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Practical bending-angle calculation for an automated surgical plate bending apparatus

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Abstract Surgical plates used for reconstructive surgery require a repetitive manual bending process to fit the plate to the defect during reconstruction. However, this process may not produce a plate that fits well, and repetitive bending may significantly increase the risk of plate fracture due to the accumulation of residual stress. In this study, the input angle is calculated using a proposed finite element process that considers the spring-back effect and improves the accuracy of the bending results without the need for repetitive bending. Bending tests for two arbitrary target angles (15° and 30°) are performed using the apparatus to demonstrate its effectiveness. Accurately bent plates are obtained from a single bending trial, unlike the use of another input angle that does not consider spring-back. Therefore, the proposed bending procedure could potentially replace the repetitive manual bending process and reduce the residual stress within the plate, thus lowering the risk of plate failure.

1. Introduction

Surgical plates are widely used in orthopedic, oral, maxillofacial, plastic, and other forms of reconstructive surgery. During surgery, a plate is generally required to undergo repetitive manual bending in order for it to fit the defect, a process conducted by the surgeon using tools such as a bending press or bending iron. This process typically involves multiple trials to fit the plate to the shape of the surgical area; this repetitive bending not only prolongs the operating time but also reduces the life of the plate [1]. Plate removal due to fracture is required in 3–18 % of mandibular reconstruction surgeries [2-6], and one of the major causes of these fractures is the residual stress in the plate that accumulates during repeated bending. Martola et al. reported that the adjustive bending of plates during surgical operations generates residual stress, eventually resulting in the fracture of the plate [7]. Using finite element (FE) analysis, we have also previously demonstrated that the residual stress in a plate generated during the bending process adversely affects plate stability [8]. It is thus crucial to bend the plate to the desired angle in a single trial to minimize the risk of plate fracture and the need for additional surgery.

In the bending procedure, spring-back occurs when the bending load is removed; as such, the final bent angle is lower than the input angle. To obtain the desired angle in a single trial, the input angle must be greater than the target angle to compensate for spring-back. However, there is no practical way to predict the input angle required because the degree of spring-back varies with the material, bending angle, and plate geometry [9-12]. Conventional trial-and-error methods are based on a table of empirical input and final bent angles for specific plates, but this method is time-consuming and expensive. Additionally, empirical rule-based adjustments for spring-back may not apply to complicated plate geometries [13, 14]. Various numerical approaches to estimating the amount of spring-back based on FE analysis have been reported

Table 1. Specification of the components used for the motorized bending apparatus.

Component	Model
Power supply	LRS-150F-24, Mean Well, Taiwan
Microcontroller	Arduino UNO, Arduino, Italy
Motor driver	MD5-HD14, Autonics, Korea
Geared stepper motor	A200K-599-G10, Autonics, Korea
Bending element	Clamp, clamp base, pusher plate, rotary knob

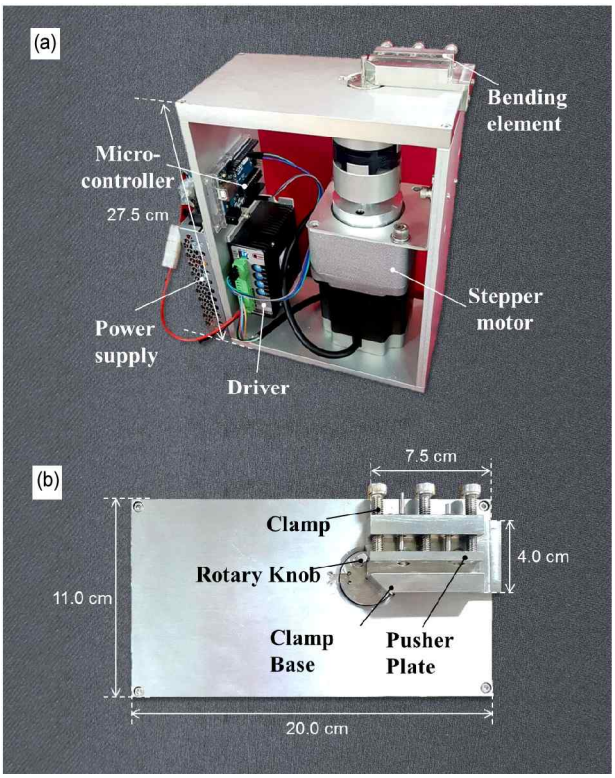


Fig. 1. The proposed motorized bending apparatus: (a) Overall appearance; (b) top view of the components of the bending element.

