Original Article | Clinics in Orthopedic Surgery 2025;17:46-52 • https://doi.org/10.4055/cios24051

Mechanical Effects of Offset and Length of the Cementless Stem for Initial Fixation to the Femur

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Background: Implants with different neck offsets for hip replacement surgery are now available from various implant manufacturers and have become a widely used option for achieving postoperative hip stability. This study aimed to compare the impact of neck offset on initial stem fixation and the mechanical effects of different stem lengths when using cementless stems.

Methods: We performed a finite element analysis using Mechanical Finder ver. 12.0. CAD models of the Profemur Preserve and Profemur TL cementless stems. Each stem was appropriately sized, and the von Mises stress was calculated. We defined micromotion as the relative displacement between the stem node and the surface of bone contact. The maximum micromotion values of these finite element models were compared under standing conditions.

Results: The stress per zone for both stems (Preserve and TL) was the highest in zone 5, followed by zones 3 and 4, which were almost in line with each other. The high offset (HIGH) stress was higher than the standard offset (STD) stress in each stem and zone. The micromotion of each stem was higher at each load in the following order: Preserve HIGH, Preserve STD, TL HIGH, and TL STD, with HIGH being higher than STD at each stem.

Conclusions: The choice of higher offset or shorter length stems induced higher micromotion at the interface to the bone in the early postoperative period. Therefore, surgeons should be more careful to get appropriate initial fixation using shorter stems with higher offset necks due to the relatively high incidence of loosening or fractures.

Keywords: *Total hip arthroplasty, Femur, Finite element analysis*

Total hip arthroplasty (THA) provides pain relief and improves physical function and quality of life by reconstructing the hip joint in patients with hip pain due to osteoarthritis or osteonecrosis of the femoral head.[1] Implant alignment, position, and offset in THA are important for improved muscle strength, stability, and reduced wear rates, and surgeons attempt to reconstruct normal anatomy and biomechanics. Reconstruction of the femoral offset reduces the risk of dislocation, lowers the risk of bone and soft-tissue impingement, improves range of motion, provides adequate abductor muscle strength without altering gait, and minimizes polyethylene wear.[2-6] In contrast, inadequate femoral offset reconstruction can lead to a number of complications, including loss of abductor muscle tone, dislocation, gait disturbance, increased end loading of the acetabular component, and polyethylene wear, while excessive femoral offset can be associated with lateral femoral pain and gait changes.[3,7-10] Therefore, it is important to reconstruct the appropriate femoral offset.[11,12] Most models now have a high offset neck, and this option is widely used clinically because it is beneficial to surgeons. However, the mechanical effects on the bone around the stem when using the high offset stem are not clear.

Different stem designs have been developed based on various concepts of cementless stems in THA, as classified by Khanuja et al.[13] Short stems have the advantage of minimizing the amount of bone resection and bone

Received February 1, 2024; Revised May 27, 2024;
Accepted June 30, 2024
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invasion in the proximal femur during surgery, preventing penetration into the distal medullary cavity, and maintaining bone volume and quality around the implant by reducing stress shielding,[14] which has the advantage of maintaining more bone stock after removal of the stem at the time of revision. Some reports have suggested that to ensure initial fixation of short stems, anatomical geometry, proximal femoral fit, and a high percentage of the medullary cavity are necessary.[4,5] Metaphyseal diaphyseal fixation of the Profemur Preserve occupies a high percentage of the medullary cavity, with good outcomes and survival rates averaging 78 months (range, 53–87 months) postoperatively.[6] Short stems showed good long-term clinical results, while the same manufacturer also has a tapered wedge with a relatively long stem length (Profemur TL). Problems with short stems include size mismatch, intraoperative fractures, early postoperative subsidence, loosening, and other difficulties in obtaining initial fixation.[15] An experimental study has reported that short stems fail with less stress compared to taper wedges,[16] and clinical studies have also reported the possibility of intraoperative fracture.[17] Conventional type stems have a reported fracture rate of 0.6%–1.2%, while short stems have a reported early fracture rate of 1.1%, which is higher than that of conventional stems.[18] Previous studies demonstrated that stem length affects early postoperative stem mechanics. However, although different neck offsets exist in short stems, no studies to date have simultaneously evaluated the mechanical influence of different neck offsets and stem lengths. To examine real-world clinical results regarding the influence of stem length, it is necessary to compare the existing short stem with the tapered wedge type. However, few studies have directly compared tapered wedges with short stems.

