

# Effect of stem position and length on bone-stem constructs after cementless hip arthroplasty

A FINITE ELEMENT ANALYSIS



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## Aims

There are concerns regarding initial stability and early periprosthetic fractures in cementless hip arthroplasty using short stems. This study aimed to investigate stress on the cortical bone around the stem and micromotions between the stem and cortical bone according to femoral stem length and positioning.

## Methods

In total, 12 femoral finite element models (FEMs) were constructed and tested in walking and stair-climbing. Femoral stems of three different lengths and two different positions were simulated, assuming press-fit fixation within each FEM. Stress on the cortical bone and micromotions between the stem and bone were measured in each condition.

## Results

Stress concentration was observed on the medial and lateral interfaces between the cortical bone and stem. With neutral stem insertion, mean stress over a region of interest was greater at the medial than lateral interface regardless of stem length, which increased as the stem shortened. Mean stress increased in the varus-inserted stems compared to the stems inserted neutrally, especially at the lateral interface in contact with the stem tip. The maximum stress was observed at the lateral interface in a varus-inserted short stem. All mean stresses were greater in stair-climbing condition than walking. Each micromotion was also greater in shorter stems and varus-inserted stems, and in stair-climbing condition.

## Conclusion

The stem should be inserted neutrally and stair-climbing movement should be avoided in the early postoperative period, in order to preserve early stability and reduce the possibility of thigh pain, especially when using a shorter stem.

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**Keywords:** Hip arthroplasty, Stem length, Stem position, Finite element analysis

## Article focus

■ To investigate the stress distribution on the cortical bone and the micromotion between the stem and bone depending on the length and position of the stem.

## Key messages

■ The stem should be inserted in neutral position, especially when the shorter stem is used, to lower stresses in medial and lateral interfaces, and to reduce the

possibility of a periprosthetic femoral fracture or thigh pain.

■ Stair-climbing movement should be avoided during early postoperative period, especially when using a short stem, to reduce micromotions of the stem within the femur and preserve early stability.

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## Strengths and limitations

- This is the first ever comparison of stem length and position and loading conditions.
- This can be applied only in the early postoperative period within three months.

## Introduction

Shorter cementless femoral stems rather than conventional stems have been widely used in recent hip arthroplasties, demonstrating favourable results.<sup>1,2</sup> Theoretically, a short stem preserves more bone stock and reduces proximal load transfer and stress-shielding, thereby simplifying later revision surgeries.<sup>2</sup> With these benefits, some studies have reported successful outcomes with survival rates of 99% to 100% after a follow-up period of ten to 16 years.<sup>3,4</sup>

A higher incidence rate of periprosthetic femoral fractures was observed for a short stem than for the conventional stem.<sup>5</sup> Kim et al<sup>6</sup> recently reported that periprosthetic femoral fracture was the principal reason for early revision within one year after hip arthroplasty using short stems, regardless of surgical approach. Excessive loading results in difficulty in obtaining early stability in hip arthroplasty, due to the possibility of migration and fracture.<sup>7</sup> Klasan et al<sup>8</sup> also reported that short stems had significantly lower load at failure than double-wedged stems in both cadaveric and composite models. In contrast, a biomechanical *ex vivo* study reported that use of a short stem is not a high risk factor for periprosthetic femoral fractures.<sup>9</sup> There is still a paucity of evidence on the risks associated with the use of a short stem.

Some authors have reported that varus alignment of a short stem is an important factor in restoring the normal biomechanics of the hip by increasing the hip joint offset, resulting in an increase in the length of the lever-arm. It was also reported that three-point fixation was better in varus alignment than valgus, while stem subsidence occurred more frequently.<sup>10</sup> Another study reported that varus alignment increases the strain on the medial calcar femorale located on the endosteal surface of the proximal femur and the region around the distal tip of the femoral stem.<sup>11</sup> Further, varus alignment of the stem showed significant associations with thigh pain, which is a frequently cited reason for discomfort and revision surgery after hip arthroplasty.<sup>12</sup> Thigh pain is presumably caused by overload or micromotion of the stem tip.<sup>13</sup> Similarly, some patients complained about thigh pain after hip arthroplasty using a short stem in our clinical setting. We believe that a short stem is likely to cause the above issues, especially when it is implanted into the varus, although it does have several advantages.

To date, very little has been reported about the effects of position and length of the stem on bone-stem constructs in terms of the stem stability and thigh pain after cementless hip arthroplasty. Therefore, this finite element analysis (FEA) study aimed to investigate the stress distribution and changes on the cortical bone

around the stem, and the micromotion between the stem and cortical bone depending on the length and position of the stem, comparing the short stem with the mid-short and conventional stems.

