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ORIGINAL ARTICLE

Periprosthetic fractures may be more likely in cementless femoral stems with sharp edges

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Abstract
Background Many contour designs have been developed to improve the femoral stem in cementless total hip arthroplasty.
Aims To assess the initial interfacial micromotion and stress distribution.
Methods The prosthesis–bone interfacial micromotions and stress distributions of four commonly used femoral stems were assessed by finite element simulation: Alloclassic, Ribbed Anatomic, VerSys, and Secur-Fit. The proximal interfacial micromotions and stress distributions were calculated under the loading conditions of stair climbing. Three-dimensional micromotions were calculated in three proximal sections distal to the osteotomy level with 400 mm between each section. Medial, anterior, lateral and posterior points in each section were selected for calculations.
Results The micromotions were <100 μm at all the selected points. Significant stress was detected along the sharp corners and ribs of the Alloclassic and Ribbed Anatomic stems, respectively.
Conclusions Significant stresses are associated with the stems with sharp edges.

Keywords Periprosthetic · Fracture · Finite element model · Hip · Cementless

Introduction

Intraoperative and postoperative periprosthetic femoral fractures are serious complications of cementless hip arthroplasty [1, 2]. However, previous biomechanical studies on cementless femoral stems have mostly focused on proximal femoral stress shielding and interfacial micromotion, and few have considered the initial interfacial stress distribution when evaluating the risk of periprosthetic fracture.

The long-term stability provided by osseointegration, namely, secondary or biological stability, is closely related to the primary stability. Osseointegration has been shown to occur when the interfacial micromotion is <40 μm, while fibrous tissue forms when the micromotion is >150 μm and causes insufficient stability and loosening [3]. To minimize the effects of proximal femoral stress shielding, many stems have been designed for proximal osseointegration. Therefore, the primary stability is more important proximally than distally in terms of osseointegration. The press-fit implantation technique has been developed and used to improve the primary stability. However, the press-fit technique definitely leads to increases in the initial interfacial stress. Postoperative activities have great effects on the interfacial micromotion and stress distribution [4]. Excessive stress induces osteoblast apoptosis and osteoclast activation, which may be negative for osseointegration [5]. Regional stress increases can also lead to thigh pain or femoral fracture [2, 6].

Many kinds of cementless femoral stems have been developed with various contours according to specific

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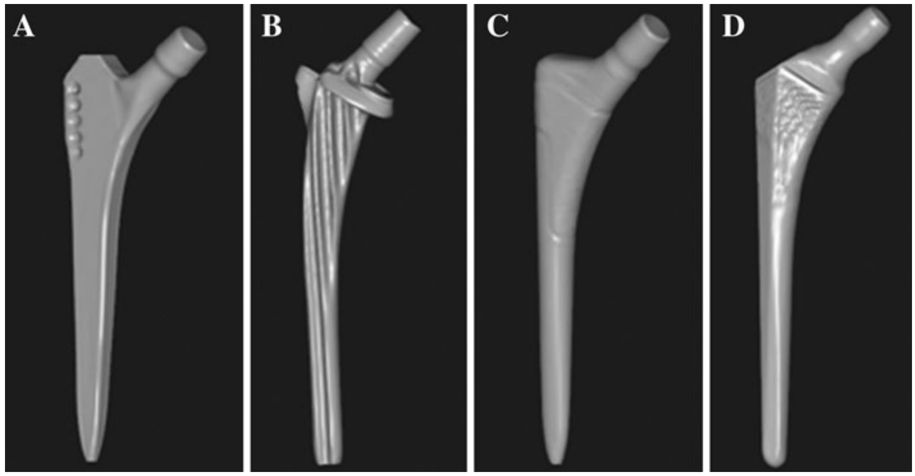

Fig. 1 The four femoral stems evaluated in this study. **a** Alloclassic SL Plus stem with rectangular sharp edges and a vertical double-taper (Zweymüller, Switzerland). **b** Ribbed Anatomic stem with proximal anatomic contours and ribs (Waldemar Link GmbH and Co., Germany). **c** VerSys Fiber Metal Taper with rounded corners and tapered contours (Zimmer, USA). **d** Secur-Fit with proximal blunt angle edges and a double-wedge (Stryker, USA)

rationales. However, no such stem designs have yet been demonstrated to achieve superior clinical results. Furthermore, no generally accepted criteria have been set up for prosthesis selection, and the prosthetic implantation techniques and rehabilitation programs have not been individualized.

