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A novel motorized bending apparatus for surgical plates †

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Abstract

Surgical plates, which are used in various bone reconstruction surgeries, must be accurately bent intraoperatively or preoperatively. Manual bending is a time- and labor-consuming process, which sometimes results in residual stress to the plate after repeated operations. To overcome these problems, we propose a motorized bending apparatus for surgical plates that can automatically bend the plates to the target angle in a single trial, which may reduce the residual stress. Finite element analysis (FEA) was used to compensate for the spring-back and provide the proper inputs. To evaluate the performance of the apparatus, we performed tests with five reconstruction plates in the manual bending group and the apparatus-bending group, respectively, for angles of 15° and 30°. The apparatus-bending showed improved accuracy and precision. Also, the apparatus took much shorter times to perform the same tasks. The proposed method should reduce the surgical preparation time and provide convenience to surgeons.

Keywords: Automatic; Bending; Motorized; Surgical plate

1. Introduction

Surgical plates are used to bridge defects, fix fractures, or graft bones in orthopedic, cranio-maxillofacial, and plastic surgeries. For example, a titanium plate is used to secure the graft to the mandibular ramus in mandibular condyle reconstruction surgery [1]. In general, reconstruction plates are bent to adapt to the bone shape, and the bending is performed manually by surgeons using special bending forceps [2]. However, this method involves multiple bending that results in residual stresses that eventually cause plate fractures [3]. This can reduce the life spans of plates and lead to severe traumas after the surgery. For example, plate removal due to plate fracture occurs in 3-18 % of mandibular reconstruction surgeries [4-8]. Moreover, the shape accuracy of the bent plate can vary depending on the surgeon's proficiency. It is important to bend the plate to the accurate target angle because any inaccuracy in the structure of the bent plate may cause functional and aesthetic errors due to malocclusion or temporomandibular disorders [9]. Inaccurate surgical results are usually caused by the variability of the anatomy between individuals [10]. Manual bending methods also require effort on the part of the surgeon to prepare the surgical plate intraoperatively or preoperatively, which may be a time consuming and bothersome burden to surgeons.

To address these problems, there have been numerous engineering attempts concerned with the plate bending. For example, Jeong et al. used a 3D printed plastic clavicle model for the plate pre-bending [11]. The clavicular locking plates were contoured to a 3D printed plastic model before the surgery, which brought about the benefit of accurate prebending with low costs in a short time. However, even if this method is better than an indirect reduction, it inevitably involves the occurrence of multiple manual bending processes to contour the plate to the complex shape of the clavicle. Similarly, in terms of using the 3D printing technology, Mazzoniet al. designed and manufactured CAD-CAM cutting guides and customized titanium plates for upper maxilla waferless repositioning [12]. By this method, the accurate reproduction of preoperative virtual planning was possible. Nonetheless, the use of 3D printing techniques has the drawbacks of additional costs compared to conventional methods, unsatisfying properties of the printed object, and problems with sterilization as some 3D objects cannot be sterilized [13].

Considering all these problems together, there is a need to develop a new method to bend conventional surgical plates

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accurately in a single step. In this study, we propose a novel motorized surgical plate-bending apparatus that automatically bends the plate to a target angle with a single trial. The contribution of this research is adopting motorized apparatus to surgical plate bending which has been performed manually. To the best of our knowledge and the literature review, this research is the first attempt to apply an automated bending apparatus to surgical plates. Existing industrial tube-bending is not appropriate for surgical plates because its size and accuracy scale are generally large. The proposed apparatus can improve postoperative results by preventing plate fracture caused by residual stress from multiple bending, and it provides convenience to surgeons. Also the accuracy and the precision of the bending can be enhanced with the apparatus, which is a great advantage since it is important to bend surgical plate precisely. We conducted the iterative finite element analysis (FEA) to compensate for the spring-back and bend the plate accurately.

There are three types of bending: in-plane bending, out-of-plane bending, and torqueing [14]. To show the feasibility of the proposed method, we initially considered the out-of-plane bending before attempting the complex multi-axis forms.