## Methods

**Finite element model.** A 3D femoral finite element model (FEM) verified in previous studies was used in this study.<sup>14-16</sup> A CT scan of an intact left femur was performed at a transverse resolution of 1.0 mm in 1.0 mm increments. After extracting the outline of each CT slice image through reconstruction using the Mimics (version 21.0, Materialise, Belgium) programme, it was stacked in three dimensions to obtain the line and surface of the entire femoral shape. Lines and surfaces constructed in three dimensions were corrected for distorted areas and then subjected to a segmentation process to obtain a final 3D femoral shape. The volume of the cortical and cancellous bone was created using this shape, and a femoral FEM was implemented through meshing process. To verify the FEM, strain was measured by attaching a strain gauge at a total of 20 points on the anterior, posterior, medial, and lateral sides of the model, and compared with the previous study according to the method conducted by Heiner et al.<sup>15</sup> To reproduce femur models, the femoral neck was cut at the length of 10 mm above the upper margin of the lesser trochanter using ABAQUS (version 6.14, Dassault Systems, France).<sup>17-19</sup>

Three types of cementless tapered wedge stems were used in this study: Type 1 (conventional stem), EcoFit (Implantcast, Germany); Type 2 (mid-short stem), Accolade II (Stryker, USA); and Type 3 (short stem), SMF (Smith & Nephew, USA). These stems form a wedge shape with the angle  $\alpha$  to the sagittal plane and angle  $\beta$  to the frontal plane. They create primary stability for the metaphyseal-diaphyseal junction at the four corners of the proximal femur. The wedge-shaped metaphyseal part contributes to the stability and strength of fixation of the stem to the bone, and it helps to resist stem subsidence. The femoral stems used in this study were made of titanium alloy (Ti-6Al-4V).

Three types of stems were designed using computer-aided design software (SolidWorks 2009 SP2.1, USA). To simulate hip arthroplasty, ABAQUS was used to construct the geometry of all stems in the intramedullary canal of each osteotomized femur. The stem was simulated to be inserted into two alignments: neutral and varus (Figure 1). The neutrally aligned stem was inserted parallel to the long axis of the femur so that it was press-fit at the medial calcar and lateral flare. The varus aligned stem was inserted to create an angle of 5° with the femur, so it was press-fit at the medial calcar and stem tip. Virtual femoral surgery was performed to create a perfect contact fit between the stem and the endosteal cortex of the femur from the surface mesh of the cementless stems that were inserted into each FEM in the varus or neutral positions.<sup>10,18</sup>

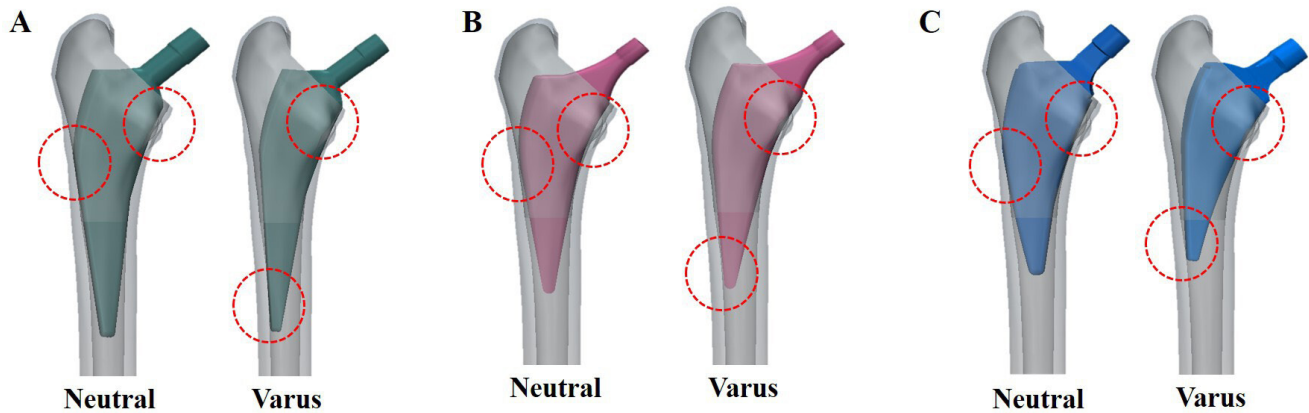


Fig. 1

The neutral and varus alignment of stems press-fit within the femoral canal; a) conventional stem, b) mid-short stem, and c) short stem. Dotted circles indicate medial and lateral interfaces in each stem.

**Table I.** Material properties applied for the finite element model analysis.

Property	Elastic Modulus (E), MPa	Poisson's ratio (ν)
Cortical bone	17,000	0.3
Cancellous bone	920	0.2
Implant (Ti6Al4V)	113,800	0.342

Ti6Al4V, titanium alloy.