The aim of the present study was to investigate the proximal interfacial micromotions and stress distributions of different femoral stems with various contours. We tried to identify the individual biomechanical characteristics of the various stems to provide basic evidence for setting up individualized prosthetic implantation techniques and rehabilitation programs to minimize the chance of periprosthetic fracture. In this study, we subjected four commonly used femoral stems to finite element analyses to determine their individual characteristics in primary hip arthroplasty. Under simulated loading, the proximal interfacial micromotions and the contact pressure and von Mises stress distributions were calculated. Since stair climbing has been demonstrated to cause higher micromotion and interfacial stress [7], we simulated the loading conditions of stair climbing.

Materials and methods

The study has been approved by the ethnics committee.

Establishment of finite element models

A digital left femur was derived from the Chinese virtual human project and corresponded to a 35-year-old 65-kg male. A finite element model was created using eight-node hexahedron isometric elements. Subsequently, finite element models of the following four femoral stems (Fig. 1) were established: (1) Alloclassic SL Plus (Zweymüller, Switzerland) with rectangular sharp edges and a vertical double-taper; (2) Ribbed Anatomic with proximal anatomic contours and ribs (Waldemar Link GmbH and Co., Germany); (3) VerSys Fiber Metal Taper with rounded corners and tapered contours (Zimmer, USA); and (4) Secur-Fit with proximal blunt angle edges and a double-wedge (Stryker, USA). Proximal femoral replacement was simulated for each of these stems. The elastic moduli of the titanium alloy and cortical bone were set to 111.0 and 15.50 GPa, respectively. The Poisson ratios of the titanium alloy and bone were 0.30 and 0.29, respectively [8].

Finite element analysis

Abaqus 6.7-1 (Simulia, USA) was used for the finite element analyses. A supracondylar femur osteotomy was simulated, and the distal end of the femoral model was fixed. The nodes and elements of each model are shown in Table 1. Press-fit frictional face-to-face contact models were set up [9]. The coefficient of friction was 0.4, and the SL was 0.1. The interface interference fit was 50 μm [10]. The loading conditions of stair climbing are shown identical to the former study [11]. Under the simulated conditions, the maximal interfacial micromotions and stresses were calculated.

Table 1 Nodes and elements of each component in the four models postoperatively

	Femur (postoperative)		Stems	
	Elements	Nodes	Elements	Nodes
Alloclassic	22,481	5,720	5,962	1,672
Ribbed Anatomic	31,864	8,096	19,375	5,027
Versys	21,558	5,567	7,653	2,044
Secur-fit	16,458	4,484	5,255	1,458

Results

Interfacial micromotions

Since proximal osseointegration is expected, we calculated the proximal interfacial micromotions. Three proximal cross-sections were selected along the stems for data extraction. We selected the proximal section at the osteotomy level, the middle section at 400 mm distal to the proximal section, and the distal section at 800 mm distal to the proximal section. Four key points (medial, anterior, lateral and posterior) in each section were used to delegate the level. The relative micromotions along the *X*-axis, *Y*-axis and *Z*-axis were calculated for the key points. The micromotions at each point are shown in Table 2. All four stems provided good primary stability at the selected key points. The micromotions were <100 µm in all points. Only 34 of the 144 selected points exhibited micromotions of >40 µm.

Interfacial stress distributions

The interfacial stress distributions are shown by color pictures in Figs. 2 and 3. The interfacial contact pressures and von Mises stresses were higher distally than proximally in all four stems. The contact pressure distributions were

Table 2 Micromotion along the *X*-, *Y*- and *Z*-axes in the interface when stair climbing loading condition was simulated

Section	Points	Micromotion (micron)											
		Alloclassic			Ribbed Anatomic			Versys			Secur-fit		
		X	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*
Proximal	1	22.24	41.257	17.416	46.89	16.368	17.185	77.43	10.87	13.104	31.24	31.312	23.379
	2	45.85	22.746	11.894	60.92	49.8	12.4075	50.56	21.12	20.386	50.18	24.922	11.692
	3	29.31	38.569	13.993	32.87	32.48	19.463	30.55	38.06	13.354	29.7	39.247	8.9
	4	40.84	41.751	5.986	45.19	30.552	2.524	33.8	40.06	8.837	39.6	37.282	7.486
Middle	1	26.09	42.611	2.183	44.45	23.012	3.849	23.14	44.335	1.2906	37.23	33.436	1.269
	2	43.91	24.191	0.471	27.82	52.961	0.0157	36.38	34.403	1.005	46.57	18.361	1.928
	3	23.57	42.983	10.641	35.33	35.207	3.988	29.4	39.317	10.059	28.07	40.237	9.927
	4	41.87	26.59	43.916	33.66	36.622	6.136	41.89	26.413	6.988	38.79	30.905	7.272
Distal	1	25.44	42.832	4.258	37.02	33.491	2.905	20.5	45.399	4.607	25.35	42.861	4.6321
	2	44.86	22.215	3.4855	46.27	33.255	1.5843	40.87	28.825	0.444	41.39	28.035	6.6851
	3	22.56	44	7.9536	31.91	38.001	6.238	28.35	40.585	7.74	30.04	39.084	6.6851
	4	42.41	26.073	4.7587	27.83	46.889	7.2465	38.19	31.7	6.0901	32.5	37.413	6.6851

