Nickel-titanium shape-memory sawtooth-arm embracing fixator for periprosthetic femoral fractures

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Abstract

Purpose We reviewed data to determine outcomes for 21 consecutive Vancouver type B1 or type C periprosthetic fractures that we treated between 2001 and 2008 using a nickel–titanium shape-memory sawtooth-arm embracing fixator.

Methods The study participants were 12 men and 9 women (mean age, 70.8 years; range, 42–85 years). The average duration of follow-up monitoring was 39.7 months (range, 1–78 months). In five cases, cables and screws were used for further stabilisation. No bone grafting was performed for any of the patients.

Results Results were satisfactory, except for one patient who died one month after surgery from a cause unrelated to arthroplasty. Bone union was achieved in the remaining 20 cases within an average of 5.25 months. No implant failures or malunions occurred in any of the patients. The average Harris hip score at the final follow-up examination was 79.3 points.

Conclusions Our results show that the embracing fixator is a valid alternative treatment for Vancouver type B1 or type C periprosthetic femoral fractures.

The treatment of periprosthetic femoral fractures presents a major clinical challenge in orthopaedic surgery [13]. Because of both the increase in average life span and the current popularity of hip-replacement, including revision procedures, this type of fracture is likely to be encountered more often in the future.

An unstable periprosthetic femoral fracture without any loosening of the implant should be fixed without removal of the prosthesis. Patients with periprosthetic fracture are typically elderly individuals with varying degrees of osteoporosis. An ideal implant should not only maintain prosthesis stem stability but also provide stable fixation of poor-quality bone around the prosthetic stem.

To fulfill these requirements, surgeons have used some special fixation methods, such as Mennen plates, Dall-Miles plates, and locking-plate systems (Table 1). The Mennen plate is a clamp-on plate and is not designed for stabilisation of weight-bearing bone fractures. Most studies have shown that use of the plate led to varus collapse in the fixation of periprosthetic femoral fractures [1, 14]. Due to the problem of lack of space for screws around the stem, the plate is combined with cables to treat periprosthetic fracture, a system that is referred to as a Dall-Miles plate. However, there is concern about the actual clinical outcomes when Dall-Miles plates are used [16–19].

Locking-plate systems tend to solve problems related to the inability of conventional unicortical screws to provide sufficient stability around the prosthetic stem [3, 7, 8, 10]. Locking unicortical screws can provide angular stability in nonosteoporotic bone. Unfortunately, the majority of periprosthetic fractures are osteoporotic fractures. Some researchers [7] have suggested using a minimum of four bicortical locking screws on each side of the fracture. In

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Table 1 Published results of internal fixation of periprosthetic femoral fracture

Reference	Number of cases	Implant type	Average time of follow-up	Number of cases of bone union	Average time of bone union	Number of cases with major complication	Others
Aluja et al. [11]	16	Mennen plate	Unspecified	4	5.7 months	12 cases of varus collapse	
Noorda et al. [14]	36	Mennen plate	27 months	26	5 months	10 cases of varus nonunion	
Tadross et al. [17]	9	Dall-Miles plate	14.6 months	3	4.2 months	2 cases of mal-union, 4 cases of nonunion	
Tsiridis et al. [18]	16	Dall-Miles plate	16 months	9	5.8 months	4 cases of plates fracture, 2 cases of non-unions	1 case died 3 months after the operation
Venu et al. [19]	13	Dall-Miles plate	6.5 months	10	4.4 months	3 cases of fixation failure or nonunion	
Chakravarthy et al. [3]	12	LCP or LISS	13.9 months	10	4.8 months	2 cases of implant failure	1 case died 2 weeks after the operation
Kääb et al. [7]	13 (2 lost)	LISS	20 months	11	Unspecified	2 cases malunion, 1 case of implant failure which was lost	
Kobbe et al. [8]	21 (2 lost)	LISS	34 months	Unspecified	Unspecified	2 cases of screw pullout	3 cases died during the follow-up
Kumar et al. [10]	18	LISS	11.7 months	15	18.6 weeks	1 case of plate failure, 1 case of plate lifted off	3 cases died during the follow-up

most situations, there is limited space for bicortical locking screws around the prosthetic stem. Consequently, implant failures are often observed [3, 7, 8].

