Injury, Int. J. Care Injured 47 (2016) 1618–1623

Contents lists available at ScienceDirect

Injury

journal homepage: www.elsevier.com/locate/injury

Finite element analysis of locking plate and two types of intramedullary nails for treating mid-shaft clavicle fractures

Ming Ni[a,b,d,1], Wenxin Niu[c,1], Duo Wai-Chi Wong[d], Wei Zeng[e,f], Jiong Mei[a,*], Ming Zhang[d]

[a] Tongji Hospital, Tongji University School of Medicine, Shanghai, China
[b] Pudong New Area People's Hospital, Shanghai 201299, China
[c] Yangzhi Rehabilitation Hospital, Tongji University School of Medicine, Shanghai, China
[d] Interdisciplinary Division of Biomedical Engineering, The Hong Kong Polytechnic University, Hong Kong SAR, China
[e] CEAS-Biomedical Engineering (BME), University of Cincinnati, 2901 Woodside Dr., Cincinnati, OH 45221, USA
[f] CEAS-School of Aerospace Systems, University of Cincinnati, 2851 Woodside Dr., Cincinnati, OH 45221, USA

A R T I C L E I N F O

Keywords:
Biomechanics
Clavicle fracture
Internal fixation
Plate
Intramedullary nailing
Finite element

A B S T R A C T

Background: Both plate and intramedullary nail fixations, including straight and anatomic nails, have been clinically adopted for the treatment of displaced mid-shaft clavicle fractures. However, the biomechanical performances of these fixations and implants have not been well evaluated. This study aims to compare the construct stability, stress distribution and fracture micro-motion of three fixations based on finite element (FE) method.

Methods: The FE model of clavicle was reconstructed from CT images of a male volunteer. A mid-shaft fracture gap was created in the intact clavicle. Three fixation styles were simulated including locking plate (LP), anatomic intramedullary nail (CRx), and straight intramedullary nail (RCP). Two loading scenarios (axial compression and inferior bending) were applied at the distal end of the clavicle to simulate arm abduction, while the sternal end was fixed.

Results: Under both conditions, the LP was the stiffest, followed by the CRx, and the RCP was the weakest. LP also displayed a more evenly stress distribution for both implant and bone. RCP had a higher stress compared with CRx in both conditions. Moreover, all implants sustained higher stress level under the loading condition of bending than compression.

Conclusions: The plate fixation significantly stabilizes the fracture gap, reduces the implant stress, and serves as the recommended fixation for the mid-shaft clavicle fracture. The CRx is an alternative device to treat clavicle shaft fracture, but the shoulder excessive activities should be avoided after operation.

Introduction

Clavicle fractures accounts for around 4% of all fractures and approximately 80% of clavicle fractures occurs at the mid-shaft [1,2]. Clavicle fractures can be caused by falls from substantial height, traffic accidents, or sport injuries [3]. The primary treatment objective is to facilitate reduction of fracture and provide adequate fixation, preferably minimally invasive. Traditionally, non-operative management has been recommended to treat mid-shaft clavicle fracture, regardless of the degree of fracture displacement [4]. However, there is growing awareness that the outcome of conservative treatment is not as satisfactory as expected [5]. Complications (e.g., delayed union, nonunion) and shoulder pain and weakness, were discovered and reported at a high rate with non-operative management [6,7].

Surgical management of middle-shaft clavicle fractures involves various techniques. Plate fixation is considered as the gold standard for clavicle fracture since it can provide sufficient reduction and stabilization [8]. However, plate fixation requires a larger exposure and significant soft tissue stripping, which may compromise the blood supply to the clavicle and interfere with bone healing. Intramedullary fixation is another option, which can be accomplished with less soft tissue dissection and more cosmetic incisions. A variety of pin fixation devices, such as Steinman pin, Hagie pin, Rockwood clavicle pins (RCP), and elastic titanium nails, have been utilized so far. However, few of them can provide sufficient stability under physiologic conditions [9]. This could possibly lead to some complications, such as migration of device

* Corresponding author at: Department of Orthopaedics, Tongji Hospital, Tongji University School of Medicine, Shanghai, China.
E-mail address: meijiong@163.com (J. Mei).

[1] These authors contributed equally to this work.

http://dx.doi.org/10.1016/j.injury.2016.06.004

and soft-tissue irritation due to protruding hardware at the insertion site.

In response to drawbacks with RCP, a new intramedullary device, Sonoma CRx has recently been introduced [10]. It has a flexible shaft allowing itself to accommodate the curvature of the clavicle. The flexible shaft can be activated to become rigid once fracture reduction is completed. The grippers and interlocking screw at two ends can provide additional rotational and axial stability. The device asserted to stabilize the fracture site and control rotation efficiently, thereby reduce the risk of subsequent complications [11]. However, its biomechanical stability has not been extensively investigated, particularly in comparison with traditional intramedullary pins and plate fixation.

Sometimes it is difficult or infeasible to assess biomechanical stability of an implant or surgical protocols by means of clinical investigations and *in-vitro* studies. Finite element (FE) method, as a powerful computational tool, has gained wide acceptance in orthopedics research. FE method is able to quantitatively study the stress distribution of the inner and complex bone structures, adaptation of bone after damage, and optimal design of orthopedic implants [12–14]. In addition, FE analysis allows the control of condition parameters, such as loading forces, fracture type, and fixation implants to better predict the surgical outcomes than experiments using cadaveric specimens.