Eight noded hexahedral and four noded tetrahedral elements were created using ABAQUS. These elements were used to build the mesh for the osteotomized femur model and the femoral stem. They defined various different material properties and maintained contact with the stem and bone model.

**Material properties.** FEM analysis assumed that the bone structure has homogeneous and isotropic linear properties. To create a femoral model with a cancellous bone property, the elastic modulus (E) was calculated based on a mean CT Hounsfield unit (HU) value of 120.8 (standard deviation 41.8).<sup>20</sup> The relationship between HU and elastic modulus was analyzed:<sup>21,22</sup>

$$\rho = 131,000 + 1,067 \text{ HU}$$

$$E = 6,850 \rho^{1.49}$$

where  $\rho$  is the apparent density ( $\text{g}/\text{cm}^3$ ); the unit of E is MPa. The material properties of the femoral cortical bone and stem were studied from earlier publications (Table I).<sup>17</sup> For the purpose of the analysis, a titanium alloy (Ti6Al4V) was used for the femoral stems (Young's modulus 114 GPa, Poisson ratio 0.3), and a cobalt-chromium-molybdenum alloy (Young's modulus 240 GPa, Poisson ratio 0.3) was used for the implant head. Different material properties were assigned to different femoral regions.

**Boundary and loading conditions.** Two static physiological loading situations were simulated to reproduce the activities of walking and stair-climbing. The forces of hip joint reactions and abductor muscles were applied as a percentage of the body weight to simulate the peak load

during these activities, as these forces have a greater effect on the stability of the femoral stem during walking or stair-climbing than during all other daily activities. The loading situation are shown in Figure 2, while both loading conditions are shown in Table II.<sup>23</sup>

The forces of the hip joint reactions and abductor muscles were acting at a position  $20^\circ$  from the vertical line in the frontal plane (Figure 2). Frictional contact of  $\mu: 0.63$  was set as an interface between the plasma spray surface of the femoral stem and the cancellous bone. The interface between the polished surface of the stem and the cancellous bone was frictionless.<sup>24</sup> A 'tie' contact condition was applied between the bone and stem.

**FEM analysis.** We conducted FEA by using ABAQUS to investigate the biomechanical study depending upon the length and position of the femoral stem while considering the two loading conditions. Six FEMs were analyzed using combinations of three different lengths and two different positions of the femoral stem in each loading condition: normal walking and stair-climbing. The stresses around the stems and cortical bones were investigated. In order to investigate the possibility of thigh pain or periprosthetic fracture around the femoral stem, the peak von Mises stress (PVMS) and mean stress over a region of interest (ROI) were measured at cortical bone around the stem for each FEM and compared to the yield strength of the cortical bone. We set the regions, which the PVMSs at medial and lateral cortices around the stem were observed in, as a ROI in each FEM. The yield strength value (107.9 MPa) of the cortical bone was referenced from previous literature.<sup>25,26</sup> We defined the medial calcar as a medial interface independent of the position of the stem. Meanwhile, the lateral interface was a lateral flare in a neutral position and the lateral cortex in contact with the stem tip in the varus position, respectively (Figure 1).

Additionally, micromotion was measured to predict early stability of the stem. Ostbyhaug et al<sup>26</sup> reported that measurement of micromotion on a single point is not sufficient to describe the stability of a femoral stem.