[15-18]; however, these cannot be directly used to calculate the required input angle to compensate for spring-back. Rather, they are frequently used to calculate the amount of spring-back for a given input angle.

In this paper, we propose an iterative FE procedure to calculate the input bending angle to achieve the desired bending angle after spring-back. This is based on a plate-bending procedure using a motorized bending apparatus that we developed in a previous study [19]. As shown in Fig. 1 and Table 1, the motorized bending apparatus consists of a power supply, microcontroller, motor driver, geared stepper motor, and bending element. In the bending process, a surgical plate is fixed by tightening the clamp of the bending element. The stepper motor is connected to the rotary knob so that the motor rotates the knob by the set input angle. After holding this position for 5 seconds, the rotary knob rotates back to the initial position, which is when spring-back occurs. Further details on the motorized bending apparatus are provided in Ref. [19].

In the proposed bending-angle calculation, the optimal input angle is obtained using iterative FE analysis to predict the relationship between the input bending angle and the final bent angle after spring-back. To assess the performance of the proposed approach, experiments with two different target angles are conducted in the present study.

2. Material and method

2.1 Initial input-angle calculation based on geometric information

The bending angle α is a function of the rotating angle of the knob θ, the geometry $\mathbf{G}$, and the material properties $\mathbf{M}$:

$$\alpha = F(\theta, \mathbf{G}, \mathbf{M}) . \tag{1}$$

In general, Eq. (1) is a complex nonlinear function with many specific variables due to the complex nature of $\mathbf{G}$ and $\mathbf{M}$. To produce the desired bending angle α_D, we need to satisfy

$$\alpha_D = F(\theta_D, \mathbf{G}_D, \mathbf{M}_D) = F_D , \tag{2}$$

where the input angle θ_D for the desired bending angle α_D is the solution variable to be calculated. Because the bending angle has a non-linear relationship with the input rotating angle, it is necessary to iterate the solution for Eq. (2). Because the desired bending angle α_D is independent of the configuration of the plate or the rotation, the Newton-Raphson iteration for Eq. (2) becomes

$$\Delta F^{(i-1)} = \alpha_D - F_D^{(i-1)} \tag{3}$$

$$K_D^{(i-1)} \Delta\theta^{(i)} = \Delta F^{(i-1)} \tag{4}$$

$$\theta^{(i)} = \theta^{(i-1)} + \Delta\theta^{(i)} \tag{5}$$

with initial guesses $\theta^{(0)} = \theta_0$ and $F_D^{(0)} = \alpha_0$, where the superscript (i) denotes the value for the *i*-th iteration, ΔF is the increase in the bending angle, $\Delta\theta$ is the increase in the input rotating angle, and $K_D^{(i-1)}$ is the current tangent stiffness, leading to

$$K_D^{(i-1)} = \left.\frac{\partial F}{\partial \theta}\right|_{\theta^{(i-1)}} . \tag{6}$$

The iterations continue until the appropriate convergence criteria are satisfied.

A characteristic of this iteration process is that a new tangent stiffness is calculated with each iteration, which is computationally demanding. Moreover, it is not practically feasible to obtain the exact function F in Eq. (1) for a plate with general geometry and material properties; the widely used tables listing empirical values for Eq. (1) have been created only for plates with a specific geometry and material.

In this study, we use an approximated tangent stiffness:

$$K_D^{(i-1)} = \left.\frac{\partial F}{\partial \theta}\right|_{\theta^{(i-1)}} \doteq \frac{\alpha^{(i-1)} - \alpha^{(i-2)}}{\theta^{(i-1)} - \theta^{(i-2)}}. \quad (7)$$

Based on Eqs. (3)-(5), the tangent stiffness in Eq. (7) results in the following simple improved solution:

$$\theta^{(i)} = \theta^{(i-1)} + \frac{\alpha^{(i-1)} - \alpha^{(i-2)}}{\theta^{(i-1)} - \theta^{(i-2)}}(\alpha_D - \alpha^{(i-1)}). \quad (8)$$

Note that, in this iterative process, any computational method can be used in the calculation of the solution at each iteration, and a plate with a generalized geometry and material properties can be considered. For example, as in the present study, at each iteration, commercial FE software can be used to calculate the bending angle after spring-back $\alpha^{(i-1)}$ for the given input rotating angle $\theta^{(i-1)}$ and to update the input rotating angle $\theta^{(i)}$ with a simple user input code representing Eq. (8).

