

Development of an Animal Fracture Model for Evaluation of Cement Augmentation Femoroplasty: An *In Vitro* Biomechanical Study

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Abstract

Osteoporotic hip fracture is the most severe kind of fracture with high morbidity and mortality. Patients' ambulation and quality of life are significantly affected by the fracture because only 50% regain their prefracture functional status, even if they undergo surgeries. There are many issues associated with the current preventive methods e.g., cost, side effects, patient compliance, and time for onset of action. Femoroplasty, the injection of bone cement into the proximal femur to augment femoral strength and to prevent fracture, has been an option with great potential. However, until now femoroplasty has remained at the stage of biomechanical testing. No *in vivo* study has evaluated its safety and effectiveness; there is not even an animal model for such investigations. The objective of this study was to develop a proximal femur fracture goat model that consistently fractures at the proximal femur when subject to vertical load, simulating osteoporotic hip fractures in human. Six pairs of fresh frozen mature Chinese goats' femora were obtained and randomly assigned into two groups. For the experimental group, a cylindrical bone defect was created at the proximal femur, while the control was left untreated. In addition, a configuration to mimic the mechanical axis of the goat femur was developed. When subjected to load along the mechanical axis, all the specimens from the bone defect group experienced femoral neck fractures, while fractures occurred at the femoral neck or other sites of the proximal femur in the control group. The biomechanical property (failure load) of the bone defect specimens was significantly lower than that of the control specimens ($p < 0.05$). Osteoporotic hip fractures of humans were simulated by a goat fracture model, which may serve as a reference for future femoroplasty studies *in vivo*. The newly developed configuration simulating a femoral mechanical axis for biomechanical tests was practicable during the study.

Key words: aging; femur fracture; hip fracture; osteoporosis

Introduction

OSTEOPOROTIC HIP FRACTURE is the most severe kind of fracture caused by osteoporosis. Hip fracture patients have a high mortality rate of up to 30% during the first year after fracture.¹ In addition, their ambulation and quality of life are significantly affected by the fracture, and only 50% regain their prefracture functional status.² This constitutes a significant health problem and a major burden to society. Hence in the past few decades, there have been numerous attempts to improve the management of these fractures, both through surgical treatment and preventive measures.

The currently available methods of prevention include noninvasive physical protection and various pharmacological agents. Padded hip protectors and energy-absorbing mat-

tresses have been shown to have limited effectiveness in reducing hip fractures.³⁻⁵ An array of drugs, including calcium, vitamin D, bisphosphonates, and strontium ranelate, have been used to improve bone mineral density, thus decrease the risk of fractures. However, there are many issues associated with the use of these methods (e.g., cost, side effects, patient compliance, and time for onset of action) that can inhibit efficacy.⁶⁻⁸ A logical solution is the development of a prophylactic surgical intervention to increase the strength of the proximal femur and to decrease the risk of fracture. This technique should be quick, easy, and minimally invasive and carry minimal risk to the patients. Femoroplasty, the injection of bone cement into the proximal femur to augment the femur and to prevent fracture, has been an option with great potential.

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Prophylactic bone cement augmentation of proximal femur remains at the stage of biomechanical testing. There have only been some *in vitro* studies in cadaveric bone, which showed beneficial effect of femoroplasty in reinforcing bone strength.^{9–13} However, there has not been enough evidence to support its clinical feasibility and benefits. Moreover, its acceptance in clinical application is still hampered by possible adverse effects, which include exothermic reaction during bone cement hardening, the effect on blood supply of bone and adjacent soft tissues, the increase in intramedullary pressure, and the risk of fat embolism.^{10–12} Therefore, before femoroplasty can become a viable clinical option, these potential adverse effects must be investigated with appropriate *in vivo* studies to evaluate the safety issues and therapeutic potential of femoroplasty.

The purpose of this study was to develop an animal model for femoroplasty *in vivo* study. The model can consistently fracture at the proximal femur when subject to load, simulating osteoporotic hip fractures in human. We hypothesize that with a bone defect in the proximal femur, this femur fracture model will serve this purpose well.

