability,[8] clinically using it to treat a mid-third simple transverse femoral shaft fracture can normally achieve great success.[9,10] The union rate is high and the complication rate is low. One rare technical error that may occur is missing extended frac-

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ture lines from the fragment ends, which may be caused during the injury or iatrogenically during nail insertion.[10-12] Once a fracture line appears, a locked nail should be used to prevent fragment collapse.[12]

Recently, a mid-third simple transverse femoral shaft fracture was advocated by some orthopedists to be treated using a static locked nail to avoid missing extended fracture lines.[3,13] A high success rate with a low complication rate was also reported. However, in some reports in the literature, performing locked nailing not only introduced much more complications, but also is technically much more difficult.[14-16] Thus to avoid missing extended fracture lines, more complications may be produced adversely.

In some reports in the literature, many kinds of biomechanical studies for locked intramedullary nails have been enthusiastically performed. However, to the best of our knowledge, comparison between both nails in the treatment of a mid-third simple transverse femoral shaft fracture has not been reported. We, therefore, conducted a comparison of both nails to determine the superiority from biomechanical viewpoints.

METHODS

Seven paired human femora were obtained from fresh cadavers. Five donors were male and two were female, and the ages at death ranged from 22 to 42 years. The specimens were immediately stored at -70˚C after the harvest. As early as possible, the test fracture was performed and the specimen was thawed to room temperature for 24 hours before use. A pretest roentgenogram was obtained for each specimen to ensure there were no bone defects. In addition, there were no soft tissue attachments requiring complete removal.

First, each bone was clamped in a holding jig and intramedullary reaming was performed. The inlet for the guide wire insertion was at the lateral margin of the piriformis fossa and concomitantly, slightly posterior to the midpoint in the frontal plane. Six paired femora were reamed to 14 mm and one (the fourth pair), 13 mm due to the small diameter of the shaft. Then, identical test fractures were created in each pair of femora using a power saw. The bones were still clamped in a holding jig while the saw cuts were made. The cut was transversely performed at the midpoint of the isthmus of the femur.

The fractures were reduced and stabilized using intramedullary nails. All seven left femora were stabilized using Kuntscher nails (Zimmer, Warsaw, Ind). Six nails were 13 mm of the diameter and one (for the fourth pair) was 12 mm. The adequate length of the nail was from the trochanter tip to the upper margin of the condyle. All seven right femora were stabilized using Russell-Taylor locked nails (Smith & Nephew, Memphis, Tenn). Similarly, six nails were 13 mm of the diameter and one (for the fourth pair) was 12 mm. The lengths of nails were the same for both sides. Under the guidance of an image intensifier, all locked nails were inserted using a static mode, one proximal diagonal screw and two distal transverse screws (Fig. 1).

After the fracture fragments were stabilized, the entire femur was mounted to a uniaxial Bionix 858 Material Testing System (MTS, Minneapolis, Minn) machine for mechanical testing. The shaft was kept with a 23° varus and the center of the femoral head was at the midpoint of the frontal plane. An extensometer (model: 632. 12F-20, MTS) was placed at the lateral aspect of the fracture fragments to measure the relative displacement of the fragments (Fig. 2).

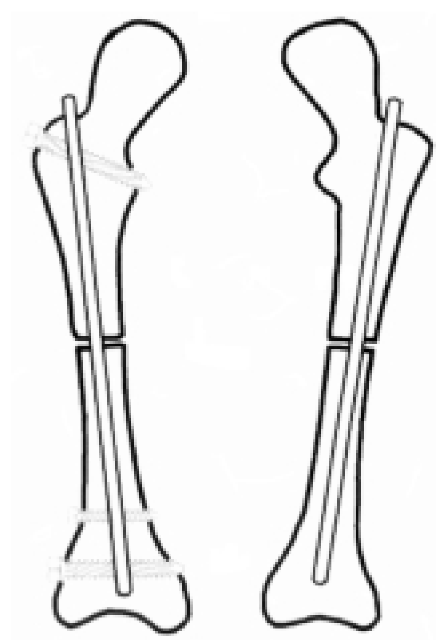

Fig. 1 After intramedullary reaming with mid-third transverse osteotomy was performed, all left femora were stabilized with Kuntscher nails and right femora, static Russell-Taylor locked nails.