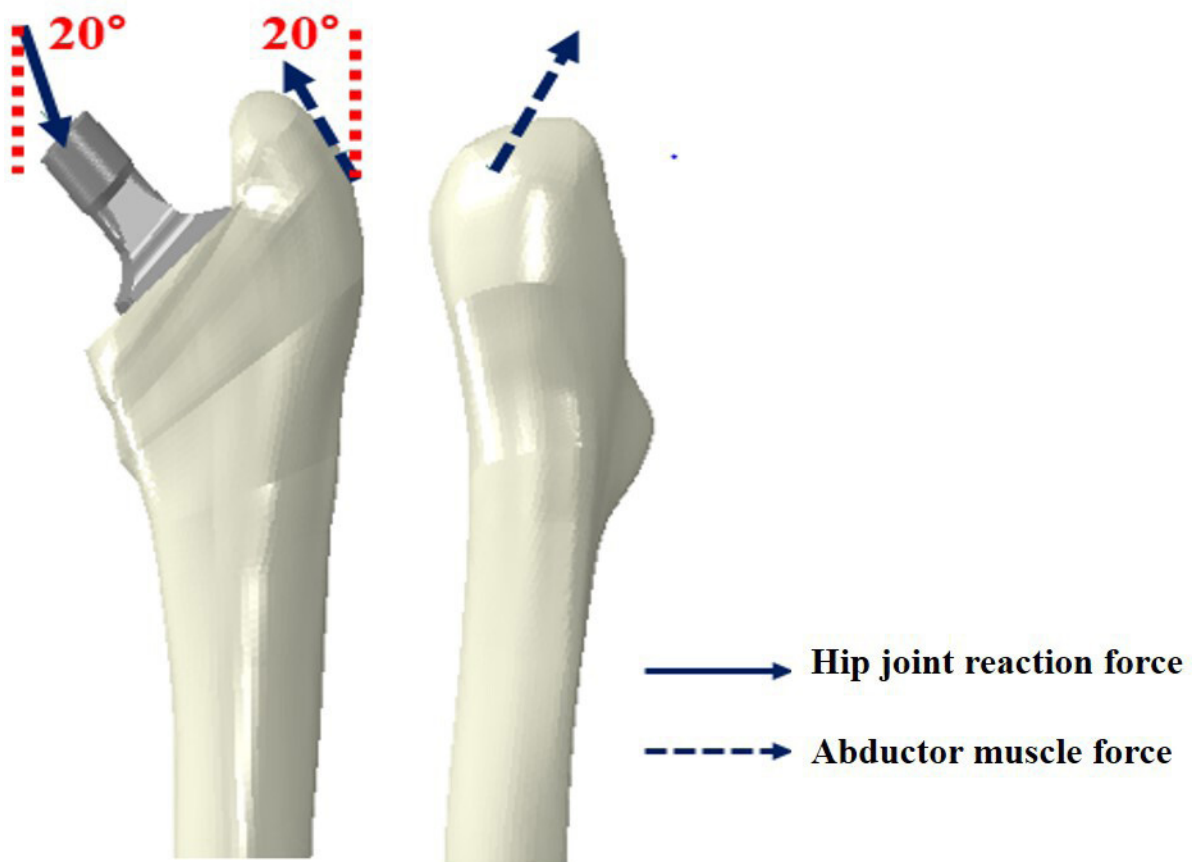


Fig. 2

Loading condition of the analysis model; hip joint force and abductor muscle force are applied as a percentage of the body weight to simulate the peak load during walking and stair-climbing, respectively.

**Table II.** Magnitude of applied forces for normal walking and stair-climbing loading conditions.

Condition	$F_x$ , N	$F_y$ , N	$F_z$ , N
<b>Normal walking</b>			
Hip contact reaction force	-432	-1,833.6	-262.4
Abductor muscles	464	692	34.4
<b>Stair-climbing</b>			
Hip contact reaction force	-474.4	-1,890.4	-444.8
Abductor muscles	560.8	679.2	230.4

Therefore, it was measured at four different sites (anterior/posterior/medial/lateral) between the bone and stem. Micromotion ( $\mu\text{m}$ ) is defined as the distance between the bone and stem before and after the application of the axial loading on each FEM.

## Results

**Stress distribution at the cortical bone.** The PVMs in each FEM were observed at the medial and lateral interfaces between the cortical bone and stem. Therefore, we set the medial and lateral interfaces, which are the contact area between the stem and cortical bone, as medial and lateral ROIs in each FEM.

In the walking condition, when the stem was inserted neutrally, mean stress over a ROI was greater at the medial than the lateral interface, regardless of the stem length; this increased as the stem was shorter. Meanwhile, when the stem was inserted in varus, mean stress was greater at the lateral than the medial interface, regardless of the stem length, and it tended to increase at the lateral interface and decrease at the medial interface as the stem was shorter (Figure 3). Mean stress at the medial and lateral interfaces increased in the varus-inserted stems compared to the stems inserted neutrally, which was in maximum at the lateral cortex in contact with the tip of a varus-inserted short stem (type 3). The difference in mean stress between the medial and lateral interfaces was the greatest in this FEM.

In stair-climbing condition, stress concentration at the cortical bone showed a similar pattern to that observed in normal walking. Mean stress over a ROI increased in stair-climbing compared to in walking condition, regardless of the stem length and position. Mean stress in neutrally inserted stem increased slightly compared to in walking condition. However, it tended to increase markedly up to four to five times at the lateral interface in the varus-inserted mid-short and short stems, compared to

