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Research Article

Biomechanical Study using Finite Element Method of Element 'Breakdown' Technique on Cutout Mechanism after Gamma Nailing

Mitsuaki Noda[1]*, Yukiko Nakamura[2], Kazuhiko Adachi[3] and Masayasu Takahashi[4]

[1]Department of Orthopedics, Nishi Hospital, Kobe, Japan

[2]Kobe University Graduate School of Engineering, Kobe, Japan

[3]Department of Mechanical Engineering, Chubu University, Kasugai, Japan

[4]Department of Orthopedics, Konan Hospital, Kobe, Japan

***Corresponding Author:** Mitsuaki Noda, Department of Orthopedics, Nishi Hospital, Kobe, Japan.

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Abstract

Background: A serious complication of cephalo-medullary nail fixation for proximal femoral fractures is cutout, where the tip of the lag screw protrudes into the surface of the femoral head.

Aims: The purpose of this biomechanical research is to evaluate the mechanism of cutout and to construct fracture model to simulate cutout under preliminarily different types of fracture reduction.

Study Design: Biomechanical study.

Methods: 3D models of osteosythesized femoral intertrochanteric three-parts fracture were constructed. Two models of different fracture reduction: Subtype N (anatomical reduced) and Subtype P (posteriorly displaced) were prepared. Force of hip contact and gluteus medius was applied until cutout. Elements that exceeded ultimate strain of 1% or more were removed, estimating that elements were destroyed, and the effect of disappeared elements leads to further displacement. This model allows simulation of a cutout mechanism.

Results: The mechanism for cutout, based on consecutive graphical images leading to cutout are: (a) sliding causing medial cortical contact followed by rotation; (b) cancellous bone breakage around femoral neck; (c) loss of medial cortical contact at fracture site; and (d) varus leading to cutout. Predicted stress values to cutout of lag screw [N] was calculated in subtype N and subtype P as 790.4, 709.5 for hip contact force, 458.2, 411.4 for gluteus medius, respectively.

Conclusion: This study provides innovative findings that spacious movement of the femoral head until cutout consists of several factors, and that anatomical reduction of subtype N is preferable to subtype P with regard to cutout, which is consistent with clinical results.

Keywords: *Finite Element Analysis; Cutout; Intertrochanteric Fracture; Varus; Breakdown; Femur*

Abbreviation

DHS: Dynamic Hip Screw; FE: Finite Element; DICOM: Digital Imaging and Communications in Medicine; PFNA: Proximal Femoral Nail Anti-Rotation

Introduction

Dynamic Hip Screw (DHS) or cephalo-medullary nail fixation procedures are the gold standard for treating intertrochanteric fractures [1]. Postoperative rehabilitation, in particular early weight bearing exercise, is encouraged to prevent several complications such as bed sore formation, thrombosis, and muscular weakness [2]. In addition, walking exercises enable the lag screw to slide and stabilize the fragments to promote bony healing. However, implant-related complications such as thigh pain, leg shortening, and cutout occur occasionally with rehabilitation. Cutout is one of the most serious complications, where the tip of the lag screw protrudes into the surface of femoral head, at a reported ratio of 3.6 - 6.8% [3]. Cutout complications place a heavy burden on the patient as additional surgery is necessary, with less satisfactory postoperative scores, severe morbidity and mortality, especially in the older age group [4,5].

Knowledge of the mechanism of cutout may be useful for orthopedic surgeons in predicting the risk of impending cutout. With this knowledge, weight-bearing exercises may be temporarily regulated until fracture healing progresses enough to sustain weight bearing. The few articles related to the mechanism of cutout discuss varus, sliding, and rotational movements around the femoral neck [6-8]. These studies are speculative and divergent in conclusion, mainly due to the limited information obtained from simple radiographic examinations where 3D movements cannot be evaluated. Therefore, other methods that can demonstrate spacious motion are necessary. Moreover, it is important to decide preventive measures of cutout. Generally, the risk factors of cutout include osteoporosis, position of the nail, fracture reduction, and the presence of an unstable fracture [7,8]. Surgeons may be able to control some of these factors, such as fracture reduction.

In this present research, we aim to discover whether fracture reduction influences the occurrence of cutout. In clinical studies, it is difficult to determine the effect of one specific factor, since morbidity may be interrelated with several other factors [9]. To address these issue, we conducted a biomechanical study to search influence of one factor, which is fracture reduction, by comparing two models of fracture reduction, while negating the effect of other factors. Among the numerous biomechanical approaches, finite element (FE) analysis is a powerful tool to assess internal stresses in bone. FE analysis provides valuable estimates of stress and strain distribution of specific structures, which are usually non-measurable *in vivo* [10]. Thus far, FE analysis studies have been designed to retain a construct, which may be improper to reproduce cutout. Therefore, to simulate cutout deformity, we utilized a technique for the "breakdown" of elements where stress exceeds a certain amount in cancellous bone or fractures at the cortex, such elements will disappear, and the remaining defect will lead to further displacement. This method may be appropriate in analyzing the mechanism of cutout [11].