The femora were sequentially loaded with 20 newtons / sec upward increment up to test failure. The data acquisition was every 0.1 mm of displacement of the femoral head and displacement limit was 20 mm. The data of mechanical loads, the relative fragment displacement, and the maximal failure load were recorded. The differences of the data between unlocked and locked nails were compared. A Wilcoxon signed rank test was used for statistical comparison and $p < 0.05$ was considered significantly different. For multiple testing, the Bonferroni correction method was used to reduce type I error.

Fig. 2 The entire femur was mounted in a uniaxial Bionix 858 Material Testing System (MTS) machine for mechanical testing. An extensometer was placed at the lateral aspect of fracture fragments to measure the relative displacement of fragments.

RESULTS

Following the upward increment of mechanical loads on the femoral head, displacement of the femoral head was also increased (Table 1, Fig. 3). In addition, the inter-fragmental distance was decreased (Table 2, Fig. 4).

When displacement of the femoral head occurred, mechanical loads on the locked nails were significantly larger than that on the unlocked nails (p = 0.02, Table 3). Also, the inter-fragmental distance was significantly decreased to a greater degree on the unlocked nails as compared with the locked nails (all values of p = 0.02 or 0.04, Table 3). However, the significant differences occurred only when the femoral head was displaced by 1 and 2 mm. No significant differences were noted when the femoral head was displaced by 3, 4 or 5 mm (Table 3).

The maximal failure load on the unlocked nail was significantly higher than that on the locked nail (6090 verse 5590 newtons, p = 0.02, Table 1).

All 14 tests ended with basal neck oblique fractures (Fig. 5, left). The starting point of the neck fracture was from the lateral edge of the nail inlet and it extended to the upper margin of the lesser trochanter (Fig. 5, right).

There was no nail or screw breakage. No nail

Table 1. Mechanical Loads and Maximal Failure Load Introduced by Increased Femoral Head Displacement

	Mechanical loads (100 newtons) in femur pair															
	1		2		3		4		5		6		7		Subtotal	
	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R
Displacement of femoral head																
1 mm	7.9	12.3	9.5	15.7	9.4	9.5	11.7	11.8	9.2	14.1	7.7	7.8	8.4	10.8	9.1	11.7
2 mm	20.3	25.9	20.5	32.1	17.7	21.2	23.3	23.9	12.4	20.2	21.1	19.5	26.6	34.6	20.3	25.3
3 mm	34.6	38.4	33.3	48.7	34.8	37.0	35.3	37.4	33.1	38.6	34.1	37.5	43.9	47.5	35.6	40.7
4 mm	49.5	49.6	46.5	---	51.0	53.4	45.5	---	55.1	60.1	48.8	47.7	47.8	---	49.2	52.7
5 mm	62.5	---	58.2	---	65.1	---	---	---	64.0	---	61.2	59.4	---	---	62.2	59.4
Maximal failure loads (100 newtons)																
	62.5	57.6	65.8	61.9	67.3	55.3	46.0	38.7	67.9	64.7	62.7	63.8	53.9	49.1	60.9 (8.1)	55.9 (9.3)

Abbreviations: ( ): standard deviation

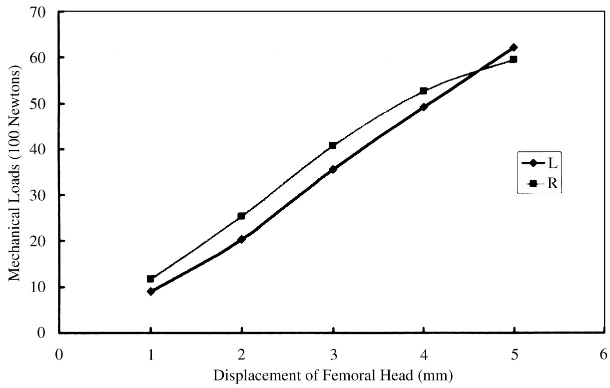

Fig. 3 Following the upward increment of mechanical loads on the femoral head (20 newtons / sec), displacement of the femoral head was also increased.