Three-dimensional interfacial micromotions in the *X*-axis, *Y*-axis and *Z*-axis in the key points (medial, anterior, lateral and posterior). The key points were selected from the following three cross-sections: proximal section at the osteotomy level; middle section at 400 mm distal to the proximal section; and distal section at 800 mm distal to the proximal section. All micromotions are <100 µm, and micromotion >40 µm are only detected in 34 of the 144 selected points

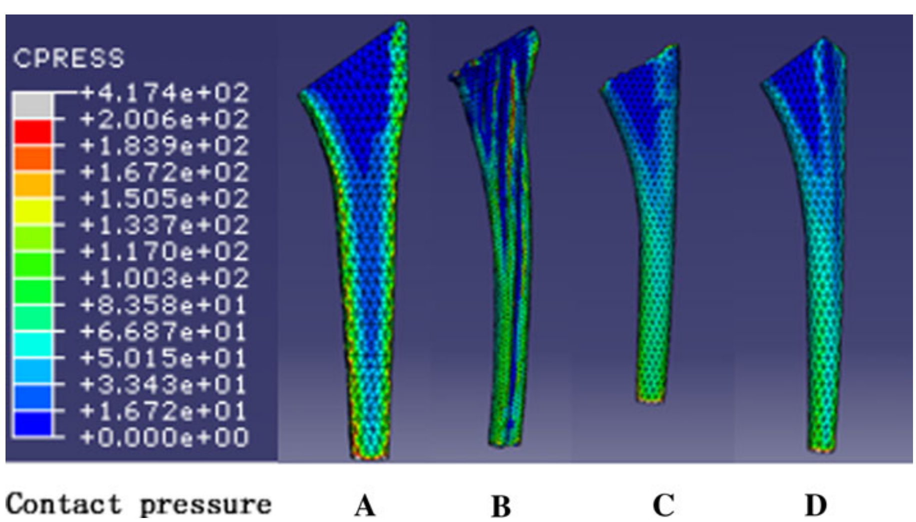

Fig. 2 Interfacial contact pressure distributions. Stress increases are detected along the corners and ribs. In the proximal section, the highest contact pressures are 115, 175, 50 and 47 MPa in the Alloclassic, Ribbed Anatomic, VerSys and Secur-Fit stems, respectively

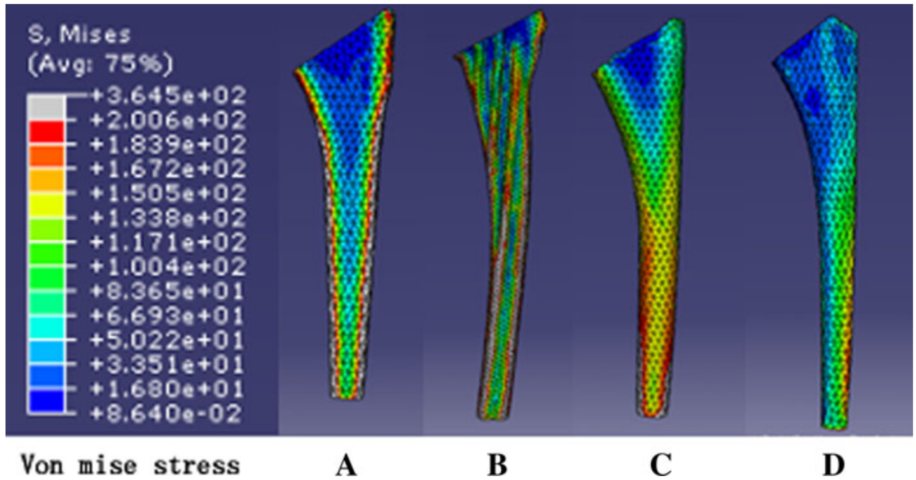

Fig. 3 Interfacial Von Mises stress distributions. Stress increases are detected along the corners and ribs. In the proximal section, the highest Von Mises stresses are 204, 192, 127 and 156 MPa in the Alloclassic, Ribbed Anatomic, VerSys and Secur-Fit stems, respectively

similar to the von Mises stress distributions. In the proximal area we focused upon, the stresses were higher along the corners and ribs. Massive stress increases were detected along the sharp corners of the Alloclassic stem and along the ribs of the Ribbed Anatomic stem. Stress increases were also detected at the rounded and blunt corners of the VerSys and Secur-Fit stems, respectively. However, the latter increases were much lower than those in the Alloclassic and Ribbed Anatomic stems. In the proximal section, the highest contact pressures were 115, 175, 50 and 47 MPa in the Alloclassic, Ribbed Anatomic, VerSys and Secur-Fit stems, respectively. The highest Von Mises stresses were 204, 192, 127 and 156 MPa in the Alloclassic, Ribbed Anatomic, VerSys and Secur-Fit stems, respectively.

