Invisible Object Locating System for Fracture Surgery by Using Eddy Current

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Abstract
This report describes an eddy current system for locating distal transverse screw holes of an intramedullary nail. In fracture surgery, screw holes on an intramedullary nail are in invisible situation. Although conventional X-ray methods can visualize screw holes in bone, they pose a danger due to X-ray exposure. Therefore, a system to find screw holes without X-ray exposure is required. We solved this problem using an eddy current system and applying a method that calculates local minimum positions of a searching signal obtained by the eddy current system. Shape characteristics of screw holes were revealed in the waveform and amplitude of the searching signal. As a result, the screw hole positions could be identified with the smallest error of 0.99 mm when the distance between the probe and the intramedullary nail was 8 mm. The screw was successfully inserted to the screw holes in this accuracy.

Keywords
Eddy Current, Orthopedic Surgery, Intramedullary Nail.

1. INTRODUCTION
In orthopedic surgery, implants are vital for reinforcing and replacing injured portions of the human body. Implants are constructed from materials, such as titanium, stainless steel, or ceramic, which are compatible with body tissues. Fractures are the one of the most popular injury to consult a doctor in orthopedic surgery. An intramedullary nail is a type of implant used to repair fractures of bone. Since fracture region is normally repaired by keeping fracture region straight, the intramedullary nail is inserted in the bone with fracture region. The intramedullary nail fixes the bone by inserting screws into the bone through the screw holes of the intramedullary nail. However, it is difficult for surgeons to insert the screws into the screw holes because the surgeon cannot locate the screw holes on the intramedullary nail due to the invisible situation. Therefore, a method is needed to find the screw holes using techniques of visualization of inside body such as X-ray fluoroscopy, and Ultrasound (US).

X-ray fluoroscopy is the most commonly used technique in orthopedic surgery. Several studies [1] [2] have resulted in methods that support doctors technically and shorten surgery time. However, X-ray devices pose a danger because of X-ray exposure.

There has been proposed a method for locating the screw holes of intramedullary nails using ultrasonography [3], which has the advantages of being noninvasive and not exposing the body to harmful X-rays. To develop this system, the problem of ultrasonic waves not being transmitted by bone tissue was overcome by transmitting the ultrasonic wave at a lower frequency, approximately 1.0 MHz [4][5]. These studies targeted bones such as bovine femurs and animal skulls. In the experiment performed only in the intramedullary nail, this method [4] located the screw holes within an error of 1.43 mm, which allows successful insertion of screws into the screw holes. However, this system could not be adapted for scanning over the skin of the leg because of the higher attenuation of ultrasound data from both the skin and bone. Ultrasonic has a serious weak point of attenuation of air. Therefore, US system is very disadvantageous in practical application.

To solve this problem, i.e., for developing a system which enables us to locate the holes over skin, an
Eddy Current system is a good candidate because the electromagnetic waves do not attenuate in soft tissue and bone in human body.

In Ref.[6], we proposed a minimally invasive orthopedic surgical support system using Eddy Current (EC). The EC system is currently employed in industrial applications, such as crack finding on the metal plate and comparison measuring of metal materials. Since this EC system has an advantage, insensitivity to bone, skin, fat and so on, we can certainly find only the intramedullary nail in the bone. The screw hole is identified with the smallest error of 0.10 mm in the old method [6]. However, this method has a problem as noise of distance increment, which express a distance between a sensor and a target object. When the distance became 8 mm, this method had only a one-third chance of success. We require a more robust method for an environment which is close to practical use.

In this study, to improve this problem, we propose an extraction and selection method, and perform a new experiment in using a swine bone. This method can be applied to any trials to focus on characteristic of waveform. The experiments have been performed by using a swine bone, and we have proved that our proposed system have an advantage of insensitive to bone. As the result, the screw hole positions could be identified with the smallest error of 0.99 mm. This error showed this system was successfully inserted in the screw hole to the intramedurally nail. We proved that our proposed system could be used in the environment which is close to practical application.

2. PRELIMINARIES

Eddy Current (EC) system is one of the popular nondestructive testing systems in the industrial applications. Eddy current means an inducted current arisen to the surface of the conductor when the coil that AC flows near to the conductor. If the surface of a conductor has a crack, voltage detected by coil is changed around the crack. By moving the coil, we find the position of the crack. When we assume that the screw holes are the discontinuous plane of the nail, we can find the screw holes with the EC system. The principle of EC is explained as follow.

The magnetic flux arises by flowing AC to a coil with EC probe, and Φ of raised flux penetrates a conductor. The eddy current flows to the conductor by Φ. The magnetic flux shows in following Eq.:

\[ \Phi = BS, \]

where \( B \) denotes the magnetic flux density. \( S \) denotes the flux pass area. \( \Phi \) becomes bigger as \( S \) becomes bigger. \( S \) corresponds with diameter of the coil. Thus, if the diameter of the coil becomes bigger, \( \Phi \) becomes bigger.