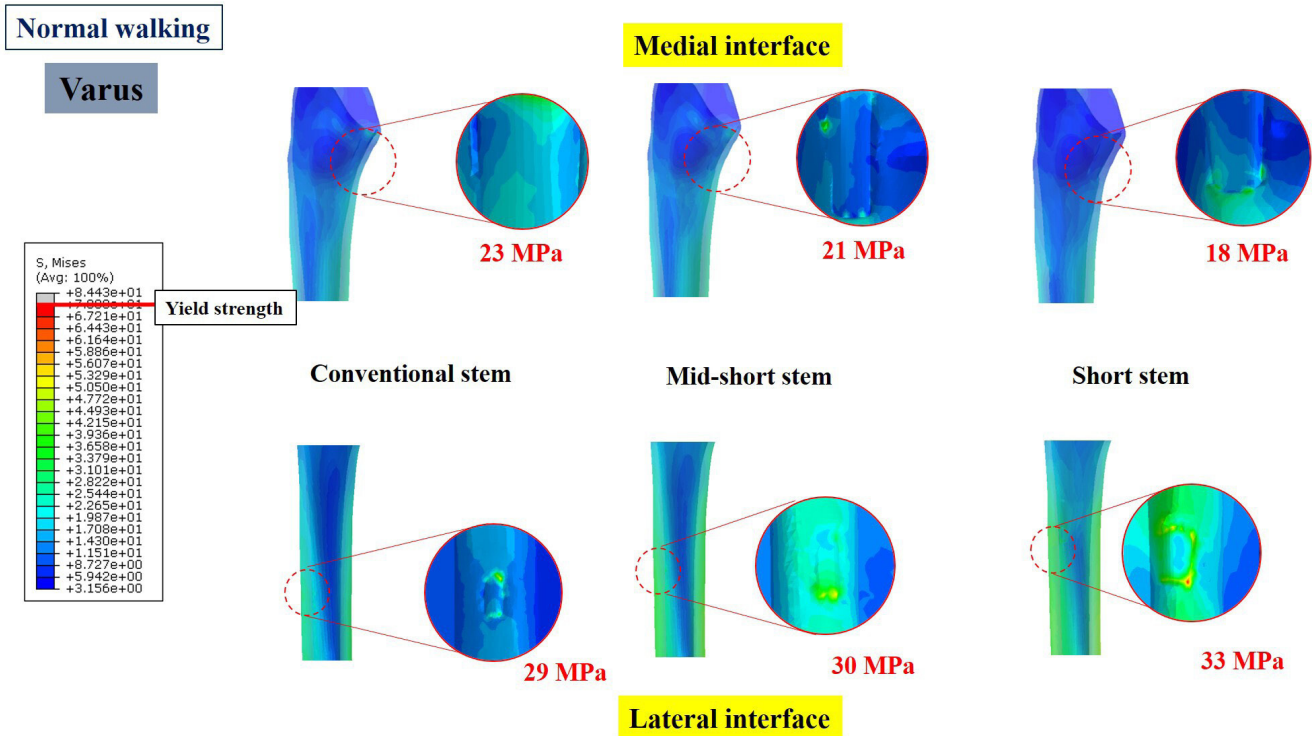


Fig. 3

Stress distribution at the medial and lateral interfaces of the cortical bone around the varus-inserted stem in normal walking condition. The circle images represent the stress concentration at medial calcar and lateral cortex region in contact with the stem tip. The number indicates the mean stress over a region of interest.

a neutrally inserted conventional stem in walking condition (Figure 4). The figures of mean stress over a ROI at medial and lateral interfaces in all FEMs, and its increasing rate compared to a neutrally inserted conventional stem in walking condition, are shown in Table III.

The results of PVMS in FEMs showed a similar pattern to those of mean stress over a ROI, which increased at the lateral interface as the stem was shorter and inserted in varus and in stair-climbing condition. PVMS showed the tendency to increase markedly at the lateral interface in the varus-inserted mid-short and short stems in stair-climbing condition compared to a neutrally inserted conventional stem in walking condition. Meanwhile, in the varus-inserted conventional stem, PVMS tended to increase similarly at the medial and lateral interfaces in both walking and stair-climbing conditions. The figures of PVMS and the increasing rate of PVMS in all FEMs, compared to a neutrally inserted conventional stem in walking condition, are shown in Table IV.

**Micromotion between the stem and bone.** The micromotion between stem and bone was lowest in the neutrally inserted conventional stem during walking. Reviewing this value, as in Figure 5, micromotion increased as the stem was shortened, inserted in varus, and in the stair-climbing condition. Consequently, the rate of increase in micromotion was greatest in the varus-inserted short stem in the stair-climbing condition, among all FEMs (Figure 5).

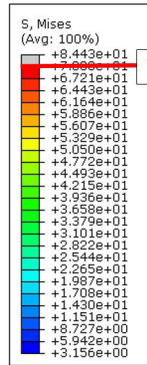
## Discussion

The present study on FEMs revealed that stress concentration at cortical bone around the stem and the micromotion between the stem and bone increased when the stem was shorter and inserted in varus and in the stair-climbing condition. Stress was concentrated more on the lateral cortex in contact with the tip of varus-inserted stem inserted, especially when using a short stem.