Discussion

Despite the worldwide use of cementless femoral stem arthroplasty, long-term aseptic looseness remains an unsolved issue, especially in younger patients with active lifestyles [12]. Many efforts have been made to improve the long-term survival of such stems [13]. Primary stability is considered to be essential for osseointegration, which is believed to determine the long-term survival of stems. Therefore, many prostheses have been developed with the aim of improving the primary stability. Furthermore, when evaluating the biomechanical properties of cementless stems, many studies have focused on the primary stability by using experimental and finite element analyses, and few have simultaneously considered the interfacial stress distribution. Some stem designs with special locking mechanisms were found to exhibit superior primary stability. However, according to the consensus on biomechanics, these locking mechanisms may cause increased stress, which is a risk factor of implant breakage or fracture and may be the origin of thigh pain. Sakai et al. [7] studied the primary stabilities of four femoral stems by finite element analyses, and concluded that the Intra-Medullary Cruciate stem with a cross bar for fixation in the proximal region had better primary stability in the sinking direction. In a subsequent study, Sakai et al. [8] demonstrated high stress distribution under the cross bar [8].

Since periprosthetic fractures are more common with cementless stems, fracture-related factors and countermeasures should be investigated. We studied the primary stabilities and stress distributions of four commonly used femoral stems, with the aim of identifying their individual mechanical characteristics. We did not carry out statistical analyses to compare the primary stabilities of the four stems because the micromotions at the selected points were within the acceptable range. The interfacial stress distributions varied significantly. The Alloclassic stem with sharp corners and Ribbed Anatomic stem with ribs were associated with significant stress increases, while the stress distributions were relatively homologous in the VerSys stem with rounded corners and Secur-Fit stem with blunt corners. Increased regional stress has been accepted as a unique factor that causes fractures. Therefore, we recommend that more attention should be paid to the prevention of intraoperative periprosthetic fractures and rehabilitation with these kinds of stems.

Clinical results for the four stems have been reported in a few studies. Swanson [14] listed many advantages of the Alloclassic SL stem without mentioning the interface stress distribution or incidence of periprosthetic fractures. Marshall et al. [15] reported good effects of this stem. The results for the Ribbed Anatomic stem were reported to be good by Fortina et al. [16], but poor by Sweetnam et al. [17]. Klein et al. [18] reported good results for the VerSys stem. Incavo et al. [19] reported good results for the Secur-Fit stem. To the best of our knowledge, no comparative studies of these four stems have been carried out to date. Further randomized prospective studies are required.

There are a few limitations to the present study. We did not carry out experimental verification because we were unable to obtain four fresh cadaver femur specimens of similar quality. The finite element analysis parameters and loading conditions were based on published reports [7–11]. The femoral model was simplified, similar to the report by Sakai et al. [7]. The femoral bone was set as a homologous isotropic material. The edges of the stems were prominent. We can expect that the increases in the proximal femoral stress would be more significant if cancellous bone was simulated because the edges come into contact with cortical bone while most of the remaining areas come into contact with cancellous bone. The time-dependent effects of loading and relaxation were not considered. The effects of the increased stress can be expected to become less significant with the process of stress relaxation [20]. Nevertheless, during the operation and rehabilitation, when the effect of stress relaxation is less significant, we believe that these mechanical characteristics can be relied upon. In comparative studies, finite element analyses are advantageous for controlling the conditions. Therefore, four simulations can be performed with one digital model, and thereby eliminate interference between subjects. Hence, we believe that our models and simulations are reliable.

In conclusion, all four stems provided satisfactory primary stability, while the Alloclassic and Ribbed Anatomic stems were associated with significant stress increases along the sharp edges and ribs, respectively, and the contact pressure and von Mises stress distributions were more homologous in the VerSys and Secur-Fit stems. We conclude that femoral contour design is an essential factor for determining the interfacial stress distribution. Based on this study, we recommend that more attention should be paid to the prevention of periprosthetic fractures when using the Alloclassic and Ribbed Anatomic stems for hip arthroplasty.

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Conflict of interest statement No commercial relationships were involved in this study.

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