While the final converged solution depends on the accuracy of the solution for each iteration, it is crucial that the initial guesses are close to the final solution to reduce the number of iterations required and to ensure convergence. For the initial guess θ_0, we use a solution that assumes no spring-back, which can be calculated from the geometrical relationship between the bending element in the developed bending apparatus and the plate. Assuming no spring-back, the input rotating angle θ_A required to create plate bending angle α_D is calculated based on the approximated shape of the bent plate shown in Fig. 2 as

$$\theta_A = \pi - \omega - \arcsin\left(\frac{r+s+t}{R}\right) + \alpha_D \quad (9)$$

For iteration $i=1$, we approximate the tangent stiffness K_D^0 as 1, assuming that the incremental amount of spring-back is the same as that of the input angle. The convergence criteria are met when i is greater than 50 or the difference between α_D and $\alpha^{(i)}$ is less than 0.05°. The step-by-step process for the iterative FE process is summarized in Table 2.

2.2 Bending-angle calculation using FE analysis

In this paper, the iterative calculations are conducted using Abaqus v.6.14 (Dassault Systèmes SIMULIA Corp., Providence, RI, USA) for the bending of the reconstruction plate (24-RS-015, JEIL Medical Corp., Korea) with the proposed motorized bending apparatus, consisting of two steps: (1) Loading the plate by rotating the knob and (2) removing the load by allowing the knob to return to its original position. Based on the bending conditions in pracitce, it is assumed that plate bending occurs for a duration of 5 seconds. The bending angles measured at each step are denoted by α_{step1} (the bending angle before spring-back) and α_{step2} (the bending angle after spring-back; $\alpha^{(i)}$); the difference between these indicates the predicted spring-back (α_{sp}). As shown in Fig. 3, the components directly related to plate bending are analyzed: The clamp base, the rotary knob, and the reconstruction plate. The material properties assigned to each component are summarized in Table 3 [20, 21] assuming they are isotropic and homogeneous. Each part is divided into four-node tetrahedral structural elements; the total number of nodes and elements in each model is listed in Table 4. In particular, the bending region of the plate is set to a much denser mesh size than the other parts to ensure accurate analysis: 0.2 mm is selected based on a mesh convergence test considering the convergence of the spring-back angle and computer analysis time.

Table 2. Step-by-step solution.

IF $i=0$ **THEN**
$\theta_i = \theta_A$
ELSE IF $i=1$ **THEN**
$\theta_i = \theta_{i-1} + (\alpha_D - \alpha_i)$
ELSE
DO
$\theta_i = \theta_{i-1} + \frac{(\theta_{i-1} - \theta_{i-2})(\alpha_D - \alpha_{i-1})}{(\alpha_{i-1} - \alpha_{i-2})}$
IF $i \geq 50$ **OR** $|\alpha_D - \alpha_i| < 0.05$ **EXIT**
$i = i+1$
ENDDO
ENDIF

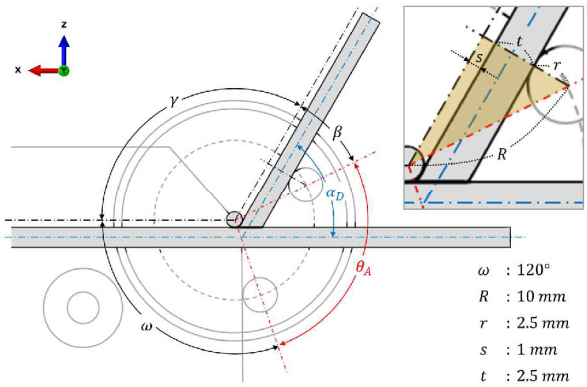


Fig. 2. The geometric relationship between the bending elements of the bending apparatus and the plate.

2.3 Experiments

Experiments are carried out for two target bending angles (15° and 30°). A total of 10 reconstruction plates that are identical to the model used in the angular calculation described above are used. Each plate has two bending regions: Between the sixth and seventh screw-holes on both sides, as shown in Fig. 4. The bending tests using the initial guess input angle (θ_A) and the calculated input angle (θ_{FE}) are conducted on each bending area and the results are compared. Each step is recorded with a camera perpendicular to the bending element

Table 3. Material properties [20, 21].