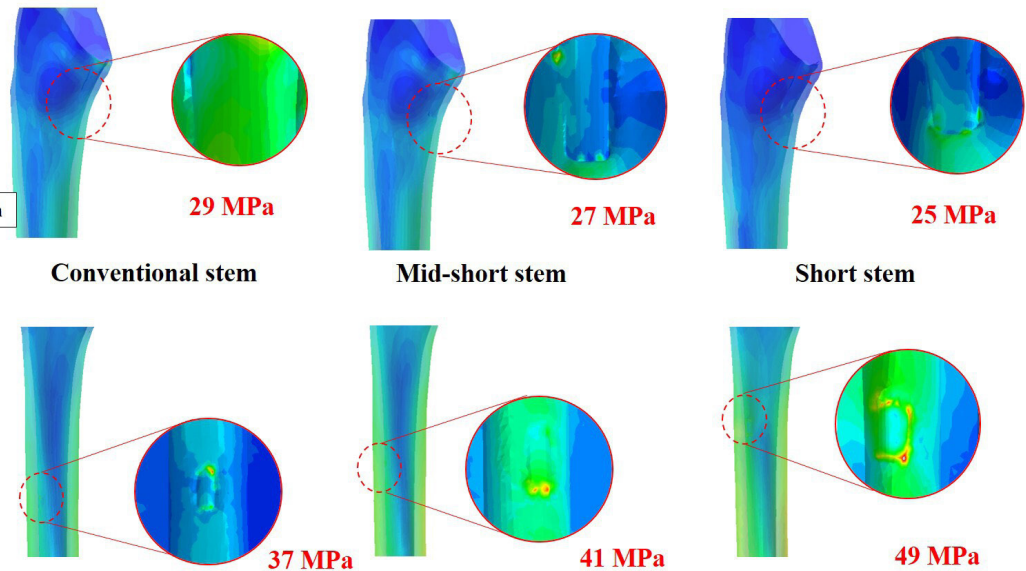
Considering the survival rate (99% to 100% for ten years) as reported by McLaughlin et al<sup>3</sup> and Sariali et al,<sup>4</sup> a short stem was suggested as an alternative to a conventional one. However, some authors associated a cementless short stem with a higher risk of periprosthetic fracture.<sup>5,6</sup> In contrast, one cadaveric study reported that a short stem was associated with a lower risk of periprosthetic fracture, as the distribution of the stress in the femur after cementless hip arthroplasty was more anatomical than that in a conventional stem.<sup>27</sup> In terms of stem alignment, some authors revealed that the incidence of early subsidence did not increase with the use of the varus-inserted short stem.<sup>10</sup> Meanwhile, another study reported that varus alignment of the stem is associated with increased strain on the surface of the medial calcar and the lateral cortex around the distal tip of the stem.<sup>28</sup> However, it remains unclear how the length and alignment of the femoral stem elicit a different effect on the stress concentrated on the cortical bone. Therefore,

Stair Climbing

Varus



Yield strength



Lateral interface

Fig. 4

Stress distribution at the medial and lateral interfaces of the cortical bone around the varus-inserted stem in stair-climbing condition. The circle images represent the stress concentration at medial calcar and lateral cortex region in contact with the stem tip. The number indicates the mean stress over a region of interest.

**Table III.** Results of mean stress over a region of interest in finite element models. The increasing rates of mean stress over a region of interest, compared to a neutrally inserted conventional stem (type 1) in walking condition, are shown in parentheses.