The purpose of this study was to compare the mechanics of the effect of the high offset with the standard offset in early postoperative stem fixation and to assess the effect of stem length using finite element analysis (FEA). Compared with the standard offset, the high offset may affect the initial fixation because of the increased bending moment against the femur. We also hypothesized that the short stem would have a different stress distribution in initial fixation than the standard-length stem because the short stem would have a smaller contact area with the cortical bone than the standard-length stem.

METHODS

This study was conducted at Oita University (Yufu City). in accordance with the principles of the Declaration of Helsinki and approved by the Oita University Ethics Committee (IRB No. 1605). Written informed consent was obtained from the clinical cases and femur patients whose data were used to create the model.

Analysis Model

Finite element modeling and analysis were performed using Mechanical Finder version 12.0 (Japan Computational Mechanics Research Center). The data were taken from a woman who had undergone THA for femoral head osteonecrosis. She had standard femoral marrow cavity geometry, which is Dorr's type B (Fig. 1A), and weighed 46 kg. Three-dimensional shape data of the left femur, that is, the normal side, were obtained from usual computed tomography (CT) images, and Bergman's coordinate[19] was used for the femur. The original position of the stem coordinates is the crossing point of the stem and neck axes; the y-axis is a vertical line from the back to the front passing the original position, the z-axis is the stem axis, and the x-axis

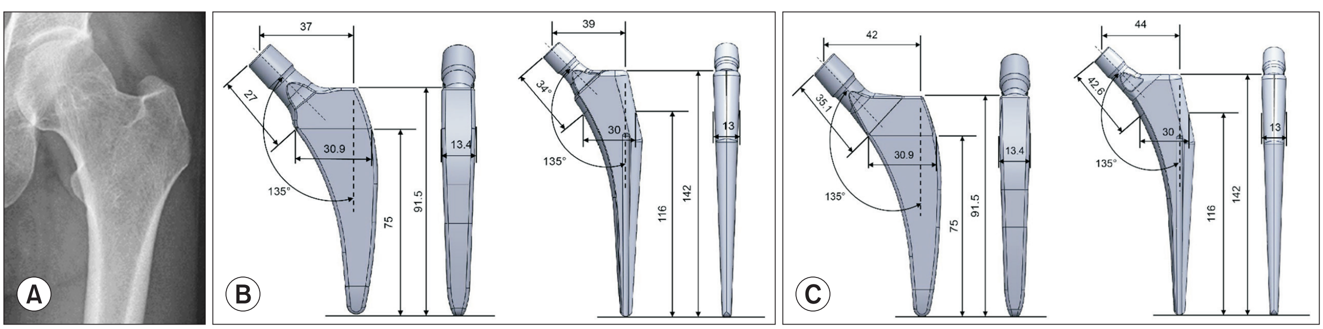

Fig. 1. (A) X-ray image of a patient's left femur. Canal flare index is 4.64 (46.9/10.1), which is Dorr's type B. (B) Dimensions of a short stem and a tapered wedge stem (standard offset; STD): Profemur Preserve (Preserve stem; MicroPort Orthopedics) on the left and Profemur TL Cementless Stem (TL stem; MicroPort Orthopedics) on the right. Dimensions other than the neck-shaft angle (°) indicate length (mm). (C) Dimensions of a short stem and a tapered wedge stem (HIGH): Preserve stem on the left and TL stem on the right. Dimensions other than the neck-shaft angle (°) indicate length (mm). The offset for the HIGH model was set by adding 5 mm from the offset value for each STD model.