In the next part, we introduce the design of the apparatus and show how it bends the plate with an illustration of the bending process. With the designed apparatus, we conducted plate bending tests to evaluate its performance and determine whether it can bend the plate accurately with a single trial. The resultant angles of plates, which were bent manually and with the apparatus, were compared to evaluate the angular accuracy and precision of the apparatus. Also, the times required to perform the same task were comparatively evaluated.

2. Methods

2.1 Design of the apparatus

The overall design with the schematic system diagram and the prototype of the apparatus are shown in Fig. 1. The hardware consists of the power supply (LRS-150F-24, Mean Well, Taiwan), the microcontroller (Arduino UNO, Arduino, Italy), the motor driver (MD5-HD14, Autonics, Korea), the geared stepper motor (A200K-599-G10, Autonics, Korea), and the bending mechanism at the top of the apparatus body. The bending mechanism includes the clamp base, the pusher plate, the clamp, and the rotary knob, which are components that directly interact with the subject plate. The stepper motor is connected to the rotary knob so that the motor rotates the rotary knob. The further detailed specifications of the motor and the driver are listed in Table 1.

The process of plate bending is represented in Fig. 2. It starts with positioning the plate at the top element of the apparatus between the clamp base and the pusher plate. The pusher plate is movable so that different kinds of surgical plates with various thicknesses can be covered. The target bending point is positioned at the edge end point of the clamp base. Multiple points at the plate can be bent by changing the position of the

Table 1. Specifications of the stepper motor and the motor driver.

Stepper motor

Model	A200K-M599(W)-G10
Frame size	85 mm
Operation type	Planetary geared type
Phase	5-phase
Max. holding torque	200 kgf·cm (20 N·m)
Rotor moment of inertial	2700 g·cm^2 (2700×10^{-7} kg·m^2)
Rated current	1.4 A/Phase
Basic step angle	0.072° (full step)
Permissible speed range	0 to 180 rpm
Backlash [min]	±15′ (0.25°)
Stop angle error	±3′ (±0.05°)

Motor driver

Model	MD5-HD14
Max. current consumption	3 A
RUN current	0.4-1.4 A/phase
STOP current	27–90 % of RUN current
Drive method	Bipolar constant current pentagon drive
Basic step angle	0.72°/step
Resolution	1, 2, 4, 5, 8, 10, 16, 20, 25, 40, 50, 80, 100, 125, 200, 250-division (0.72° to 0.00288°/step)

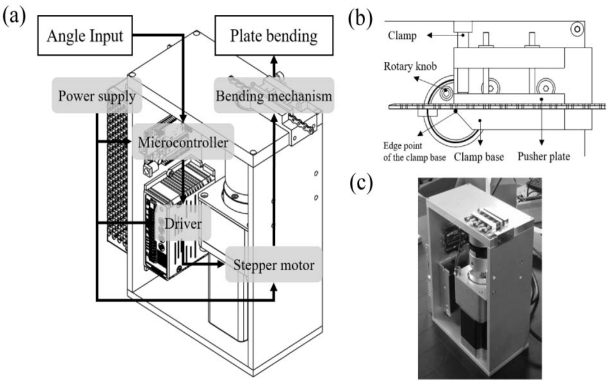

Fig. 1. Design of the apparatus: (a) The perspective view and the schematic system diagram; (b) components of the bending mechanism; (c) the prototype of the apparatus.

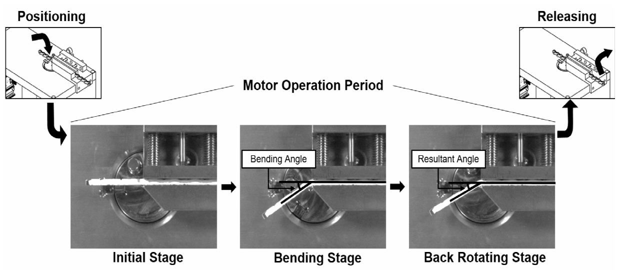

Fig. 2. Plate bending process by the rotation of the rotary knob.

plate. The plate is fixed by tightening the clamp, which is the initial stage of the bending process. When the target angle is input, the apparatus starts to work. The rotary knob is rotated by the motor by a pre-calculated amount to bend the plate to the target angle. This rotation of the rotary knob bends the plate (bending stage). The angle of the bent plate at this stage is termed the 'bending angle'. After holding for five seconds, the rotary knob rotates back to the initial position (back rotating stage). The final angle of the bent plate is termed the 'resultant angle'.