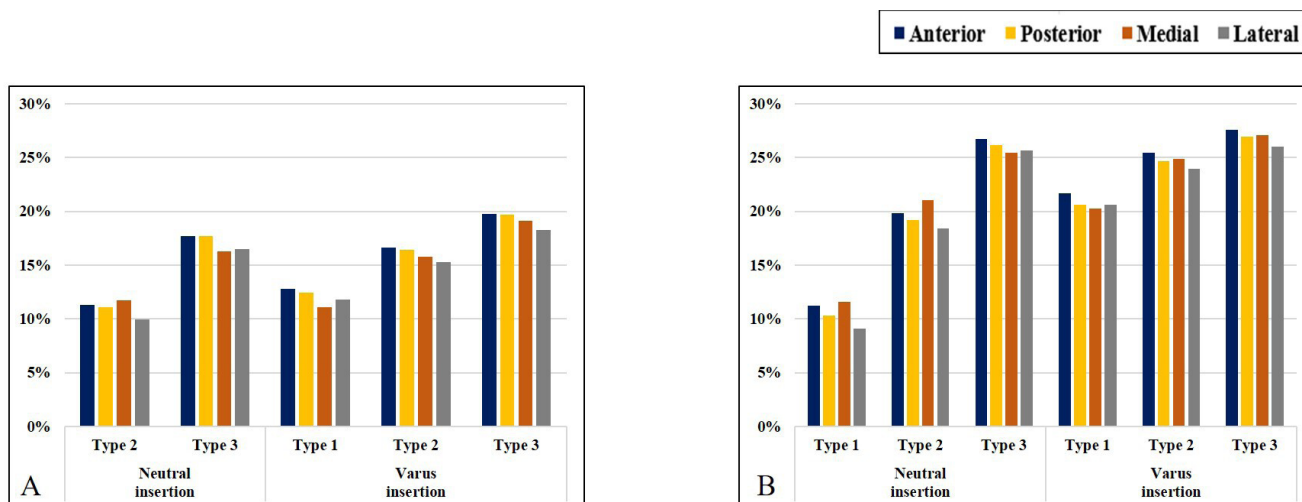
Variable	Medial interface, MPa	Lateral interface, MPa
<b>Normal walking</b>		
<b>Neutral insertion</b>		
Type 1	14	10
Type 2	16 (14%)	10 (3%)
Type 3	17 (21%)	11 (10%)
<b>Varus insertion</b>		
Type 1	23 (64%)	29 (190%)
Type 2	21 (50%)	30 (200%)
Type 3	18 (28%)	33 (230%)
<b>Stair climbing</b>		
<b>Neutral insertion</b>		
Type 1	15 (7%)	17 (70%)
Type 2	19 (36%)	17 (70%)
Type 3	22 (57%)	19 (90%)
<b>Varus insertion</b>		
Type 1	29 (107%)	37 (270%)
Type 2	27 (93%)	41 (310%)
Type 3	25 (79%)	49 (390%)

this FEA study was conducted to evaluate the distribution of stress on the cortical bone around the stem and the micromotion between cortical bones and the stem depending upon the length and position of the stem.

**Table IV.** Results of peak von Mises stress in finite element models. The increasing rates of peak von Mises stress, compared to a neutrally inserted conventional stem (type 1) in walking condition, are shown in parentheses.

Variable	Medial interface, MPa	Lateral interface, MPa
<b>Normal walking</b>		
<b>Neutral insertion</b>		
Type 1	29	24
Type 2	35 (21%)	27 (13%)
Type 3	38 (31%)	30 (25%)
<b>Varus insertion</b>		
Type 1	46 (59%)	50 (108%)
Type 2	47 (62%)	54 (125%)
Type 3	39 (34%)	68 (183%)
<b>Stair climbing</b>		
<b>Neutral insertion</b>		
Type 1	35 (21%)	28 (17%)
Type 2	34 (17%)	29 (21%)
Type 3	46 (59%)	36 (50%)
<b>Varus insertion</b>		
Type 1	63 (117%)	60 (150%)
Type 2	59 (103%)	75 (213%)
Type 3	48 (66%)	84 (250%)

In the current study, mean stress over a ROI and PVMS were greater on the medial interface than the lateral independent of the stem length in neutrally inserted stems and increased as the stem shortened. However, mean stress and PVMS on the medial and lateral interfaces



Type 1 (conventional stem), Type 2 (mid-short stem), Type 3 (short stem)

Fig. 5

Increase rate of micromotion between the stem and bone in other stems, compared with a neutrally inserted conventional stem in normal walking; a) normal walking, b) stair-climbing.

showed only slight differences in each stem. Meanwhile, mean stress and PVMS increased at both medial and lateral interfaces in varus-inserted stems. As the stem shortened, mean stress and PVMS at the lateral interface increased and those at the medial interface decreased. Among them, mean stress and PVMS at the lateral cortex in contact with the stem tip in a short stem was greatest. Although Pernell et al<sup>28</sup> reported that varus insertion improved press-fit and did not influence the survival and the outcomes, this insertion increased tensile hoop strains. De Beer et al<sup>10</sup> also reported the potential risk of stresses associated with the stem inserted in varus, and this FEA study could confirm these findings. However, we believe that it is very difficult to present an acceptable range of varus alignment of the stem numerically. If the extent of varus alignment of the stem is less than 5°, stress concentration at the medial and lateral interfaces would be less than those measured in our study simulating the varus alignment of the stem at 5°. However, we cannot guarantee that it is safe compared to the varus alignment of 5°. When the stem is inserted in varus, it may lead to uneven stress distribution of the femur. As a result, it can cause thigh pain and increase the possibility of periprosthetic femoral fracture, especially in a short stem. Therefore, we believe that it is better not to insert the stem in varus if possible, otherwise the stem tip - in contact with the lateral cortex in the varus-inserted stem - can cause stress concentration, leading to the above-mentioned complications.