This article reports our experience with the use of a nickel–titanium (Ni-Ti) shape-memory sawtooth-arm embracing fixator (Ni-Ti SSEF, Shanghai Si-Ai Hi-Tech Ltd., Shanghai, China) in repairing periprosthetic fractures with stable femoral prostheses. The nickel–titanium shape-memory metal alloy is a functional material, the shape and stiffness of which can be controlled by temperature. The metal undergoes a complex crystalline-to-solid phase transition referred to as martensite–austenite transformation. As the metal in the high-temperature (austenite) phase is cooled, the crystalline structure enters the low-temperature (martensite) phase, where it can be easily bent and shaped. As the metal is reheated, its original shape and stiffness are restored [9, 11]. In addition to these desirable qualities, the material possesses excellent springback and superelastic properties [12]. The Ni-Ti SSEF consists of three components: body, arms, and sawteeth (Fig. 1). Each pair of arms resembles a clamp. Because of the martensite–austenite transformation, the clamp can be easily extended and shaped to fix bone fractures by temperature changes.

Patients and methods

Twenty-one consecutive Vancouver type B1 and type C periprosthetic femoral fractures were reviewed in our department after surgical treatment between May 2001 and April 2008. The fractures were categorised according to Vancouver classification [2]. The indications for internal fixation that we used included type B1 and type C fractures. There were 16 type B1 fractures and five type C fractures, all of which were fixed with a Ni-Ti SSEF. These fractures involved 16 total hip replacements and five hemiarthroplasties and used 19 cementless femoral stems and two cemented femoral components. Eighteen fractures were related to a previous primary hip replacement and three were around a revision femoral component.

There were 12 men and 9 women; their mean age was 70.8 years (range, 42–85 years). The mean elapsed time from previous surgery to fracture was 64.7 months (range, 1–156 months). The average duration of follow-up was 39.7 months (range, 1–78 months). Twenty fractures were associated with hip replacement, and one was associated with ipsilateral knee and hip replacement. The demographics of the patients are shown in Table 2.

All fractures were fixed with a Ni-Ti SSEF and five oblique or spiral fractures with cables or screws for further stabilisation. No bone was grafted in any of the patients. Two surgical approaches were employed in the series, including the lateral femoral approach in 18 cases and the

Fig. 1 The fixator consists of a body, pairs of arms, and sawteeth. In the axial direction, pairs of arms were designed symmetrically to be placed on each side of the fracture (*a, b, c, d*). On the plane that is

parallel to the arms, each sawtooth appears as a triangle (*e*). The base of the triangle faces the bone fracture, and the vertex is against the bone fracture

posterolateral hip approach in three cases. After the initial reduction during surgery, cables and/or screws were often used for temporary fixation in oblique or spiral fractures. Whether cables and screws were removed after the operation depended on the judgment of the individual surgeon, because in some situations cables and screws were difficult to remove after the final fixation with the Embracing Fixator. Then, the Ni-Ti SSEF selected for surgery had a diameter 10–20% smaller than that of the treated femur and a length more than two pairs of arms on each side of the fracture line. Submerged in sterile saline at 0–4°C, the arms of the fixator were extended for use with special forceps. The fixator was placed, after fracture reduction, with its body on the tension side of the fracture. The soft tissue was isolated to an extent that allowed fracture reduction. Once the position of the Ni-Ti SSEF was ensured, it was warmed with hot saline (40–50°C) [11]. With the alteration in temperature, the memory effect of the material resulted in restoration of the arms' original shape, resulting in secure fixation of the fracture. When moving the hip and knee joint, the fracture was found to be stable. The mean operation time was 85 min (range, 60–200 min). The average blood loss and blood transfusion was 400 ml (range, 200–800 ml) and 200 ml (range, 0–600 ml), respectively.

Intravenous antibiotic therapy was given routinely to all patients in the perioperative period, and low-molecular-weight heparin was administered for thrombosis prophylaxis except for those who had a hemorrhagic tendency. The postoperative rehabilitation protocol was designed individually and based on the intraoperative stability of the final fracture fixation and the physical condition of the patient. As a general rule, patients were encouraged to start moving actively early on and were able to sit in a chair on the first postoperative day. For the first six weeks, they were instructed to limit weight-bearing by using a walker or crutches. They advanced to partial weight-bearing at six to 12 weeks after surgery. Then, depending on the outcome of postoperative radiographic evaluation, gradual full weight-bearing was permitted at a minimum of 12 weeks after surgery. However, some elderly patients in poor physical

condition could not follow this ideal rehabilitation regimen and were nearly at full weight-bearing soon after surgery.