Material	Young's modulus [MPa]	Poisson ratio	Tensile yield stress [MPa]	Ultimate tensile stress [MPa]
SUS303*	193000	0.25	-	-
Titanium grade 3	116000	0.37	450	550

*SUS303: Plate bender components

Table 4. The number of elements and nodes in the FE model.

Components	Element #	Node #
Clamp base	5616	1490
Rotary knob	5415	1263
Reconstruction plate	611627	106109

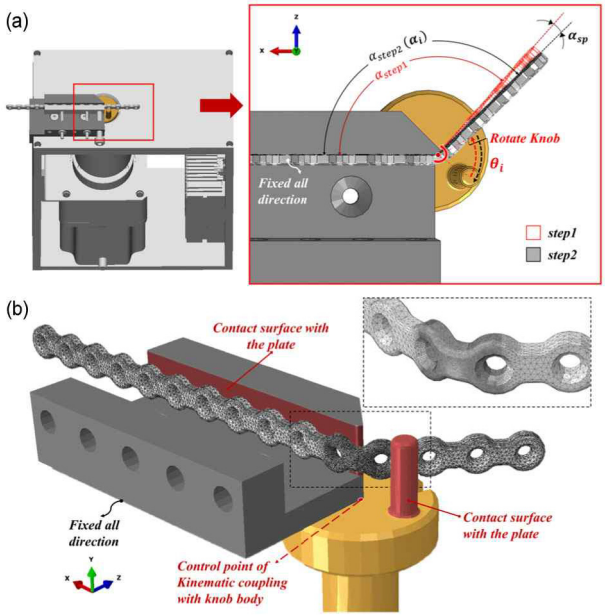


Fig. 3. Set-up of the finite element model: (a) The bent shape of the plate under loading (red line; step 1) and unloading (black line; step 2) after spring-back; (b) the red surfaces show the contact surfaces with the plate. The knob is rotated around a control point connected to the body, and the dotted box indicates the denser mesh size in the bent area.

of the bending apparatus and the resulting plate angle before and after spring-back is measured using the acquired images.

3. Results

Fig. 5 presents the plate deformation during the bending simulation for each step. As shown in Fig. 5(b), the residual stress remains after plastic deformation in the bending area of the plate. As mentioned in Sec. 2.2, if the difference between the desired angle (α_D) and the measured bent angle after spring-back (α_{step2}) is more than 0.05°, the input angle (θ) is updated using the process outlined in Table 2.

The results of the iterative FE analysis are summarized in Table 5. They show that α_i converges to the target angle with repeated simulations. The simulation for $\alpha_D = 15^\circ$ satisfies the ending condition (i.e., the difference between α_D and α_i is less than 0.05°) after the third iteration. Similarly, the simulation for $\alpha_D = 30^\circ$ is completed after the second iteration. The final input angle in each case (θ_{FE}) is calculated using a spring-back angle of 3.29° and 3.64° when α_D is 15° and 30°, respectively. When the target angles (α_D) are 15° and 30°, the error rates are 14.00 % and 2.53 %, respectively, using θ_A as the initial guess. It is expected that the error rate could be reduced to 0.27 % and 0.03 %, respectively, when θ_{FE} is used.

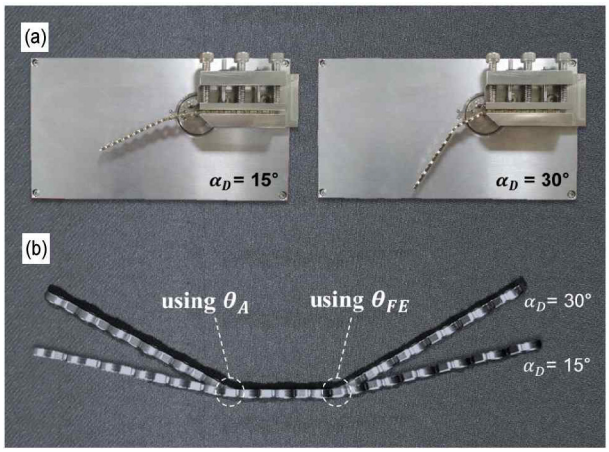


Fig. 4. (a) Experiments bending the plate by 15° and 30°; (b) bent regions (between the sixth and seventh screw hole from both ends of the plate).