Methods and Materials

Six pairs of fresh frozen Chinese mountain goat femurs were utilized in this study. Any focal bone pathology was precluded by using radiographs in two planes. The specimens were divided into two groups. The left femur from each pair served as the bone defect group, and the right femur was left untreated and served as the control. For the bone defect group, a cylindrical bone defect was created through the lateral wall of the proximal femur to the femoral head. Afterward all specimens were subjected to biomechanical tests using the Material Testing System (MTS 858 Mini Bionix, Minneapolis, MN) with a newly created configuration. Based on the concept of the human mechanical axis of the lower extremity, the goat femoral mechanical axis was defined as the line from the center of femoral head to the center of knee. The vertical load was applied through the femoral mechanical axis until fractures occurred.

Creating a bone defect

First each femur from bone defect group was fixed on the experiment table, simulating the position of human surgery. The entry point was defined by the line passing through the greater trochanter along the long axis of the bone at the level of lesser trochanter. A hole was made at this point with a 5-mm-diameter bone drill. A 4-cm-long cylindrical cancellous bone defect at an angle of 45° to the longitudinal axis of the femur was then made with a 5-mm-diameter burr, reaching the dense cancellous bone in the femoral head (Fig. 1).

Biomechanical testing

All femora were stored in sealed plastic bags at –20°C after the development of bone defect until 1 day before biomechanical testing, at which time they were removed from the freezer and allowed to thaw overnight to room temperature in the same sealed plastic bags.

Biomechanical tests were performed in a configuration that simulated the mechanical axis of the goat femur (Fig. 2). The distal femur of the specimen was embedded into a cylindrical tray with Huntsman glue mixture (Araldite AW2104+ Hardener HW2934, Huntsman, Switzerland). The femoral shaft was oriented so that the center of femoral head and the center of the knee joint were located in the same vertical line, which represented the biomechanical axis for load testing. The specimens were left wrapped in gauze soaked in saline solution for 24 h to ensure glue fixation of the distal end of femur. The whole construct was placed in a servo hydraulic grip control testing machine (MTS 858 Mini Bionix) under a custom-made stainless steel spherical pressing shell. The femoral head was preloaded to 40 N through the pressing shell attached to the actuator of MTS. The actuator was displaced downward at a rate of 1 mm/s until failure occurred (Fig. 3). The fracture position and fracture load were recorded.

Statistical analysis

Significant differences, defined by $p < 0.05$, in the variables of interest (fracture load, yield load) between the bone defect group and the control group using paired *t*-tests. All statistical calculations were performed with SPSS version 15 software (SPSS Inc., Chicago, IL).

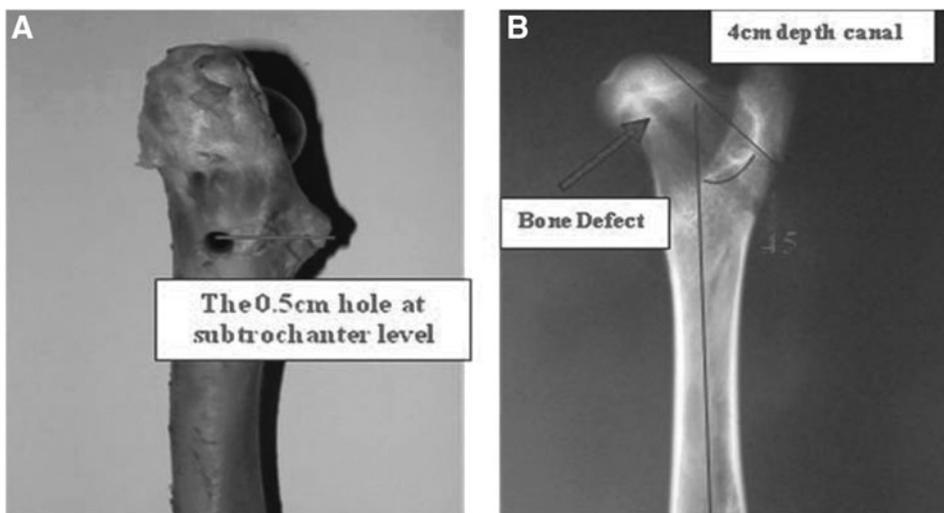
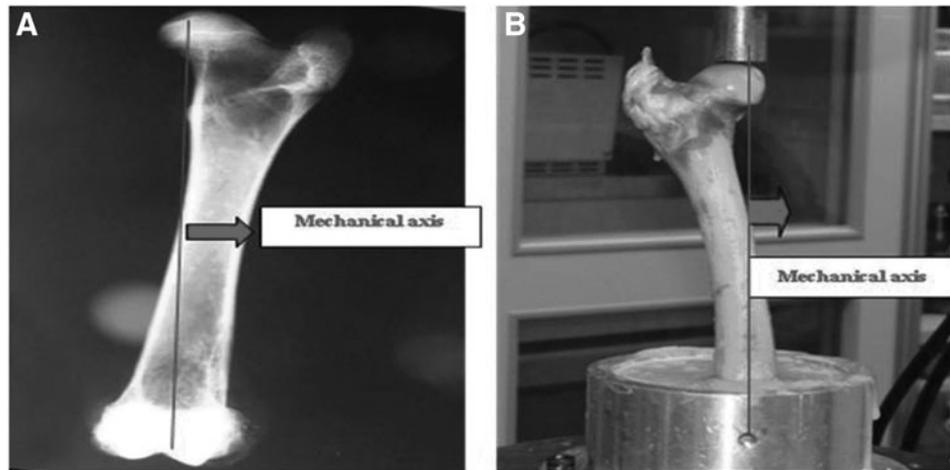