is a line passing the original position and rectangular to its y and z. In the 3-dimensional finite element model, the stem was inserted into the femur, with the femoral neck dissected into the femoral diaphysis. We determined the suitable size of each stem using a Computer Aided Design (CAD) model of Profemur Preserve (MicroPort Orthopedics), which is a short stem, and Profemur TL Cementless Stem (MicroPort Orthopedics), which is a tapered wedge stem. The appropriate stem size was determined when the stem contour was tangential to the medial cortical bone. The short and tapered wedge stem sizes are shown in Fig. 1B. Each was defined as "Preserve STD (standard offset)" and "TL STD." Based on each "STD" model, offset models defined as "Preserve HIGH (high offset)" and "TL HIGH" were created using Solidworks (Dassault Systemes SolidWorks Corporation). Offsets were set by adding 5 mm from the offset value of each STD model. The size of each stem is shown in Fig. 1C. The femur consists of a 4-node tetrahedral element, with element sizes ranging from 2 to 4 mm and stem models ranging from 1 to 4 mm. Table 1 lists the number of elements and nodes in each model. The stems of these models were placed at a height that did not cause differences in the leg length. Stem alignment was achieved by matching the stem axis to the femoral axis in the neutral position and the stem axis to the femoral neck axis (Table 2). The Young's modulus of the femur was determined using the equation proposed by Keyak et al.[20] according to the bone density obtained from CT, and the Poisson's ratio of the femur was assumed to be 0.4. The Young's modulus and Poisson's ratio of the stem were assumed to be 108.9 GPa and 0.28, respectively, based on the material properties of Ti-6Al-4V. The coefficient of friction between the stem and femur was set to 0.64.[21] FEA was performed with the femur in an upright position as the loading and constraint conditions. The stresses acting on the femur and stem are shown in Fig. 2A. A vertical load of 451.3 N (X: 0, Y: 0, Z: –451.3) was applied against the end face of the stem neck.[22] The distal femur was assumed to be completely restrained. The load was assumed to increase linearly, reaching a maximum value of 1.0 second. A static implicit method was used for calculations. After analysis, a volume of interest (VOI) was defined at the medial and lateral contact points of the stem on the femoral model based on the Gruen Zone (Fig. 2B).[23] The von Mises stress at each VOI was calculated. The relative displacement between the stem nodes and the bone contact surface is defined as micromotion (MM).[24] The maximum MM values of these finite element models were compared under standing conditions. In terms of load values, considering that large loads can occur at the joints due to stepping off, analyses were conducted under the same conditions for 1,000, 1,500, and 2,000 N, assuming 2 to 4 times the body weight.

Table 1. Nodes and Elements of the Finite Element Models in the PROFEMUR Preserve and PROFEMUR TL Stems

		Stem		Whole	
		Nodes	Elements	Nodes	Elements
Preserve	STD	11,967	56,166	48,670	232,554
	HIGH	11,384	52,394	48,148	229,261
TL	STD	21,184	100,597	67,129	322,298
	HIGH	21,271	100,505	67,501	323,522

Preserve: Profemur Preserve (MicroPort Orthopedics), TL: Profemur TL Cementless Stem (MicroPort Orthopedics), STD: standard offset, HIGH: high offset.

Table 2. Width of Each Zone and Distance from the Stem Top Edge of the Finite Element Models

	Preserve		TL	
	Zone width (mm)	Distance from the stem top edge (mm)	Zone width (mm)	Distance from the stem top edge (mm)
Zones 1, 7	30.5	30.5	47.3	47.3
Zones 2, 6	30.5	61.0	47.3	94.6
Zones 3, 5	30.5	91.5	47.3	141.9
Zone 4	30.5	122.0	47.3	189.2

Preserve: Profemur Preserve (MicroPort Orthopedics), TL: Profemur TL Cementless Stem (MicroPort Orthopedics).

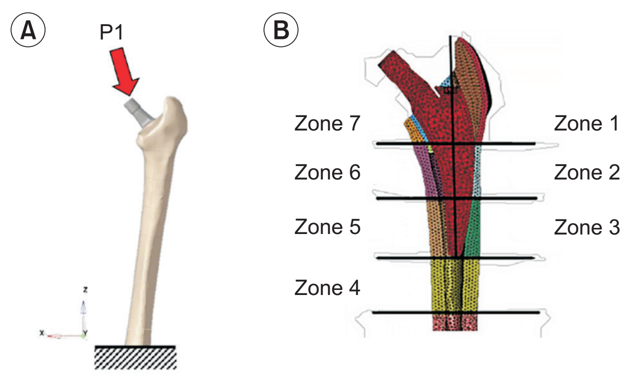

Fig. 2. (A) Loading conditions for the postoperative femoral finite element model. The loading conditions were assumed to be those of the standing position. The distal femur was fully restrained. (B) Seven volumes of interest, based on the Gruen zone. We divided the bone around the stem into a series of 7 three-dimensional sections based on Gruen's zone classification.