Several authors reported that stair-climbing was detrimental to hip arthroplasty due to high torsional loads.<sup>29</sup> Our study on the FEMs revealed that mean stress as well as PVMS increased in stair-climbing condition compared to walking regardless of stem length and position. Of all

six FEMs, the FEM of a varus-inserted short stem in stair-climbing condition showed the greatest mean stress and PVMS at the cortical bone, especially at the lateral cortex in contact with the stem tip. Based on these findings, we suggest that excessive loading such as stair-climbing should be avoided in the early postoperative period to lower the risk of thigh pain or periprosthetic fracture, especially when using a short stem. However, it is difficult to suggest a definite period to avoid stair-climbing exercise after cementless hip arthroplasty, because the duration for the maintenance of primary stability and the physical ability to climb stairs varies from person to person. Zweymüller et al<sup>30</sup> reported that primary stable implanted prosthesis completely maintained its primary stability after three weeks postoperatively. Therefore, we recommend protected weight-bearing with assistant devices such as crutches for at least one month after surgery, although the duration depends on the patient's physical ability, especially when a short stem is used and implanted in varus. Stair-climbing exercise should also be avoided during this early postoperative period.

After the implantation, bone ongrowth, which affects the stability of the stem, occurs on the surface of the cementless stem treated by plasma spray.<sup>30</sup> A previous study indicated that the amount of bone ongrowth is inversely proportional to the amount of micromotion.<sup>31</sup> Therefore, the biomechanical properties of this cementless stem are usually evaluated by measuring the micromotion at the interface between the bone and stem. In this study, the micromotion measured in all four directions between the bone and the stem increased when the stem was shorter, inserted in varus, and during stair-climbing. Thus, it is important to insert a short stem neutrally and avoid stair-climbing exercise during the

early postoperative period to preserve primary stability of the stem.

There are some limitations to the current study. First, the complex physiological force components around the proximal femur were simplified during walking and stair-climbing, as physiological loading during activities is more complex, and greater loading can occur in real-life situations. This FEA used axial loading to simulate the loading forces during walking and stair-climbing. Second, we investigated the stress distribution including PVMS instead of strain to focus on the stress concentration at the lateral cortex in contact with the stem tip in this study. However, this value occurs in a single element and is not necessarily representative of a part or ROI. Therefore, we added the results of mean stress over a ROI along with PVMS. Third, we used only a single-wedge tapered stem design and single patient's model in this study. The relationship between implant position and primary stability may depend on the patient and the stem design, therefore our results may vary accordingly.<sup>32</sup> Moreover, we used a linear model reporting the stress in a single patient's model. Therefore, the current results cannot predict the periprosthetic fracture risk and be generalized to the entire population of various femoral geometries.<sup>33</sup> However, we believe that our findings reveal the increased tendency of stress concentration on the lateral cortex around the stem tip as the stem was shorter and inserted in varus, especially in stair-climbing condition, which can increase the possibility of thigh pain or periprosthetic fracture. Besides, it is very difficult to reproduce every different shape of the femur and various designs and material properties of the stem, especially in the experimental study. Recently, tapered-wedge short stems have been widely used in hip arthroplasty because they preserve more proximal bone stock and can be easily used regardless of the femoral geometry. However, several issues such as thigh pain, early loosening, and periprosthetic fracture have been raised continuously,<sup>5-8</sup> and we have experienced these problems in our practice. Therefore, we believe that our results provide fundamental basic outputs to understand and resolve these issues when using a short stem in hip arthroplasty.

Despite these limitations, to the best of our knowledge, the current study is the first FEA to investigate stress distribution at the cortical bone around the femoral stem according to the stem length and position and loading conditions such as normal walking and stair-climbing. We also investigated the micromotions at the interfaces between the bone and the stem (anterior/posterior/medial/lateral) in each FEM to evaluate the stem stability in the early postoperative period. However, our results will have to be substantiated by further biomechanical and clinical trials.

In conclusion, our FEA study revealed that mean stress as well as PVMS increased on the surface of the lateral cortex in contact with the stem tip when the stem was shorter and during stair-climbing in the varus-inserted

stems. Eventually, stress concentration was maximal at the lateral interface during stair-climbing in a varus-inserted short stem. Additionally, micromotions increased in all four directions between the stem and bone as the stem was shorter, and inserted in varus and during stair-climbing. Accordingly, we suggest that the stem should be inserted neutrally if possible and stair-climbing movement should be avoided in the early postoperative period to preserve early stability and reduce the possibility of thigh pain or periprosthetic femoral fracture, especially when using a shorter stem.

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- D-K. Kwak: Conceptualized the study, Drafted the manuscript.
  - S-H. Bang: Used software to construct the finite element model and loading condition.
  - S-J. Lee: Advised on the methodology, Supervised the experiment.
  - J-H. Park: Curated the data, Conducted the investigation.
  - J-H. Yoo: Conceptualized and supervised the study, Reviewed and edited the manuscript.
- D-K. Kwak and S-H. Bang are joint first authors.

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