FIG. 1. (A) The entry point was defined by the line passing through the greater trochanter along the long axis of the bone at the level of lesser trochanter. A cylindrical cancellous bone defect, 4.0 cm long at an angle of 45° to the longitudinal axis of the femur, was then made with a 5-mm-diameter burr, reaching the dense cancellous bone in the femoral head. (B) The bone defect under X-ray.

FIG. 2. (A) Mechanical axis under X-ray. (B) Setup for mechanical testing: the center of the femoral head and the midpoint between femoral entepicondyle and the lateral epicondyle were located in the same vertical line.



Results

All six specimens from the bone defect group fractured at the femoral neck (Fig. 3), while fractures occurred at the femoral neck or other sites of proximal femur in the control group.

For biomechanical properties, the average failure load in the control group was 3635 ± 820 N while 2348 ± 944 N in the bone defect group. The difference regarding yield and failure load between the two groups was significant ($p = 0.030$ and $p = 0.02$, respectively; Fig. 4).

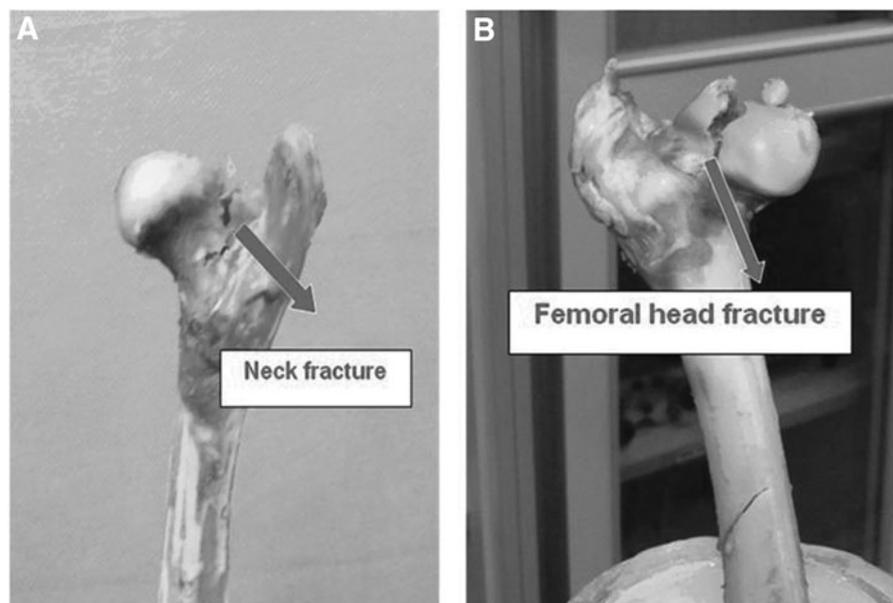
Discussion

Osteoporotic hip fracture is a great challenge to most orthopedic surgeons, and the complication rates after surgery are high. The most effective methods may be preventive procedures. However, the currently available preventive methods, including noninvasive physical protection and various pharmacological agents, are far from ideal and hindered by

adverse effects, patients' compliance, or onset time of action. Hence in the past few decades, doctors have attempted to develop a prophylactic surgical procedure to protect the osteoporotic hip.