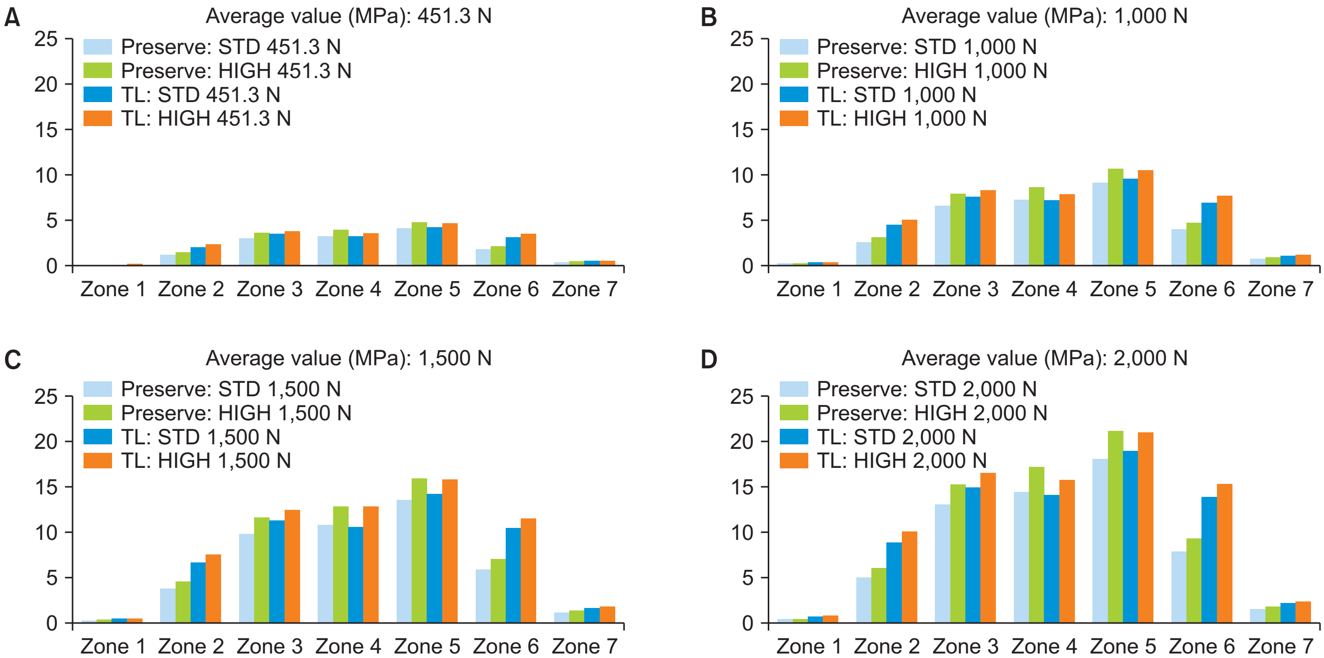

Fig. 3. Von Mises stress at each load (average value). For the load values, 2 to 4 times the body weight were assumed. (A) The actual body weight. (B-D) The results of increasing the load (Von Mises stress at each load [average value]). In both Preserve and TL, stresses were highest in zone 5, followed by zones 3 and 4, which were almost in line with each other. Stresses increased proportionally with increasing load, and the trend did not change; in zones 2 and 6, stresses in TL were significantly higher than in Preserve. In each stem and zone, HIGH stresses were higher than STD. Preserve: Profemur Preserve (MicroPort Orthopedics), STD: standard offset, HIGH: high offset, TL: Profemur TL Cementless Stem (MicroPort Orthopedics).