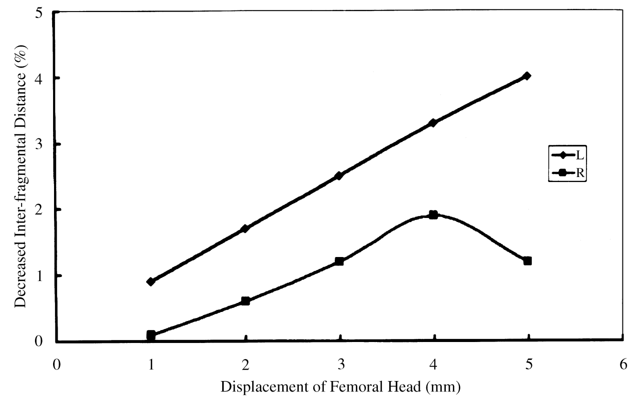

Fig. 4 Following increased displacement of the femoral head, the inter-fragmental distance was decreased.

Table 2. Decreased Inter-Fragmental Distance Introduced by Increased Femoral Head Displacement

	Decreased inter-fragmental distance (%) in femur pair															
	1		2		3		4		5		6		7		Subtotal	
	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R
Displacement of femoral head																
1 mm	1.1	0.3	0.4	0.0	0.8	0.1	0.2	0.1	2.3	0.4	0.8	0.1	0.6	0.0	0.9	0.1
2 mm	2.5	0.9	1.0	0.5	1.4	0.8	0.4	0.3	3.1	1.4	1.3	0.3	2.0	0.2	1.7	0.6
3 mm	4.5	1.8	1.9	0.9	1.7	1.2	0.9	0.8	4.0	2.3	1.7	0.7	2.9	0.5	2.5	1.2
4 mm	6.5	2.7	2.8	---	1.8	1.4	1.0	---	4.8	2.6	2.0	1.0	4.0	---	3.3	1.9
5 mm	7.0	---	3.7	---	2.0	---	---	---	5.0	---	2.3	1.2	---	---	4.0	1.2

Table 3. Comparison of Mechanical Load and Decreased Inter-Fragmental Distance between Both Nails

		Mechanical loads		Decreased inter-fragmental distance	
		(100 newtons)	*p* value	(%)	*p* value
Displacement of femoral head					
1 mm	L	9.1 (1.3)		0.9 (0.7)	
	R	11.7 (2.9)	0.02	0.1 (0)	0.02
2 mm	L	20.3 (4.4)		1.7 (0.9)	
	R	25.3 (5.9)	0.05 [0.1]	0.6 (0.4)	0.02 [0.04]
3 mm	L	35.6 (3.7)		2.5 (1.3)	
	R	40.7 (5.1)	0.02 [0.06]	1.2 (0.6)	0.02 [0.06]
4 mm	L	49.2 (3.2)		3.3 (1.9)	
	R	52.7 (5.5)	0.30	1.9 (0.9)	0.15
5 mm	L	62.2 (2.7)		4.0 (2.0)	
	R	59.4 (0)	N.A.	1.2 (0)	N.A.

Abbreviations: Mean (Standard deviation); N.A.: not available; [ ]: with Bonferroni correction.

migration was noted. The stability on the osteotomy site was still well maintained as compared with the pretest condition (Fig. 5, left).

DISCUSSION

In the single-legged stance of a walking cycle, the femoral head sustains at least 3 times the body