In 2004, Heini et al.¹² first reported that femoroplasty, bone cement (polymethylmethacrylate [PMMA]) augmentation of the proximal femur, could reinforce the proximal femur and potentially decrease the risk of hip fracture. Subsequent biomechanical studies further proved that femoroplasty using different bone cements (including PMMA and other bioactive cements) and different augmentation patterns could improve femoral biomechanical properties, decreasing the risk of osteoporotic hip fracture. The side effects related to this surgical procedure were presented and roughly addressed using cadaveric osteoporotic bone. However, until now the safety and feasibility issues had not been addressed *in vivo*; a specific animal model for femoroplasty *in vivo* study did not even exist. To our knowledge, the goat is a well-established animal model to study femoral

FIG. 3. After biomechanical testing, the fractures occurred (A) at the femoral neck in bone defect group and (B) at the femoral head in the control group.



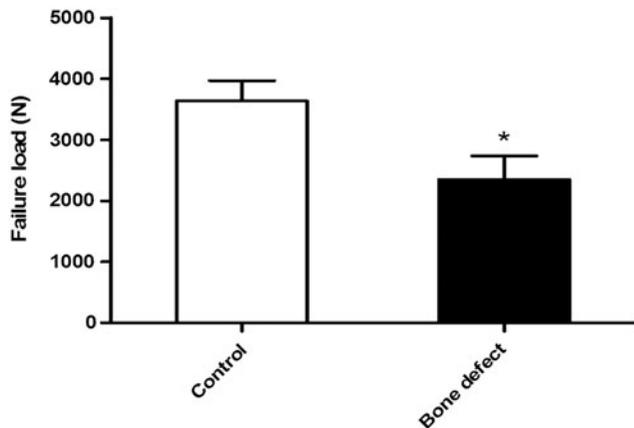


FIG. 4. The failure load in bone defect group was much lower than in the control group. * $p < 0.05$.

head osteonecrosis.^{14,15} So we developed the proximal femur fracture goat model to simulate human osteoporotic hip fracture for future *in vitro* and *in vivo* studies of femoroplasty.

Through creating a cylindrical bone defect in the goat proximal femur, we simulated a fracture. Due to this weak point between the femoral neck and calcar, the bone defect specimens experienced femoral neck fracture. This result was consistent with our original hypothesis. In addition, the fracture load and yield load in the control group were 1.5 and 2.2 times higher, respectively, than in the bone defect group (Fig. 5).

In this study, we aimed to develop an animal model to mimic human hip fracture. The results showed that the goat model consistently fractured at femoral necks when subjected to vertical load, and the fracture line was similar to osteoporotic femoral neck fracture that occurs in humans. In addition, the mechanical axis of the goat femur was tested biomechanically, and the newly developed configuration was practicable during this study.

There are some limitations in this study. First, human osteoporotic hip fracture can hardly be duplicated on a large four-legged animal. Most osteoporotic hip fractures happen

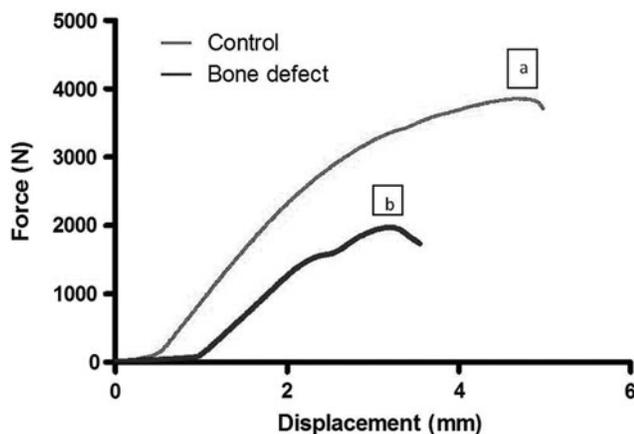


FIG. 5. The representative curves of load versus displacement. Data shown are fracture loads for the control specimens (a) and for the femoroplasty specimens (b).