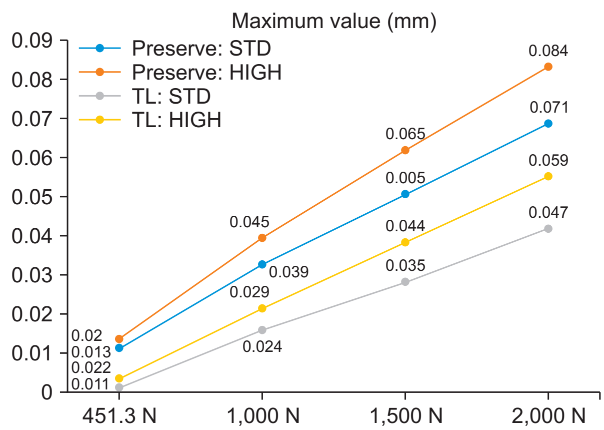

Fig. 4. Micromotion (MM) at each load (maximum value). MM for each stem increased proportionally with increasing load. At each load, the MM was the highest for Preserve HIGH, followed by Preserve STD, TL HIGH, and TL STD and HIGH was higher than STD in each stem. The difference between HIGH and STD increased with increasing load. Preserve: Profemur Preserve (MicroPort Orthopedics), STD: standard offset, HIGH: high offset, TL: Profemur TL Cementless Stem (MicroPort Orthopedics).

RESULTS

The stresses (von Mises stress averages) per zone for each stem are shown in Fig. 3. TL stresses were highest in zone 5, followed by zones 3 and 4, which were almost equally high. In zones 2 and 6, the stress in the TL was significantly higher than that in Preserve. The stress at HIGH was higher than that at STD in each stem and zone. The maximum MM for each load on each stem is shown in Fig. 4. The MM for each stem increased proportionally with load. At each load, the MM was the highest for Preserve HIGH, followed by Preserve STD, TL HIGH, and TL STD, and HIGH was higher than STD in each stem. The difference between HIGH and STD increased with increasing load. The distribution of MM at a load of 2,000 N for each stem is shown in Fig. 5: for Preserve, the maximum value of MM occurred at the distal posterior portion of the stem, whereas for TL, the maximum value of MM occurred at the proximal anterior portion of the stem.

DISCUSSION

Offset is a key element of stable hip reconstruction in THA. This offset option for cemented and cementless stems is present in most models and is clinically wide-

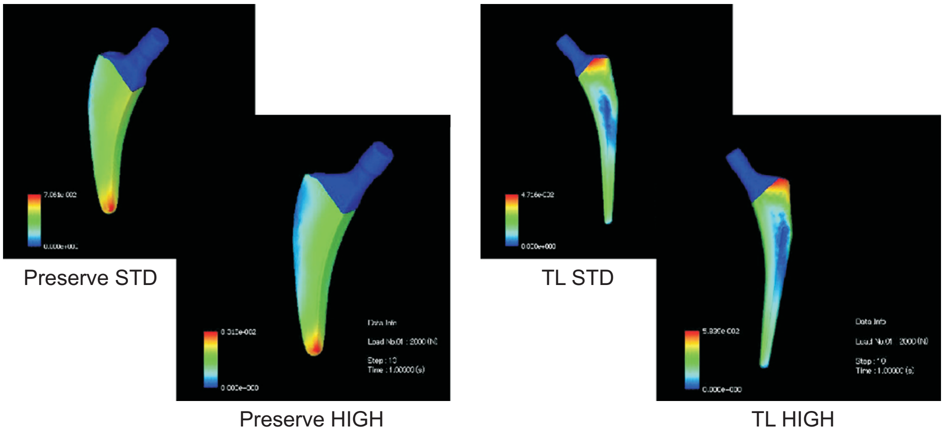

Fig. 5. Micromotion (MM) distribution diagram at 2,000 N load. In Preserve, the maximum MM value occurred at the posterior distal portion of the stem, while in TL, the maximum MM value occurred at the anterior proximal portion of the stem. Preserve: Profemur Preserve (MicroPort Orthopedics), STD: standard offset, HIGH: high offset, TL: Profemur TL Cementless Stem (MicroPort Orthopedics).

spread. However, very few studies have evaluated the bone around the stem mechanics of offset neck selection, and none have compared the differences in stress and MM using finite element analysis. In the present study, stress and MM were higher for HIGH than for STD in each stem, and MM was higher for Preserve than for TL.