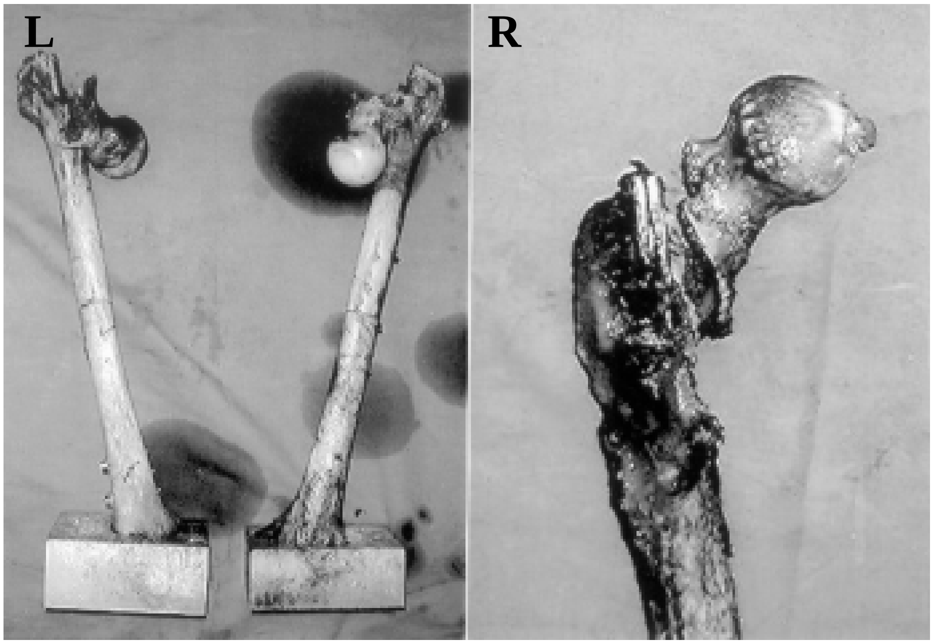

Fig. 5 (left) Both femora failed due to basal neck oblique fractures. All nails, screws, and osteotomy sites were still intact. (right) The starting point of the neck fracture was from the lateral edge of the nail inlet and it extended to the upper margin of the lesser trochanter.

weight of loads due to contracture of hip abductors to keep the body balanced.(15,17) The reacting vector is inclined 16° from the vector line. Because the anatomic axis of a femur is on average 7° valgus,(18) mounting the femur at 23° varus on the MTS machine can simulate the physiologic loads.(17)

The stability provided by a Kuntscher nail in the treatment of a long bone fracture is by way of the three point contact.(16,20) After over-reaming within 1 mm of the shaft diameter, bone fragments are only splinted.(21,22) Therefore, axial compressive force can compel fragments to further contact. Loads can be transferred partially by the nail and partially by the bone. This load-sharing effect can lower the incidence of implant failure. Clinically, breakage of a Kuntscher nail is relatively uncommon. Because clinically the fracture line is usually in a zigzag pattern, closure of the fracture gap by compression can enforce the torsional stability. In some reports in the literature, using a Kuntscher nail to treat a mid-third simple transverse or short oblique fracture is normally successful. Nevertheless, in an animal study by Utvag et al, a static locked nail achieved better fracture healing due to better torsional rigidity as compared with an unlocked nail for middle femoral shaft osteotomy.(23) Thus, in the clinical practice, torsional instability seems to be not so important.

On the other hand, the stability provided using a static locked nail in the treatment of a long bone fracture is due to screw fixation, especially the proximal diagonal screw and the upper distal transverse screw. The lower distal transverse screw may not be absolutely necessary.(24-26) Despite over-reaming to within 1 mm of the shaft diameter, loads on the nail are totally sustained by the screws and the nails can not effectively close the fracture gap. This load-bearing effect may elevate the incidence of screw or nail breakage. Clinically, locked nail breakage is not uncommon.(15,27,28) In this study, following the compression of the femoral head, the gap between the upper and lower fragments continuously decreased (Table 2, Fig. 4). Nevertheless, in comparison with the unlocked nail group, the gap in the locked nail group was more resistant to compression ($p = 0.02$ or 0.04), which sequentially had greater mechanical loads ($p = 0.02$).

The test failure in this study was due to femoral neck oblique fractures (Fig. 5) and there were no nail or screw breakage. It was largely different from the failure mode in clinical use.(27-29) In some reports in the literature, locked nail or screw breakage was usually associated with the delayed fracture healing process and implant failure was due to mechanical fatigue.[27,28,30,31] In this study, both nails tolerated more than 5500 newtons of loads. However, because the femoral head in locked nail group sustained higher mechanical loads due to larger resistance to compression, the neck failed earlier (Table 1). As for the maximal failure load, the unlocked nail group was also better (p = 0.02) because it had the better load transfer (load-sharing verse load-bearing). Theoretically, all proximal loads had to be transferred through the proximal diagonal screw on a static locked nail, which introduced a stress-concentration phenomenon. Furthermore, all test failure was due to stress-concentration on the femoral neck at the nail inlet.[29,32]