The purposes of this preliminary biomechanical research are first, to trace the displacement of the proximal femur three-dimensionally until cutout occurs; and second, stress values of cutout were measured among contrasting positions of reduction, for comparison with clinical studies. We hope to understand mechanism for cutout, and establish cutout model in various models.

Materials and Methods

FE modeling

A patient-specific FE model of the hip joint and proximal femur was constructed from CT images (cortical and cancellous bone maps of the femur) of a healthy female in her nineties. CT images were taken at 0.625 mm intervals about the proximal femur, obtained in the supine position with a Phillips MX 8000 (Phillips Medical Systems, Cleveland, Ohio, USA) spiral CT-scan using an axial scanning protocol (140kVp, Auto mA, Noise Index 13). For model production, all data were converted to DICOM files (Digital Imaging and Communications in Medicine). The 3D geometric models were reconstructed using 3D Slicer ver. 3.41.0 (The Brigham and Women's Hospital, Inc.) and SolidWorks 2013 (Dassault Systems SolidWorks Corp.).

The 3D geometric models were composed of the proximal femur and the implants. In this study, we prepared two models of osteosynthesized femoral intertrochanteric three-parts fracture (AO/OTA 31-A2.1) treated with cephalomedullary nail fixation of 125 degree collo-diaphyseal angle (Gamma nail®, Stryker, Mahwah, NJ, USA). Two models of different fracture reduction were prepared based on Ikuta's classification (in lateral view) as Subtype N (anatomically-reduced) and Subtype P (posteriorly-displaced proximal femoral neck against the distal femoral shaft) [12,13] (Figure 1). Detailed structures of the implants were measured manually. The 3D geometric models were subsequently imported into ANSYS ver.14.0 (ANSYS Inc., Canonsburg, PA), a meshing tool for FE analysis and meshed into 4-noded tetrahedral (C3D4) elements. The models were discretized to 1342,496 elements with 23,559 nodes. Mechanical properties (Young's modulus and Poisson's ratio) were used [14] (Table 1). Young's moduli for cortical bone and the implant were set at 13.3, and 110 GPa, respectively. The moduli for cancellous bone varied in accordance with the location on the femur; namely head, neck, or shaft as 0.44, 0.32, 0.15, respectively. Poisson's ratio was assigned as 0.3 for both cortical and cancellous bone. The coefficient of friction was 0.1 for implant-bone pairing. All materials were assumed to be homogeneous, isotropic, and linearly elastic.

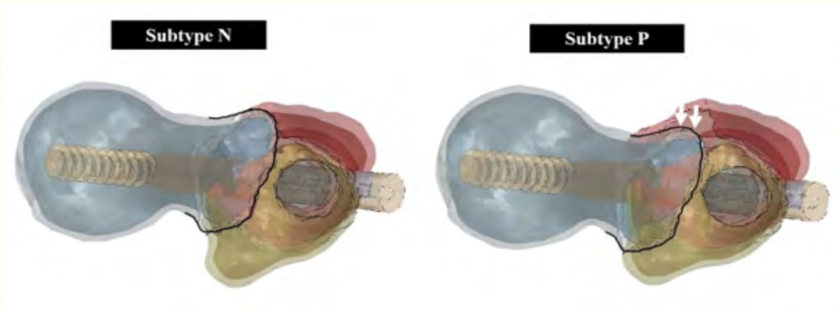

Figure 1: *3D fracture models with implants for fixation; (a) subtype N and (b) subtype P without cortical contact at anterior fracture site (white arrows indicating posteriorly displaced femoral neck fragment in lateral view). The tips of lag screw were placed at the center of femoral head in both antero-lateral and lateral view.*

		Young's modulus [MPa]	Yield Stress [MPa]	Poisson ratio	Mass density [Kg/m^3]
Cortical bone		13,300	208	0.3	1,141
Cancellous bone	Head part	440	6.8	0.3	138.8
	Neck part	320	5		120.1
	Distal part	150	2.4		85.1
Implant (Titanium alloy)		110,000	-	0.3	4,620

Table 1: *Material properties of finite element models.*

Loading and boundary conditions

Hip contact force was applied to the hemispherical surface of the femoral head, and gluteus medius force was added to the tip of greater trochanter (Figure 2). The magnitude of this external stress increased linearly until cutout occurs. In this study, the value of cutout stress was defined as when the tip of the lag screw protrudes into the femoral head. The direction of hip contact force and gluteus medius was constant and outlined in a straight line. For boundary conditions, the distal end of the femur was fully clamped.