Patients were monitored after surgery through clinical and radiographic examinations at three-month intervals until their fracture healed. Implant failure and femoral alignment were assessed radiographically. Fracture union was defined by two criteria: (1) the patient was able to bear full weight with or without assistance and (2) there was radiographic evidence of a callus bridging the fracture. Malunion was defined as angular deformity of >5°, leg-length discrepancy of >1 cm, and rotational deformity of ≥10° [15]. Final clinical results were evaluated using Harris hip scores.

Results

The results of fracture repair are shown in Table 3. Patients 2 and 6 died from causes unrelated to their arthroplasties at three years and at one month after surgery, respectively. With the exception of patient 6, who died soon after surgery, all patients were monitored clinically and radiologically. Bone union was apparent radiographically in the remaining 20 cases within an average of 5.25 months after surgery (Figs. 2, 3, 4, 5, 6, 7). By six months after surgery, 11 patients were able to walk without assistance. The remaining nine patients, who had been unable to walk without assistance before the fall that caused their fracture, were able to walk after surgery with the assistance of a cane. At the final follow-up evaluation, the average Harris hip score was 79.3 points.

No implant failures or malunions occurred in our series. One patient did have valgus femoral malalignment of 4° because of an unsatisfactory reduction, but it did not worsen during bone healing. Patient 4 experienced loosening of the prosthesis five years after treatment with an embracing fixator, so another operation was performed at our institution to revise the prosthesis without removing the embracing fixator. Other complications included cerebral hemorrhage in patient 6 one month postoperatively who died soon after, and pneumonia in patient 13 one week

Table 2 Patient demographics

Patient	Age (years)	Gender	Primary Diagnosis	Time elapsed from original surgery to fracture (years)	Preoperative Implant Type	Injury	Classification	Fracture pattern
1	60	M	Congenital hip dysplasia	5	THA	Falling down stairs	VB1	Displaced, oblique
2	75	F	Femoral-neck fracture	1 month	Hemiarthroplasty	Standing fall	VB1	Displaced, oblique
3	42	M	Post-traumatic arthritis	3	THA	Traffic accident	VB1	Displaced, oblique
4	58	M	Congenital hip dysplasia	8	THA	Standing fall	VB1	Displaced, oblique
5	82	F	Femoral-neck fracture	1 month	Hemiarthroplasty	Standing fall	VB1	Displaced, spiral
6	84	F	Femoral-neck fracture	9	Hemiarthroplasty	Standing fall	VB1	Displaced, oblique
7	77	F	Femoral-neck fracture	2	THA	Standing fall	VC	Displaced, oblique
8	78	M	Osteoarthritis	3 months	THA	Standing fall	VB1	Displaced, spiral
9	80	F	Femoral-neck necrosis	11	THA	Intraoperative fracture during revision THA	VB1	Displaced, transverse
10	60	M	Femoral-neck fracture	4	THA	Traffic accident	VC	Displaced, oblique
11	70	M	Femoral-head necrosis	5	THA	Standing fall	VB1	Displaced, oblique
12	62	F	Rheumatoid arthritis	5	THA+TKA	Falling down stairs	VB1	Displaced, oblique
13	85	M	Femoral-neck fracture	7	THA	Standing fall	VB1	Displaced, oblique
14	78	F	Femoral-neck fracture	3	THA	Standing fall	VB1	Displaced, oblique
15	65	M	Femoral-head necrosis	7	THA	Standing fall	VC	Displaced, oblique
16	76	M	Osteoarthritis	10	THA	Intraoperative fracture during revision THA	VB1	Displaced, oblique
17	65	M	Femoral-head necrosis	4	THA	Standing fall	VB1	Displaced, spiral
18	76	F	Femoral-neck fracture	3	Hemiarthroplasty	Standing fall	VB1	Displaced, oblique
19	76	M	Femoral-neck fracture	8	Hemiarthroplasty	Standing fall	VC	Displaced, spiral
20	62	M	Congenital hip dysplasia	6	THA	Standing fall	VC	Displaced, oblique
21	76	F	Congenital hip dysplasia	13	THA	Intraoperative fracture during revision THA	VB1	Displaced, oblique

THA total hip arthroplasty, TKA total knee arthroplasty, M male, F female, VB1 Vancouver type B1, VC Vancouver type C