The purpose of this study includes: 1) to compare the biomechanics of the plate, CRx, and RCP fixation; and 2) to investigate the sensitivity of implant geometry and position on fracture stability by FE method. Construct stiffness, implant stress, and fracture micro-motion would be evaluated. We hypothesized that plate fixation would provide better stabilization, reduce implant stress, and may be potentially suitable for the treatment of mid-shaft clavicle fractures.

Material and methods

Finite element modeling

The serial CT images of the clavicle were acquired from a male volunteer (age: 45 years; weight: 60 kg; and height: 176 cm). The slice thickness of the CT images was 0.75 mm in a 512 × 512 matrix. The DICOM data were imported into Mimics 15.0 software (Materialise, Belgium) to reconstruct the geometry of the clavicle. The clavicle bone was segmented into 2 partitions, the cortical layer and cancellous core, using a threshold of 600 Hounsfield units [15]. The material of the cortical and cancellous bone was assumed homogeneous and isotropic.

Three types of fixation/implants were modeled and simulated: Locking Plate (LP), Sonoma intramedullary nail (CRx) and Rockwood clavicle pin (RCP). The three dimensional models of plate and intramedullary nails were drawn according to the manufacturers' specifications using software Solidworks 2014 (Dassault Systemes Solid-works Corp., USA). The locking plate was modeled from a 3.5-mm plate (Trauson, China) and the screws were modeled as 3.5-mm diameter solid cylinders. The intramedullary implants include CRx (Sonoma Orthopedic Products Inc., Santa Rosa, CA, USA), and RCP (DePuy, Warsaw, Indianan). The CRx was 120-mm long with a distal transverse locking screw on a shaft curved distally at 4.2-mm diameter. The RCP was 4.5 mm in diameter and 110 mm in length.

To simulate clavicle fracture, a transverse gap of 0.5 mm was created on the mid-shaft of the clavicle. The implants were then positioned across the gap. For the LP fixation, the plate was positioned on the superior surface of the clavicle according to recommended surgical guidelines (Fig. 1a). The CRx and RCP were positioned as recommended by the manufacturers as demonstrated in Fig. 1b and c.

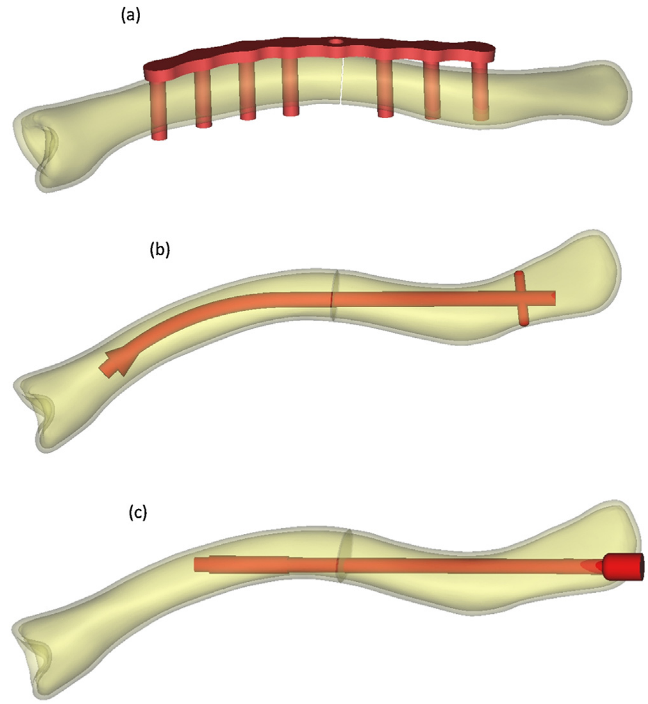

Fig. 1. Finite element model of mid-shaft clavicle fractures fixed by the locking plate (LP, a), Sonamora CRx (b), and Rockwood clavicle pin (RCP, c).

The models were processed by Geomagic Studio 10.01 (3D System Inc., Rock Hill, SC, USA) and then, were input to the FE software ABAQUS 6.14 (Dassault Systems, Simulia Corp., RI, USA), through which the models were assembled and meshed with four-node tetrahedral three-dimensional elements. The numbers of nodes and elements of clavicle and implants are shown in Table 1. A mesh convergence test was conducted so that the deviation was less than 2%.

In this study, the mechanical properties of clavicle and implants were adopted from previous published reports [16,17] (Table 2). All contact pairs were assigned with 0.3 coefficient of friction [18], except that the bone-implant interfaces were tied.

Boundary and loading conditions

Two types of boundary and loading conditions (axial compression and inferior bending) were used by Favre et al. [19]. Both conditions applied a total force of 100 N at the distal part of the clavicle [20,21] as illustrated in Fig. 2. The sternal end of the clavicle was fixed in all degrees of freedom.

Analysis and validation

The FE analysis was conducted using ABAQUS 6.14. The construct stiffness was defined by the ratio of applied load to the displacement of the distal clavicle at the load direction [17]. The fracture micro-motion was calculated according to the change of fracture gaps after load-bearing. The von Mises stresses of the clavicle and implants were also analyzed.

Table 1
Numbers of nodes and elements of bone and implants.

Model	Bone	LP	CRx	RCP
Node	7385	11,632	9634	5523
Element	36,949	58,522	44,588	24,789

LP = locking plate. CRx = Sonoma intramedullary nail. RCP = Rockwood clavicle pin.