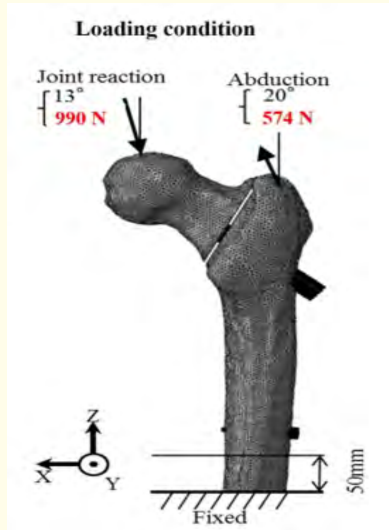

Figure 2: *Load of hip contact force and gluteus medius with linearly increased magnitude up to cutout (if MAX 990N, 594N, respectively). Direction was constant.*

Reproduction of cutout using 'elements breakdown' technique

FE analysis was performed using the dynamic explicit method ABAQUS (ver.6.14-5 Dassault Systèmes Simulia Corp., Providence, RI). Elements that exceeded the ultimate strain of 1% were removed, estimating that the elements were destroyed [15]. The values of yielding stress [MPa] at cortical bone, and cancellous bone of femoral head, neck, and distal to neck were 208, 6.8, 5, and 2.4 respectively. The void after removing elements invited further displacement of fragments. Stress was continuously applied on the displaced model following removal of elements.

Ethical approval and consent

This study was approved by the Ethical Review Board of (Author's) Hospital. A written informed consent was provided for radiography, CT scanning, and creation of the FE model hip joint.

Results

Consecutive graphic images showed the mechanical behavior of the fracture site until cutout occurrence: (a) sliding caused medial cortical contact secondary to increased stress at the medical cortex followed by rotation around the screw; (b) cancellous bone breakage observed in a slice of fracture surface leading to caudal displacement of the femoral neck; (c) medial cortical contact of the femoral head against the distal medical cortex was lost in an AP view of the FE model demonstrating reduction of stress at this site; and (d) femoral head without medial cortical sustainment resulted in varus, later leading to cutout during further loading (Figure 3).

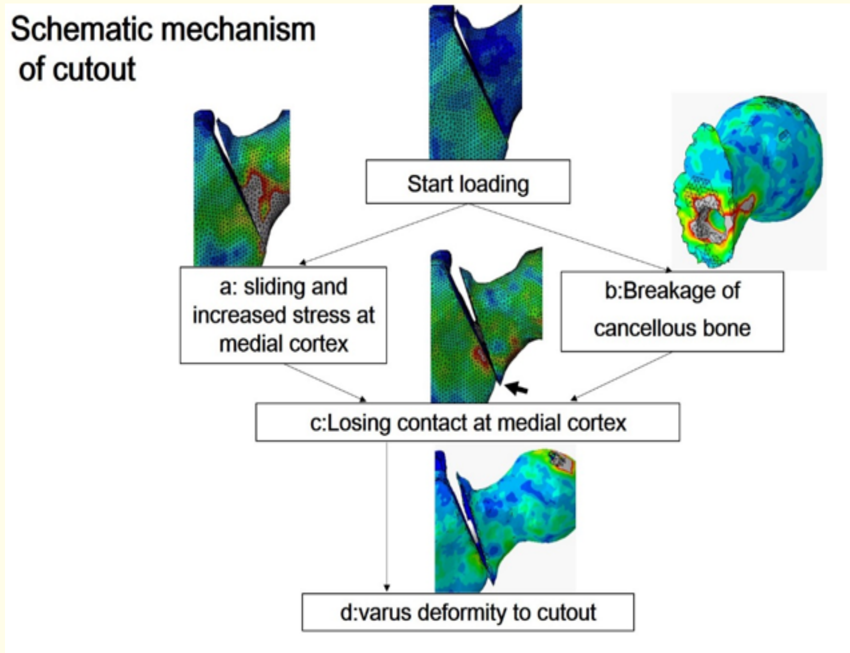

Figure 3: *Mechanism of cutout under linearly increased loading: (a) sliding resulted in contact of medial cortex and elevated cortical stress followed by rotation; (b) cancellous bone breakage around the femoral neck; (c) loss of medial contact proved by declined stress (a black arrow); and (d) varus deformity leading to cutout after loss of medial sustaining.*

Predicted stress values reaching to cutout of lag screw [N] were calculated in subtype N and subtype P as 790.4, 709.5 for hip contact force, and 458.2, 411.4 for gluteus medius, respectively. In both groups, stress of medial cortex at the fracture site decreased prior to cutout, revealing contact losing (Figure 4).

