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Biomechanical simulation of healing process of fractured femoral shaft applied by composite intramedullary nails according to fracture configuration

Ali Mehboob, Seung-Hwan Chang*

School of Mechanical Engineering, Chung-Ang University, 221, Heukseok-Dong, Dongjak-Gu, Seoul 156-756, Republic of Korea

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A B S T R A C T

Flexible composite implants are receiving increased attention in this modern era of orthopedics for the stabilization of long bone fractures because they facilitate tissue development in calluses. An endochondral ossification process involves generation of calluses, and it is well known that this significantly affects the stabilization and healing of the broken bones. Therefore, the exact configuration of callus formation is highly important for the accurate simulation of bone healing. In this study, finite element analysis was performed to estimate the external callus shape by using the rejection coefficient (RC) algorithm. Regarding the application of a fractured femur by an intramedullary (IM) nail, the bone healing simulation was conducted by employing the biphasic mechano-regulation algorithm according to the fracture type (transverse (0°) and oblique (35°)), fracture location (proximal, medial, and distal ends), and nail property. The simulation results revealed that a glass/polypropylene fabric composite (Twintex $[0]_{2nT}$) IM nail, which has the similar Young's modulus to the cortical bone, provided the most appropriate bio-mechanical environment for bone healing.

1. Introduction

Femur is the most proximal long bone in tetrapod vertebrates and femoral fractures are common among the fractured long bones in the human body. Intramedullary (IM) nails are extensively used for their successful treatment. Intramedullary nail is a metallic rod temporarily or permanently (depending on the fracture's nature) inserted into the medullary cavity of the bone. Depending on their insertion technique they can be categorized as retrograde or antegrade nails. Antegrade femoral nails are inserted from the femoral neck towards knee in proximal-distal direction while retrograde nails are driven backward from the knee towards femoral neck in distal-proximal direction. Technically, retrograde femoral IM nails are more advantageous because of the high rate of fracture union, alignment of the fractured fragments, decreased complications and impressive post-operative results [1–6]. Conventional metallic implants have a high Young's modulus, and thus, tend to bear most of the applied load. The stress reduction at the fracture site during the healing process causes stress shielding that leads to bone resorption resulting in screw loosening, implant failure, mal-union, and occasionally re-fracture [7–10].

Calluses are the transient tissues which are generated at the fractured parts of bones under hematoma (clotted blood) formation. These tissues turn into soft cartilage then woven bone and finally absorbed under remodeling phase, and transforms into the bones when the healing process is done. An appropriate biomechanical environment at the fracture site is much more important, and therefore, flexible composites ensure a better quality callus formation, accompanying the wide bridging, with an improved biomechanical stimulus for the tissue differentiation process in the calluses [11,12]. Therefore, biocompatible composites are of major interest in the current research scenario in biomedical surgery as orthopedic implants to cooperate with the biomechanics of bones [13–17]. Desired mechanical properties of the composites can be realized by simply varying the stacking sequence without disturbing the basic design of the implant [18]. Fiber reinforced polymer composites have been proven as one of the leading candidates for effective bone healing in the field of orthopedic research [19–23].

In most of the computer models of bone fractures, predefined callus geometries have been used to simulate the healing process [24,25]; however, these are unrealistic shapes of the calluses. A few studies have used different algorithms to predict the callus shape using shear strain, fluid flow, and principal strain [26]. Comparative studies have shown that compressive principal strains as well as shear strain are capable of generating the same strain fields under an interfragmentary

* Corresponding author.
E-mail address: phigs4@cau.ac.kr (S.-H. Chang).