For the bending experiments, the average bending angle before and after spring-back is presented in Fig. 6. In the 15° bending test, the final bent angle obtained using the input angle θ_A is 12.89° and the error is 14.06 %. The bent angle obtained using θ_{FE} as the input angle is 15.02° and the error is reduced to 2.53 %. In the 30° bending test, the error rate decreases from 0.13 % to 0.07 % when using θ_{FE} instead of θ_A.

4. Discussion

A surgical plate used to repair a defective mandible must fit the surgical region well. The shape of the plate governs the stability of the reconstruction and facial appearance. To prevent plate fractures, two approaches have been taken to reduce the accumulation of stress in plates. One approach involves the design of customized plates and the other is related to developing bending methods to minimize the change in the mechanical properties of the plates.

Customized plates are advantageous in that they do not require intraoperative bending and offer higher accuracy compared to stock plates. However, their costs due to virtual planning exceed the costs of standard plates [22]. Additionally, depending on the design of the custom plate, the results of the surgery can vary [23-26], so additional research is needed to establish a method to improve the design. Therefore, in the present study, we focus on developing a bending method that

Table 5. Results of the simulations for bending-angle calculations.

α_D	15°					30°				
i	α_{step1}	$\alpha_{step2}(\alpha_i)$	α_{sp}	$\lvert\alpha_D-\alpha_i\rvert$	θ_i	α_{step1}	$\alpha_{step2}(\alpha_i)$	α_{sp}	$\lvert\alpha_D-\alpha_i\rvert$	θ_i
0	16.15°	12.90°	3.25°	2.10	38.13°	32.87°	29.24°	3.63°	0.76	53.13°
1	18.42°	15.13°	3.29°	0.13	40.23°	33.74°	30.10°	3.64°	0.10	53.89°
2	18.29°	14.93°	3.36°	0.07	40.10°	33.65°	30.01°	3.64°	0.01	53.80°
3	18.33°	15.04°	3.29°	0.04	40.15°	-	-	-	-	-

α_D : Desired angle, α_{step1} : Bending angle after loading (before spring-back), α_{step2} : Bending angle after unloading (after spring-back), α_{sp} : Amount of spring-back predicted, θ_i : i-th input angle calculated, i : Iteration number