There is a phenomenon called 'spring-back' which is defined as the change in a deformed part from a target configuration after unloading the external force [15]. It makes the bent plate springs back somewhat when the rotary knob moves back from the surface of the plate. Because of this spring-back, an angular difference occurs between the bending angle and the resultant angle after the back rotating stage. This bending procedure without considering the spring-back may not provide a well-fitted plate shape. To accurately bend the plate to the target angle, we have also conducted the iterative FEA for the input angle considering the spring-back effect. Practical solutions to spring-back have two strategies: reducing spring-back by applying tension during the bending process, or compensation by bending with intended errors calculated from spring-back prediction to achieve a target final shape [16]. The iterative FEA approach employed in this research is based on the latter strategy.

In the FEA bending simulation, the 3D components of the same geometry and material properties as the actual bending apparatus and surgical plate were used. We assigned SUS303 and Titanium grade 3 for the bending apparatus and surgical plate, respectively, and assumed isotropic and homogeneous properties. Each part was divided into four-node tetrahedral structural elements. The bending region of the plate was especially set to a fine mesh size (0.2 mm) through the mesh convergence test for accurate analysis results. Each iterative calculation was conducted using Abaqus v.6.14 (Dassault Systèmes SIMULIA Corp., Providence, RI, USA) in the following two steps same as the actual bending: (1) Loading the plate by rotating the knob (bending stage in Fig. 2) and (2) removing the load by allowing the knob to return (back rotating stage in Fig. 2). The bending angle measured at each step was recorded. The difference between them indicated the amount of the predicted spring-back. The input angle to bending apparatus was updated by applying the Newton-Raphson method until the appropriate convergence criteria (the difference between the target angle and the resultant angle in each step are less than 0.05°). Based on the result of the simulations performed on the two arbitrary target angles (15° and 30°), 18.33° and 33.65° were used for the input angles, respectively.

2.2 Experiments

To confirm whether the apparatus can bend the plate to the target angle at a single trial, five reconstruction plates (Leforte System Bone Plate 24-RS-015, Jeil Medical Corp., Seoul, Korea) were bent to 15° and five other plates were bent to 30° with the apparatus. We used this plate because it is difficult to bend manually since its material property is titanium grade 3. We referenced a patented manual bender for surgical plate [17] to select 15° and 30° as the target angles. It is stated that bend of 10° to 15° can be performed manually with the bender. We chose 15° to show that our apparatus can bend as much as the currently used plate bender. In addition, we chose 30° for an angle larger than 15°.

The accuracy and precision of the apparatus were assessed by comparing the resultant angles of apparatus-bent plates (apparatus-bending group) with the results of manually bent plates (manual bending group). For the manual bending group, a skilled clinical assistant professor bent five plates with manual plate benders (111-033 and 111-034, Jeil Medical Corp., Seoul, Korea). The manual bending was performed with a 3D printed template which has corners of 15° and 30°. This procedure is similar to the traditional manual plate bending operation. After the plates were bent, they were photographed and the resultant angles were measured with angle measurement software ImageJ (Rasband, ImageJ, U. S. National Institutes of Health, Bethesda, Maryland, USA, https://imagej.nih.gov/ij/, 1997-2016).

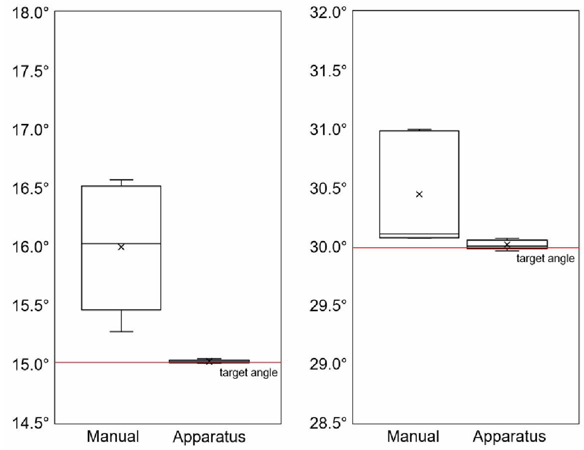

Fig. 3. Resultant angles of the plates in the manual bending group and the apparatus-bending group.