The stress distribution was similar for both Preserve and TL, with higher stress at the distal end of the stem and higher stress values for TL than for Preserve at the proximal stem. This finding is similar to our previously reported results.[22] Other studies have demonstrated that the greater the stem length, the higher the stress.[25] The percentage of stress was smaller in TL than in Preserve, indicating that Preserve can reduce stress loading on the surrounding bone. The stress of the stem at each load was higher at HIGH for each stem and zone, and the increase in Preserve was greater when Preserve and TL were compared. This may be because the stress increases due to an increase in the bending moment caused by a higher lever arm due to an increase in the femoral offset when comparing STD and HIGH at load. In addition, when comparing TL and Preserve, because the stem length was shorter in Preserve, the ratio of femoral offset to stem length was larger, which was considered to be more affected by increased stress.

The MM for each stem increased proportionally with load. At each load, Preserve was higher than TL when compared to stem length, and HIGH was higher than STD for each stem. Contrary to our hypothesis, however, the effect of increasing the offset was 1.18 times greater for Preserve versus 1.26 times greater for TL. This suggests that the proximal part of the TL was more affected by the offset because of the different sites at which MM occurred in each stem. Both Preserve and TL are proximal femoral fixation stems; however, Preserve is more proximal because of its stem shape. The cross-section of the stem shows that Preserve is more angular in shape than TL and is fixed by interlocking with the cortical bone. On the other hand, the TL has an oval shape, which has an advantage in stem insertion but may leave a small amount of mobility when compared with the fixation force. Therefore, Preserve is primarily used in proximal fixation. This is supported by the results of the MM distribution map, which showed that the fixation site of Preserve was more proximal than that of MM. The medullary cavity shape of the model used in the present study was type B according to the Dorr classification,[26] and the relatively thick cortical bone of the proximal femoral canal may have influenced this fixation site. FEA has shown that short stems increased MM.[22,27,28] However, these results could be affected by stem type and medullary cavity shape. MM was greater when HIGH was used, and the short stems had greater amounts of MM. Animal studies suggest that excessive MM (> 150 μm) leads to the failure of cementless implants to acquire biological fixation through osteogenesis.[29] In 2000 N, the MM at Preserve HIGH was 84 μm, which is considered to have little adverse effect on osseointegration, but MM has been reported to increase with stem insertion position[28] and bone shape.[30] Therefore, it is probable that the use of short stems and the choice of offset neck may require relatively more attention to early postoperative loosening and fracture and may require particular attention depending on the bone shape.

This study has several limitations. First, the FEA results were not directly compared or verified with the mechanical experimental results. The obtained results should only be used as reference values. Second, the 2 stems had different shapes and surface finishes. Therefore, the results of this study may not directly reflect the actual changes caused by shorter stems. In addition, the Profemur Preserve stem's proximal edge is located 1 mm outside of the Profemur TL, although the implant is placed so that the leg length remains the same. In the present study, only 1 patient's femur was used, and individual differences between patients in terms of weight, bone strength, and femoral bone shape could not be evaluated. Furthermore, only standing conditions were considered in this study. Two more demanding loading conditions, walking and stair climbing, were not considered in this study. Using finite element method analysis, Kwak et al.[28] demonstrated that MM increased during stair ascent and descent. Despite these limitations, FEA under the same conditions, except for stem length and offset, would have shown effects on the initial fixation of the stem and femur.

When the stem length was the same, changing from a standard offset to a high offset stem resulted in an increase in stress and MM. In addition, in the 2 different lengths of stems presented in this study, increased MM occurred in the short stems. Clinically, stem selection should consider the bone quality and medullary cavity shape. The choice of higher offset or shorter lengths of stems induced higher MM at the interface to the bone in the early postoperative period. Surgeons should be more careful to get appropriate initial fixation using shorter stems with higher offset necks due to the relatively high incidence of loosening or fractures.

CONFLICT OF INTEREST

No potential conflict of interest relevant to this article was reported.

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