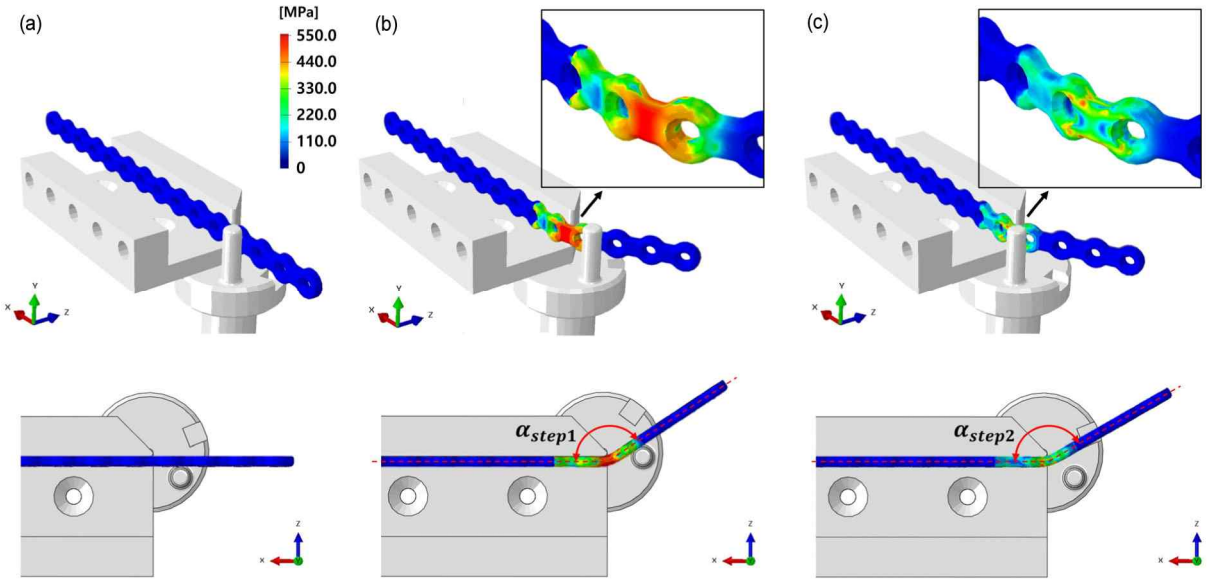


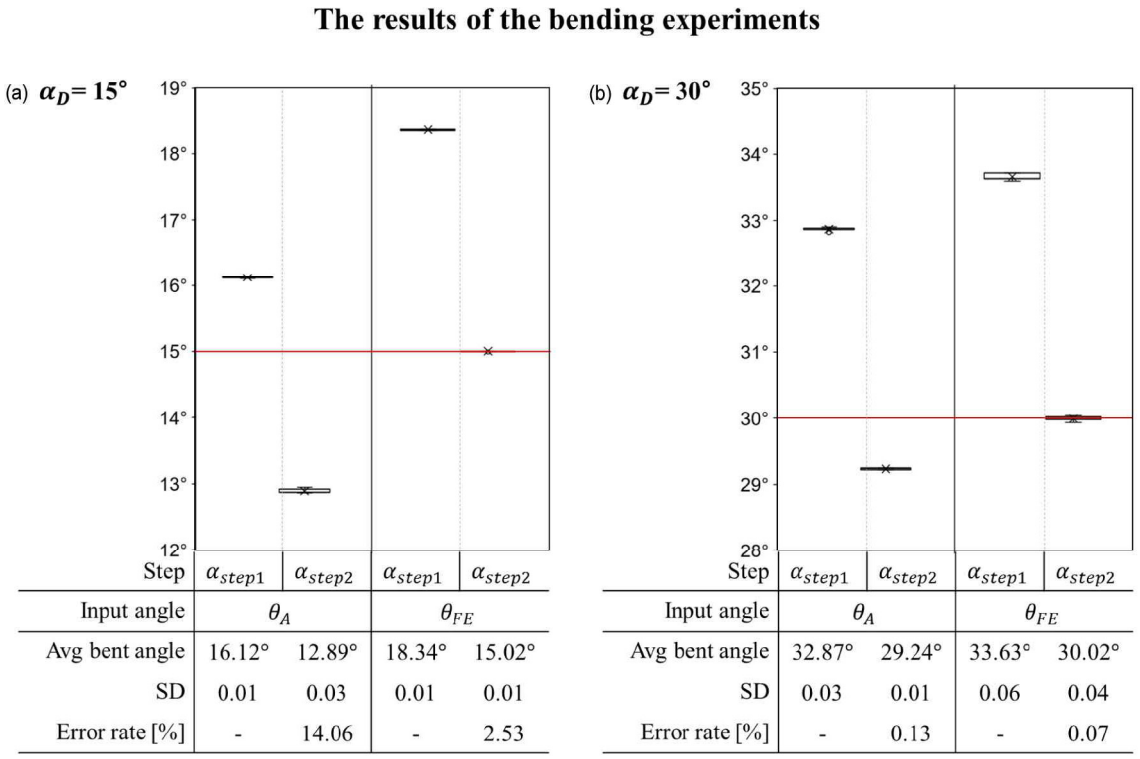
Fig. 5. Deformation and von Mises stress distributions within the plate during the bending simulation: (a) Initial state before applying the bending load; (b) during the application of the bending load using the knob (step 1); (c) after spring-back following the removal of the bending load (step 2).

considers the biomechanical stability of conventional plates.

Several studies have conducted FE simulations of the surgical plate-bending process. For example, Harith et al. investigated the optimal shape for tibial plates required for optimal fit within a given dataset and investigated whether they could be obtained by manually deforming a conventional plate [27]. The bending methods assumed that current bending tools were used to obtain the desired plate shape, and the safety factor of the resultant plate was calculated to determine whether it was viable for tibial reconstruction. Although it can be used to produce an optimal shape with existing tools, this process had to be repeated many times because the spring-back of the plate was not considered in the bending process. Ridwan-Pramana et al. used calculated stiffness values for a fixing plate subject to tension, torsion, bending, and shear processes to investigate the effect of the shape and the bone-implant interface on the stress distribution within skull implants [28]. Although segmented bending processes were considered, their study did not consider the number of repetitions required in the bending process.

In the present study, we develop a new bending apparatus that improves upon three limitations of the current manual bending process [19]. The first limitation is the inconvenience of current bending equipment such as the bending press and bending irons. Because conventional bending equipment is operated manually, the physical force depends on the surgeon's experience. In particular, when bending a thick plate, manipulation is often difficult because it requires a lot of force.