Subtype N and subtype P revealed a lag screw shortening [in mm] of 1.38, 1.76, and rotational angle around the femoral neck [deg] as 6.6, 4.3, respectively.

Discussion

Mechanism of cutout

The current study demonstrates a mechanism for cutout in subtype N as follows: sliding until medial cortical contact, rotational movement of femoral head, breakdown of cancellous bone surrounding lag screw causing medial contact lost, and varus translation leading to cutout. This mechanism is supported by consecutive image findings with the corresponding stress changes at each image viewpoint, as calculated by a biomechanical method.

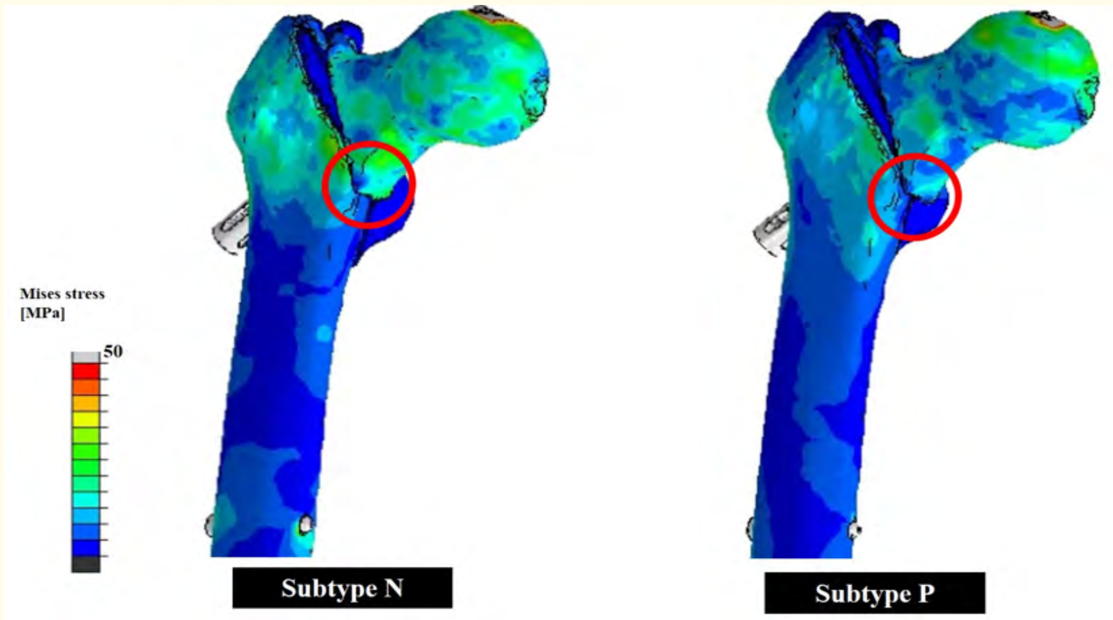

Figure 4: *The instant of cutout occurrence in both groups. Noting losing of medial cortical contact demonstrated with declined stress at the fracture site (in red circles).*

Most researches to explore the mechanisms of cutout have been conducted through (1) simple radiographs, (2) CT scan images, and (3) biomechanical methods using cadavers.

First, most of the clinical studies were done using simple radiographs [6-8]. Baumgaertner., et al. [16] showed varus collapse of the femoral head and superior cutout of the lag screw. Chinzei., et al. [6] hypothesized a mechanism for cutout in gamma nail as follows: (1) in fractures with insufficient contact between bones, an excessive degree of sliding of the femoral head shape occurs due to lack of bony support; (2) femoral head rotation; (3) varus collapse and cutout of the lag screw through the femoral head. In a screening study of 71 cutout patients, Bojan., et al. [7] proposed that the cutout pattern was highly dependent on the primary position of the lag screw in the femoral head, and that the cranial migration of the lag screw and varus collapse of the femoral head were accompanied by a predominantly anterior movement. However, all the above-mentioned articles have drawbacks, as the results are mostly speculative and are based on radiographic images. Owing to the two-dimensional or static nature of simple radiograms, spacious movements like rotation, and dynamic contact between the proximal and distal fragments, were evaluated hypothetically.