Table 3 Results of surgery

Patient	Implant type	Duration of follow-up monitoring (months)	Preoperative mobility	Postoperative mobility at 6-month examination	Time elapsed until radiographic union (months)	Harris hip score at final examination	Nonunion, malunion	Additional information
1	EF	60	Independent	Independent	6	82	—	
2	EF	36	Single cane	Single cane	6	75	—	Died 3 years after surgery
3	EF	78	Single cane	Independent	3	95	—	
4	EF	70	Independent	Independent	6	63	—	Prosthesis loosening 5 years after surgery
5	EF	60	Single cane	Single cane	6	83	—	
6	EF	1	Single cane	—	—	—	—	Died 4 weeks after surgery
7	EF+cables	24	Single cane	Single cane	6	71	—	
8	EF	18	Single cane	Independent	3	72	—	
9	EF+revision THA	36	Crutches	Single cane	6	85	—	
10	EF	36	Independent	Independent	6	84	—	
11	EF	10	Independent	Single cane	6	77	—	
12	EF	32	Independent	Independent	3	78	—	
13	EF	27	Single cane	Single cane	6	74	—	Pneumonia one week postoperatively
14	EF+cables	18	Single cane	Single cane	3	80	—	
15	EF+screws	48	Independent	Independent	6	82	—	
16	EF+revision THA	67	Crutches	Independent	6	78	—	
17	EF+cables	56	Independent	Independent	6	84	—	
18	EF	43	Single cane	Single cane	6	80	—	
19	EF	42	Independent	Independent	6	81	—	
20	EF	35	Independent	Independent	3	86	—	
21	EF+cables+revision THA	38	Crutches	Single cane	6	76	—	

EF embracing fixator, THA total hip arthroplasty, TKA total knee arthroplasty

Fig. 2 Patient 7 had poor bone quality and suffered from a periprosthetic fracture caused by a low energy fall following primary hip replacement. Callus information was apparent on eight-month postoperative radiogram. **a** Preoperative radiograph. **b** Radiograph at six-week follow-up. **c** Radiograph at eight-month follow-up

Fig. 3 Patient 8 had a periprosthetic fracture following primary hip replacement. Callus information was observed on 6-month postoperative radiogram. **a** Preoperative radiograph. **b** Radiograph at one week follow-up. **c** Radiograph at six-month follow-up

Fig. 4 Patient 10 experienced a periprosthetic fracture following primary hip replacement. Callus information was observed on the six-month postoperative radiograph. **a** Preoperative radiograph. **b** Anteroposterior and lateral radiograph at six-month follow-up

postoperatively who was treated successfully with antibiotics. No wound infection, deep vein thrombosis, or pulmonary embolism developed in any patients.

Discussion

All of the patients in our series except one, who died one month after surgery, had satisfactory results. All remaining patients were able to walk with or without the assistance of a cane six months after surgery. As a result of the fractures, we could not obtain preinjury Harris hip scores. We assessed preinjury status by the patients' degree of mobility—dependence on walking aids or ambulation independently (Table 3). All patients recovered their preoperative mobility. The average elapsed time to bone union, as verified by radiography, was 5.25 months. Most patients returned to preinjury activities without pain at some point in the follow-up period. The average Harris hip score was 79.3 at the final

evaluation, reflecting a satisfactory result. In addition, none of the patients experienced implant failure or malunion.

The Ni-Ti SSEF was introduced in our hospital in the 1990s [4] and was successfully used to fix long-bone fractures, including periprosthetic femoral fractures. The two-thirds circumference of the fixator's cross-section, which is composed of a body and arms, increases the fixator's antibending effects, and the sawteeth on the arms improve its anti-torsion strength [4]. Control in the axial direction is relatively weaker than that of more commonly used plates. With the embracing fixator, there may be some micromovement of the bone fracture in this direction. In the axial direction, pairs of arms were designed symmetrically to be placed on each side of the fracture (Fig. 1). The sawteeth protrude axially. On the plane parallel to the arms, each sawtooth appears as a triangle. The base of the triangle faces the bone fracture, and the vertex is against the bone fracture (Fig. 1). The design of each sawtooth, which is like a fishhook, prevents distraction of the bone fracture and permits compression axially.