Another limitation is the time-consuming nature of the bending process. According to manual bending tests conducted by Clijmans et al., an operator needed about 26 minutes to bend a 2.4-mm uni-lock reconstruction plate to fit a synthetic mandible model [29]. The manual bending process is performed repeatedly to bend the plate accurately at the desired angle. Because this repetitive bending is usually performed during surgery, the increase in operating time directly leads to an increase in operating room costs. According to Toto et al., even though additional pre-operative costs would be incurred, establishing a meticulous surgery plan helps to reduce the total cost of surgery [30].



Step	α_{step1}	α_{step2}	α_{step1}	α_{step2}
Input angle	θ_A		θ_{FE}	
Avg bent angle	16.12°	12.89°	18.34°	15.02°
SD	0.01	0.03	0.01	0.01
Error rate [%]	-	14.06	-	2.53

Step	α_{step1}	α_{step2}	α_{step1}	α_{step2}
Input angle	θ_A		θ_{FE}	
Avg bent angle	32.87°	29.24°	33.63°	30.02°
SD	0.03	0.01	0.06	0.04
Error rate [%]	-	0.13	-	0.07

* α_D: desired bending angle, θ_A: input angle assuming no spring-back, θ_{FE}: input angle obtained by the FE simulations, α_{step1}: the bent angle before spring-back, α_{step2}: the bent angle after spring-back, Avg : average, SD : Standard deviation

Fig. 6. The results of the bending experiments when (a) α_D = 15°; (b) α_D = 30°.

The third issue is the biomechanical stability of the bent plate and its role in plate fractures. Fatigue and changes in the mechanical properties within a plate due to the repeated bending of the plate can create micro-cracks that can lead to plate failure after surgery [7, 31-34]. Therefore, it is necessary to minimize the plastic deformation process of the plate to reduce cumulative stress and changes in the mechanical characteristics within the plate.

We thus propose a new bending apparatus to overcome the challenges associated with conventional manual bending, including the inconvenience of existing tools, the requirement of great physical strength to bend thick plates, inconsistent bending results, and prolonged operating times. We can also predict the plate spring-back angle using FE simulations to produce the desired angle with a single bend. Because automatic equipment is used, it is much easier to obtain accurate results without operator variation. Furthermore, accurate results can be achieved in less time. The spring-back predictions using the proposed process agree well with bending experiments designed to determine whether the process leads to an improvement in terms of accuracy. One limitation of the present study is that it only considers bending with respect to one point along one axis. Future research is required to consider a more generalized bending process that incorporates various bending axes and points. Also, further studies should include a strain-stress curve for different strain rates.

5. Conclusions

In this paper, we introduced a surgical plate bending process with an automated bending apparatus that can replace repetitive manual bending with conventional bending equipment. Using the proposed process, bending angles to be used as input to the apparatus were calculated considering the predicted spring-back. The results of the experiments testing the effect of the input angle in the proposed bending apparatus revealed that the predicted angle of spring-back was very similar to the measured angle and that the accuracy of the bending angle for the plate was greatly improved. In addition, because the bending tests using the proposed apparatus required only a single bend, the concentration of the residual stress within the bent area would be lower than for repetitive manual bending. The higher accuracy of the plate shape and the simplified bending process offer significant advantages for reconstructive surgery, such as reduced operating times, increased convenience, and improved plate stability.

Acknowledgments

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Republic of Korea (HI18C1224).

Nomenclature

R : Radius of the rotary knob
r : Radius of the knob directly in contact with the plate
s : Radius of the center point of the rotary knob
t : Thickness of the plate
α_D : Desired bending angle
α_i : The bent angle after spring-back of the plate for the i-th iteration
α_{step1} : The bent angle before spring-back in a plate
α_{step2} : The bent angle after spring-back in a plate
β : Angle between the center of the knob and the bent plate
γ : Angle between the bent plate and clamp base
ω : Angle indicating the position of the initial knob relative to the clamp base
i : The number of iterations
θ_A : Input angle to rotate the knob from the initial position, related to geometric approximate expressions
θ_{FE} : Input angle to rotate the knob from the initial position, calculated using finite element analysis
θ_i : Input angle entered for the *i*-th iteration

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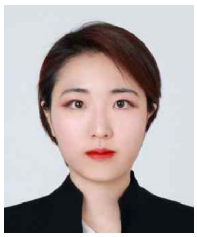

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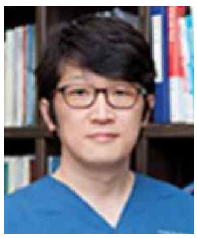

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