when individuals sustain low-energy trauma falling from standing height. Goats have little chance of falling on the great trochanter. Second, most human hip fractures are intertrochanteric fractures. Possibly because the goat femur is much shorter than the human femur, this model's fracture location was at the femoral neck rather than the intertrochanteric region. Third, the configuration of falling on the greater trochanter is widely accepted as a test of the biomechanical properties of the femur; however, when it is applied to a goat femur, we found that fracture location was different. So, the configuration of one leg stance was selected. In addition, because osteoporotic goat bone can hardly be obtained, the goat femora used in this study were healthy.

In conclusion, the aim of establishing this goat femoral fracture model was to evaluate the safety and feasibility of femoroplasty. The limitations of this model will not matter too much for further *in vivo* study of femoroplasty.

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Author Disclosure Statement

No competing financial interests exist.

References

- Keene GS, Parker MJ, Pryor GA. Mortality and morbidity after hip fractures. *BMJ*. 1993;307:1248–1250.
- Sernbo I, Johnell O. Consequences of a hip fracture: a prospective study over 1 year. *Osteoporos Int*. 1993;3:148–153.
- Kannus P, Parkkari J, Niemi S, et al. Prevention of hip fracture in elderly people with use of a hip protector. *N Engl J Med*. 2000;343:1506–1513.
- Zacker C, Shea D. An economic evaluation of energy-absorbing flooring to prevent hip fractures. *Int J Technol Assess Health Care*. 1998;14:446–457.
- Sawka AM, Boulos P, Beattie K, et al. Do hip protectors decrease the risk of hip fracture in institutional and community-dwelling elderly? A systematic review and meta-analysis of randomized controlled trials. *Osteoporos Int*. 2005;16:1461–1474.
- Courtney AC, Wachtel EF, Myers ER, Hayes WC. Effects of loading rate on strength of the proximal femur. *Calcif Tissue Int*. 1994;55:53–58.
- Oden ZM, Selvitelli DM, Bouxsein ML. Effect of local density changes on the failure load of the proximal femur. *J Orthop Res* 1999;17:661–667.
- Recker RR, Barger-Lux J. Risedronate for prevention and treatment of osteoporosis in postmenopausal women. *Expert Opin Pharmacother*. 2005;6:465–477.
- Beckmann J, Springorum R, Vettorazzi E, et al. Fracture prevention by femoroplasty—cement augmentation of the proximal femur. *J Orthop Res*. 2011;29:1753–1758.
- Sutter EG, Mears SC, Belkoff SM. A biomechanical evaluation of femoroplasty under simulated fall conditions. *J Orthop Trauma*. 2010;24:95–99.
- Beckmann J, Ferguson SJ, Gebauer M, Luering C, Gasser B, Heini P. Femoroplasty—augmentation of the proximal femur with a composite bone cement—feasibility, biomechanical properties and osteosynthesis potential. *Med Eng Phys*. 2007;29:755–764.

12. Heini PF, Franz T, Fankhauser C, Gasser B, Ganz R. Femoroplasty-augmentation of mechanical properties in the osteoporotic proximal femur: a biomechanical investigation of PMMA reinforcement in cadaver bones. *Clin Biomech* (Bristol, Avon). 2004;19:506–512.
13. Fliri L, Sermon A, Wähnert D, Schmoelz W, Blauth M, Windolf M. Limited V-shaped cement augmentation of the proximal femur to prevent secondary hip fractures. *J Biomater Appl*. 2013;28:136–143.
14. Yang S, Wu X, Mei R, et al. Biomaterial-loaded allograft threaded cage for the treatment of femoral head osteonecrosis in a goat model. *Biotechnol Bioeng*. 2008;100:560–566.
15. Tang TT, Lu B, Yue B, et al. Treatment of osteonecrosis of the femoral head with hBMP-2-gene-modified tissue-engineered bone in goats. *J Bone Joint Surg Br*. 2007;89:127–129.

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Abbreviations Used

MTS = Material Testing System
PMMA = polymethylmethacrylate