3. Results and discussion

As demonstrated in Fig. 2, the rotation of the rotary knob bent the reconstruction plate by transferring the power from the stepping motor. The apparatus was able to bend the subject reconstruction plate in a single operation. Bending the plates in a single step with the apparatus may reduce the residual stress of the plates, which can increase their life spans and decrease additional traumas after surgeries.

Fig. 3 shows the measured resultant angle of the plates in the manual bending group and the apparatus-bending group

Table 2. Values concerned with the resultant angles in the manual bending group and the apparatus-bending group.

Manual bending group

Target angle	15°	30°
Average	16.00°	30.45°
Standard deviation	0.55	0.49
Average difference with target	+1.00°	+0.45°
Max difference with target*	+1.57°	+1.00°

Apparatus-bending group

Target angle	15°	30°
Average	15.02°	30.02°
Standard deviation	0.01	0.04
Average difference with target	+0.02°	+0.02°
Max difference with target*	+0.05°	+0.07°

*The "max difference" indicates that its absolute value is the maximum.

when the target angles were 15° and 30°, respectively. It shows that the average value, which is marked with an 'X' sign, is closer to the target angle in the apparatus-bending group than in the manual bending group. Also, the standard deviation was smaller in the apparatus-bending group as shown by the fact that the box is more squashed than in the manual bending group.

The specific values associated with the resultant angles are presented in Table 2. The average differences between the resultant angle and the target angle decreased by 98 % (from +1.00° to +0.02°) and 95.56 % (from +0.45° to +0.02°) in the apparatus-bending group for the case of 15° and 30°, respectively. Likewise, the maximum angular differences between the resultant angle and the target angle were decreased in the apparatus-bending group for all target angle cases. The results generally showed drastic improvement of angular accuracy in the apparatus-bending group. The standard deviations decreased by 98.18 % (from 0.55 to 0.01) and 91.84 % (from 0.49 to 0.04) in the apparatus-bending group for the case of 15° and 30°, respectively. Some parts of the deviations and the differences with the target angle might be caused by the angle measurement error. However, the error seemed to be slight in that the maximum difference and the standard deviation is less than 1° in the apparatus-bending group.

In the test of manual bending three points of five reconstruction plates, it took 243, 256, 164, 159 and 151 s, respectively for each of the five plates. It typically took from 50 to 85 s to manually bend one point. Compared with this, it took only 7 s to bend the plate at one point with the apparatus. Hence, the apparatus can reduce the preoperative preparation time to bend the plate and also provide convenience to surgeons.

We only tried the target angle cases of 15° and 30° in this study. A wider target angle range could be attempted for further study with advanced FEA to predict spring-backs. Also, other types of bending, such as in-plane bending and torqueing, need to be investigated further.

4. Conclusions

The traditional surgical plate manual bending method requires multiple bending trials to adapt the plate, causing residual stresses in the plate that eventually result in fractures in the worst case. Moreover, the accuracy and the precision of the bent plate will vary depending on who bends the plate, and preparing the plates is a time-consuming and annoying tasks for the surgeons. In this study, we propose a motorized bending apparatus for surgical plates to solve these problems.

The apparatus was designed to bend the plate by means of the rotation of a knob by a motor. The angular value data from FEA was used to compute exact inputs considering the spring-back. The designed apparatus could automatically bend the plates to the target angle in a single trial, which may reduce the residual stresses. From the tests with five reconstruction plates in the manual bending group and the apparatus-bending group for the target angles of 15° and 30°, the apparatus-bending showed greatly improved accuracy (over 95 % improvement) and precision (over 90 % improvement) compared with manual bending. Further, the time required to bend the plate was dramatically reduced. This can shorten the preoperative or intraoperative preparation times and provide convenience to surgeons.

Acknowledgments

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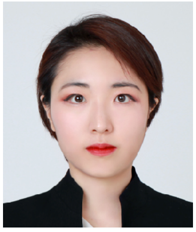

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