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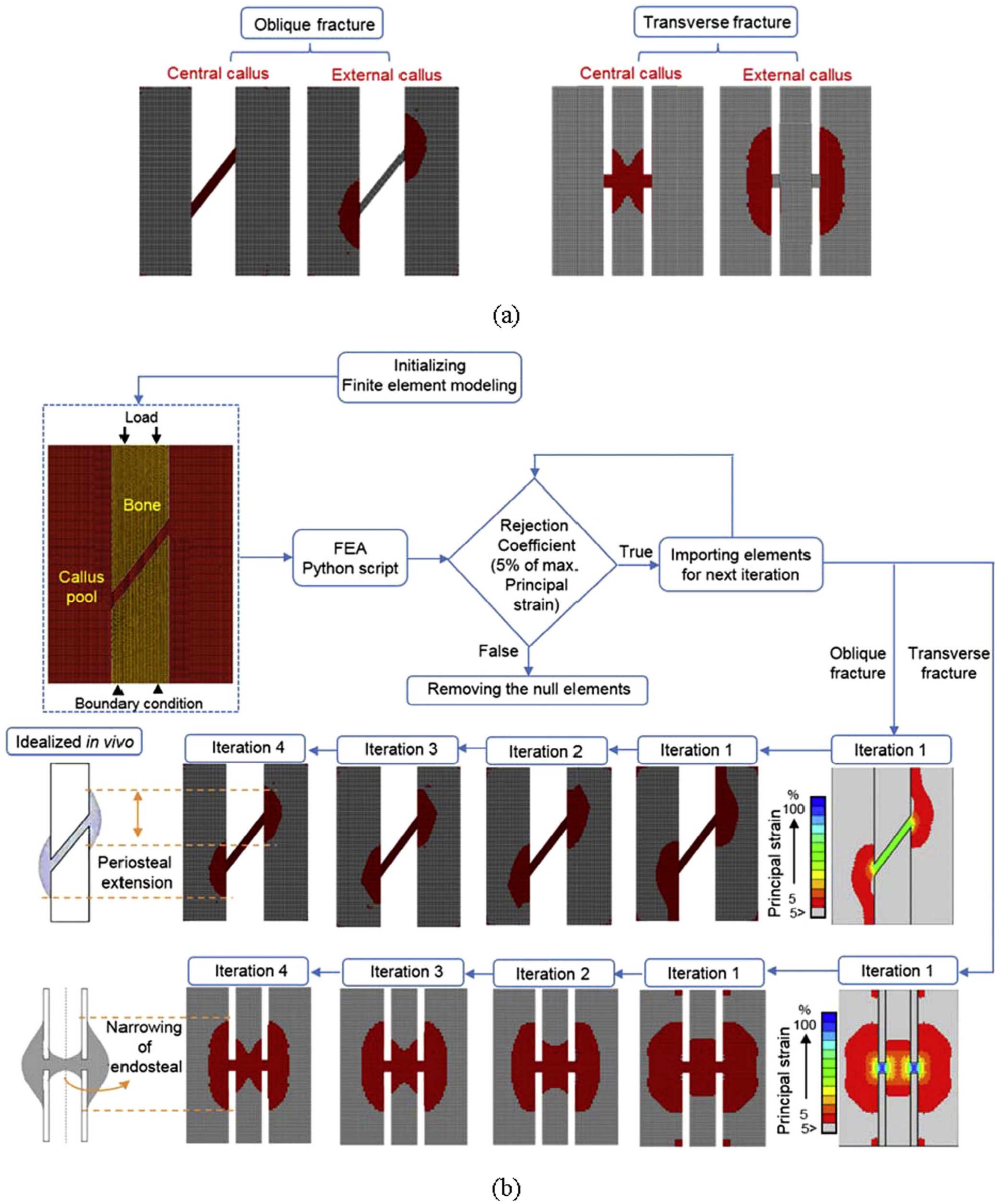

Fig. 1. Prediction of the callus shape according to the fracture configuration; (a) central and external calluses and (b) calibration of the rejection coefficient (RC) algorithm with idealized *in vivo* calluses [26].

compression to predict the callus shape [27]. For the simulation of the tissue differentiation process within the calluses, several simulation techniques using various mechano-regulation algorithms [28–30] have been tested, and recently, a biphasic mechano-regulation algorithm has been successfully used to predict the bone healing process [31,32].

In this study, we have developed a shape prediction algorithm for an external callus using the maximum compressive principal strain for a better estimation of bone healing. Three-dimensional (3D) models of different fracture geometries at various locations in a femoral shaft were constructed to investigate the healing process when composite