Animal studies have shown that the embracing fixator has strong antibending and anti-torsional effects analogous to those of commonly used plates, but its antiload stress is relatively low [4, 5]. In the three-point bending test in which the embracing fixator and common plate were pressed from the opposite side, the yield bending moments of the embracing fixator and of the common plates were 3.56 ± 1.42 and 3.27 ± 2.56 , respectively. When pressed from the plate side, the yield bending moments of the embracing fixator and of the common plate were 4.08 ± 2.51 and 5.52 ± 2.38 , respectively. In the torsion test, the torsional moments of the embracing fixator and the common plate were 1.37 ± 1.53 and 1.76 ± 1.64 , respectively. However, the antiload stress of the embrace fixator was significantly lower than that of the common plate. With these biomechanical characters, the procedure of bone healing within the embrace fixator was indirect bone healing. Loading stress enhances fracture healing and reduces stress shielding. The low stress-shielding effect of the fixator is in part due to the

Fig. 5 Patient 15 had a periprosthetic fracture following primary hip replacement. **a** Preoperative radiograph. **b** Radiograph at three-month follow-up. **c** Radiograph at two-year follow-up

Fig. 6 Patient 14 suffered from a periprosthetic fracture due to a low-energy fall following primary hip replacement. He had callus information on six-month postoperative radiograph. **a** Radiograph at six-week follow-up. **b** Radiograph at three-month follow-up. **c** Anteroposterior and lateral radiograph at six-month follow-up

low elastic modulus of Ni-Ti, 54 GPa, which is similar to that of cortical bone [4–6]. In most cases of our series, obvious callus developed during the fracture union, which was related to indirect bone healing and low stress shielding (Figs. 2, 3).

Because intramedullary prosthetic stems are used, conventional plates and intramedullary fixators are unsuitable for the treatment of periprosthetic femoral fractures. With the same antibending and anti-torsion effects as more commonly used plates [4, 5], the Ni-Ti SSEF is a true extramedullary fixator, solving the problem of lack of space for screws around the prosthesis by means of extramedullary clamps and working around the inability of poor-quality bone (as in osteoporotic fractures) to support screw fixation. In our series, most elderly patients had poor bone quality, and periprosthetic femoral fractures resulted from a fall from a standing height (Table 2) (Fig. 2).

Among all instruments that have been used for periprosthetic femoral fractures, the Mennen plate has a morphology that mostly resembles that of the Ni-Ti SSEF. However, their principles of fixation are different. The clamp-on Mennen plate was originally designed for the

stabilisation of non-weight-bearing bone fractures. It is fixed to the bone by crimping clamps. Most studies found that the plate was unable to counter the medial compressive forces on the femur, leading to a varus collapse of the fracture [1, 14]. The arms of the Ni-Ti SSEF can provide constant embracing force by virtue of shape memory. In addition, the sawteeth on the arms improve the fixator's strength. The Ni-Ti SSEF can be used for the treatment of weight-bearing bone fractures [4].

Our experience has revealed that the surgeon must keep three key points in his mind in order to achieve a greater embracing force using the Ni-Ti SSEF. First, the embracing fixator selected should be 10–20% smaller in diameter than the femur being treated [21]. Second, the free ends of the arms should be extended only to the distance at which they can be placed on the fractured bone; extension beyond this should be avoided [21]. Finally, the fracture should be centered within the fixator, and the selected embrace fixator should have a length of more than two pairs of arms on each side of the fracture line.

Our study had some limitations. The sample size was small and there was no control group. The morbidity of periprosthetic femoral fractures was low, and only 21 patients with Vancouver type B1 and type C periprosthetic fractures were required for surgical treatment in our department from 2001 to 2008. The disadvantage of the Ni-Ti SSEF is that it renders impossible the use of percutaneous insertion techniques for the protection of the extramedullary vasculature. This is a particular concern in cemented femoral stems, where no medullary blood supply exists. Because of these considerations, we avoided extensive periosteal stripping and minimised soft-tissue disturbance during the procedure.

In conclusion, the Ni-Ti SSEF is useful in the treatment of periprosthetic femoral fractures. Its utility is based on several factors: (1) by virtue of its not being fixed to the bone with screws, the implant does not impair the stability of the prosthesis; (2) the shape-memory effect of the Ni-Ti alloy and the shape of the fixator provide a constant

Fig. 7 Patient 9 underwent a hip revision surgery. Displaced transverse fracture was encountered during the surgery due to severe osteoporosis. **a** Preoperative radiograph. **b** Radiograph at ten-day follow-up. **c** Radiograph at six-month follow-up

embracing force to stabilise the fracture [4, 5]; and (3) the lower elastic modulus of the Ni-Ti alloy avoids stress-shielding, resulting in improved bone healing and reduced post-fixation osteoporosis [20]. Treating our patients with Vancouver type B1 and type C periprosthetic fractures with the Ni-Ti SSEF produced good clinical results. The Ni-Ti SSEF is a valid alternative instrument for the treatment of periprosthetic femoral fractures in patients with a well-fixed femoral prosthesis.

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