In this study, a non-slotted Russell-Taylor locked nail was used for testing. In some reports in the literature, the mechanical strength between non-slotted and slotted locked nails was compared. When distal femoral shaft osteotomy with a 3-cm segment bone defect was tested, Covey et al found that slotted nails had significantly higher maximal failure loads than non-slotted nails (3050 vs. 2490 newtons).[33] The reason was explained as slotted nails were less rigid, which might facilitate greater load sharing. The mode of test failure in their series was all due to implant failure without neck fractures. Our study revealed that non-slotted locked nails or unlocked nails could withstand more than 5500 newtons of axial loads. The higher maximal failure load in our study should be due to the better load-sharing effect without segmental bone defects. When mid-third femoral shaft osteotomy with a 5-cm segment bone defect was tested, Alho et al found that non-slotted nails had higher torsional strength.[34] However, both nails had similar clinical results in their series.

Theoretically, a non-slotted nail can avoid stress-concentration effects on the slot end of a locked nail.[22,35] Moreover, nails per se around distal transverse screw holes have less open sections.[36,37] The incidence of nail breakage should be lower naturally. However, it contrarily becomes more rigid, which may introduce blowup of fragments if the curvature of nails and bone is unmatched.[33,34] Therefore, a non-slotted locked nail should be more suitable for segmental comminuted fractures and, not for a simple transverse middle shaft fracture.

The shortcomings for the locked nail in clinical use have been reported.[14-16] Some technical complications are even very complex. Although some techniques can be improved after continuous training, some disadvantages on nails per se and surgical techniques are still difficult to be ameliorated. Practically, when using a static locked nail we must compare its merits and demerits. For treating a simple transverse femoral shaft fracture, an unlocked nail has been reported to have great success clinically. In our biomechanical study, it was also revealed to have significant superiority. As long as the fracture site is carefully inspected, a static locked nail should not be considered preferentially.

In conclusion, we performed a biomechanical comparison between an unlocked and a locked reamed intramedullary nail in the stabilization of a mid-third transverse femoral shaft osteotomy. The results revealed that an unlocked nail permitted fragments to slide and to gain more contact after axial compression. The mechanical loads were significantly lower and the maximal failure loads were statistically higher. This load-sharing effect should be able to lower the incidence of implant failure. From both clinical and biomechanical considerations, an unlocked nail should be superior to a static locked nail in the treatment of a mid-third simple transverse femoral shaft fracture.

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以非鎖定型或鎖定型擴腔式骨髓內鋼釘治療股骨中段單純橫斷骨折在生物力學上優劣的比較

吳基銓 戴金龍

背 景： 儘管股骨中段單純橫斷骨折，傳統上是以非鎖定型擴腔式骨髓內鋼釘治療；近年來有一些骨科醫師，另主張以鎖定型擴腔式骨髓內鋼釘治療，以避免誤判疏漏的骨折延伸線。文獻上報導，兩者都能得到極高的成功率。本研究從生物力學上的觀點，前瞻性去比較兩種鋼釘的優劣處。

方 法： 七對均爲新近得到的健康的捐贈人體股骨，施以中段橫斷截骨。所有的七隻左側股骨，以崑氏鋼釘（Kuntscher nail，一種常用的非鎖定型擴腔式骨髓內鋼釘）固定。剩下的七隻右側股骨，則以拉－泰氏鋼釘（Russell-Taylor locked nail，一種常用的鎖定型擴腔式骨髓內鋼釘）固定。最後，所有的 14 隻股骨，均接受力學測試機的測試，以比較承受的機械力道、最大的失敗負荷力、相對的骨段位移。

結 果： 鎖定型鋼釘造成較大的機械力道負擔。非鎖定型鋼釘則有較大的骨段位移及較高的失敗負荷力。最後，所有的測試都終止於股骨頸傾斜性骨折。

結 論： 從生物力學上的觀點，非鎖定型鋼釘是分攤負荷力的裝備，而鎖定型鋼釘則是完全承擔負荷力的裝備；因此，對股骨中段單純橫斷骨折的治療，前者較優。加上，臨床上施行鎖定型鋼釘手術時，合併症多很多。臨床上治療此類骨折時，應先詳查骨折類型；再選擇適當的鋼釘類型，才是最恰當的做法。不要一昧地，都以鎖定型鋼釘去治療。

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關鍵字： 生物力學上的比較，非鎖定型鋼釘，鎖定型鋼釘，股骨幹骨折。

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