Second, three-dimensional CT scan images provide more information regarding spacious position between bony fragments [17]. Although a series of CT images during the postoperative course is necessary to fully evaluate and understand the occurrence of cutout movement, multiple scanning may be unrealistic.

A third method used to evaluate cutout mechanism was done using cadavers for 3D motion analysis of the femoral head under cyclic loading [18-20]. Metal markers were attached on the experimental model to evaluate displacements as the number of loading cycles increased. A motion capture imaging system recorded fracture displacement during the cycling. These studies are valuable in the viewpoint of loading that reproduces walking, and enabling 3D motion analyzing including rotation. However, most of these research studies concentrated on calculating cutout values, and not on the actual mechanism of cutout itself. Among these cadaveric studies, only Kouvidis., *et al.* [21] evaluated mechanical movement similar to our current study, revealing that the initial motion was rotation around the lag screw followed by varus collapse. This data coincides with the results of our study. Compared to these methods, our current study demonstrates a more reliable mechanism for cutout based on a biomechanical framework.

Influence of fracture reduction

Another important finding of the present biomechanical study is that the anatomically reduced subtype N is more tolerable to higher stress than the posteriorly displaced Subtype P. This outcome correlates with the results of radiographic analysis and functional recovery studies [1,13]. For example, Takigawa., *et al.* [13] reported that an anatomically reduced Subtype N resulted in a lesser risk for cutout, although Bendo., *et al.* [22] refuted Takigawa's study, as Subtype N does not always lead to less complication of collapse. This divergence of outcomes may be due to the fact that clinical cases have multifactorial risks, which may include the presence of osteoporosis, individual differences between bony structures, amount of fracture reduction, and positioning of the nail in the femoral neck or head. In general, it is very difficult to conclude on the influence of a single particular factor in clinical studies.

Rotation and loss of medial cortical contact

This biomechanical research demonstrates that femoral rotation of 6.6 and 4.3 degrees occurred in subtype N and subtype P, respectively, followed by loss of medial cortical contact before occurrence of cutout. Although several studies on fixation stability of different implant types after axial load have been performed, only a few evaluated rotational stability [21,23,24]. As a result of this biomechanical finding, preventing femoral rotation may avoid sequential movements leading to cutout, which is coincident with our results. To adapt this assumption into practical use, the proximal femoral nail anti-rotation (PFNA) device, the helical blade of the PFNA system have been biomechanically proven to compact cancellous bone and achieve increased rotational stability [25]. InterTAN and Targon proximal nail systems are equipped with two cephalo-cervical screws in an integrated mechanism, which will strengthen rotational stability of the head or neck fragment [13,26]. Further, implant development are needed to maintain medial cortical contact.

It is our strong belief that identifying the potential risks for cutout complication is imperative and the best method of prevention is through close follow-up to detect signs of cutout such as loss of medial cortical contact, which will expectedly avoid revision surgery [27].

Strong point of our research

First, our FE analysis enables simulation of bony displacement leading to cutout by adopting a technique of elements removal, as performed by Sasaki., *et al*. [11], where elements exceeding yield stress were excluded. The results of this research bring us a step closer to the actual clinical situation compared to other conventional models without considering influence of displacement. Second, we are able to modify models that allow evaluation of a single factor, while neutralizing the effect of other factors. Third, we can effectively visualize 3D motion, such as sliding, rotation, medial cortical loss, and cutout under steadily increasing stress. Fourth, rotational displacement of the femoral head, or bony contact can be calculated, as this motion is difficult to evaluate in simple radiograph images.

Limitations

This study has its limitations. First, external force was restricted in number from the models. We initiated an innovative 'breakdown' technique in this simplified structure. Second, linearly increased loading was one directional. However, Schmidt., *et al.* [28] suggested that their simulation system under one way static loading showed similar results to that of cyclic loading regarding stress values of peak loading. Further studies should be conducted under repeated dynamic walking stress. Third, a particular limitation of our bone model is that the actual macroscopic property of cancellous bone, which is orthotropic, was not taken into account (i.e. isotropic and heterogeneous properties were assumed for both cortical and cancellous bone). This drawback is uncontrollable, based on the current technical standard.

Conclusion

Our study presents the following valuable biomechanical information: (1) cutout mechanism starts with sliding, rotation, cancellous bone destruction around the lag screw near the fracture site, loss of medial cortical support, and varus; (2) anatomical reduction of subtype N is preferable to posteriorly displaced subtype P in regards to occurrence of cutout complications; and (3) rotation and losing of medial cortical contact is one of the precedent risks for cutout, and innovative implants should be aimed to control this movement.

Conflict of Interest

There are no financial interest or any conflict of interest exists.

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