Figure 1 shows the principle of EC probe in differential transformer. Figure 1 (a) shows the distance between the target object and the EC probe is long. Figure 1 (a) shows the distance between the target object and the EC probe is short. In Figure 1 (a), the magnetic flux penetrated coil B1 is almost the same as the magnetic flux penetrated coil B2. However, in Figure 1 (b), the magnetic flux penetrated coil B1 is different from the magnetic flux penetrated coil B2. Thus, the terminal voltage V1 is different from V2. Because the EC probe detects that difference, V becomes bigger if the distance between the EC probe and the target object \( x \) becomes shorter.

Experimental information is presented in Figure 2. The EC probe is connected to an instrument (ST-02X, SyuuTec) fixed on the robot manipulator (PA10-7, 7DOF, Mitsubishi Heavy Industries, Ltd., Japan), and is scanned along the \( d \) mm of the intramedullary nail with \( v \) mm/s along the principal axis of the nail. Test frequency of the EC probe is 256 kHz.

Sampling rate of the obtained data by EC probe is 150 Hz. The principal axis of a real intramedullary nail (Smith & Nephew) is shown in Figure 3(a). The nail has a concave section toward the end. This portion indicates the rotation of the screw holes because the surgeon can see it during surgery. Thus, we were not concerned with the rotation of the nail. Figure 3(b) shows a model of the intramedullary nail, for which the size of the first screw hole 1 is 10.0 mm, and the size of the second screw hole 2 is 5.0 mm. The values of H1s, H1e, H2s and H2e represent the edges of the screw holes. Figure 4 shows a swine bone used in this study. The swine bone is used instead of the human bone. This swine bone may be used in this study because its composition is similar to the human bone in practical situation. The swine bone has the fresh and is including blood. The thickness of the swine bone is about 8 mm that is close to the distance between the nail and the surface of the human bone, which ranges from 5 to 10 mm. The swine bone is set on the nail as shown in Figure 5. That one is put on the nail.
In the EC system, as the distance between the probe and the target object increases, the searching signal decreases as above. The searching signal changes when the probe locates the screw holes because of the distance changes of the screw holes. In detail, the searching signal changes when the probe locates discontinuities along the nail, such as the end and edge positions. Figure 3(b) shows that $H_1s$, $H_1e$, $H_2s$, and $H_2e$ represent the start position of hole 1, end position of hole 1, start position of hole 2, and end position of hole 2, respectively. A typical waveform of EC searching signal is shown in Figure 6, in which Wave A, Wave B, Wave C_s, Wave C_e, Wave D_s, and Wave D_e represent the change in the searching signal related to the end.
position, edge position, \( H_1 \), \( H_1 \), \( H_2 \), and \( H_2 \), respectively. Figure 7 shows a real searching signals obtained in this experiment. Figure 7 (a) shows the searching signal with large current, and Figure 7 (b) shows one with small current. These searching signals are obtained in the speed of the probe \( v = 20 \text{ mm/s} \). The distance between the probe and the nail, denoted by \( d \), is 4 mm in Figure 7 (a) and 8 mm in Figure 7 (b). The real waveform shown in Figure 7 has more complicate form than the model waveform. This real waveform depends on the shape of the target object, scanning speed of the probe, distance between the probe and the target object and so on. Especially, if experimental environment is in these cases the distance between the probe and the target object changes frequently and the probe inclines at the plane of the target object, noise is included in these waveforms.

In our previous study [6], we performed two experiments to find the experimental environment which produces the best result. In the first experiment (Case A), the speed of the probe \( v \) was adjusted to 5 to 30 mm/s in steps of 5 mm/s. We performed Case A to find best \( v \) that produces a minimum error to determine the two screw holes. Table 1 shows the errors obtained in our previous study, which applied the screw hole position locating method. In Case A, the error at \( v = 20 \text{ mm/s} \) was the smallest of all. When \( v = 5 \text{ mm/s} \) or \( v = 30 \text{ mm/s} \), errors are bigger than others. Figure 8 shows maximum amplitude for each of the \( v \) value. At \( v = 30 \text{ mm/s} \), the maximum amplitude was the biggest of all, but error was bigger than others. In the second experiment (Case B), the distance \( d \) between the probe and nail was adjusted to 4, 6, 8 and 10 mm. We performed Case B to find \( d \) which is the limit error cause of distance increment to determine as the two screw holes at \( v = 20 \text{ mm/s} \).

Table 1 shows the errors and failed count by applying the screw hole position locating method in our previous study. Failed count means the trial count which could was incremented when the method failed to be applied. In Case B, the error at \( d = 8 \text{ mm} \) was the biggest of all. For \( d = 10 \text{ mm} \), the method failed to be applied to the screw hole positions in our previous study. For \( d = 8 \text{ mm} \), the method had only a one third chance of success.

\( S/N \) rate becomes smaller when amplitude becomes smaller. In such cases, it is assumed that our previous study cannot be applied because the waveform of the searching signal loses shape of the model of the waveform due to noises. Thus, what is required is a method which can be applied even in such cases. One of solution approach to this problem is to raise the value of \( v \), to 25 mm/s in Table 1 for example, within possible range. In this paper, we performs the experiment with \( v = 25 \text{ mm/s} \). According to our experiment condition, the thickness of the bone used this experiment is 8 mm. However, when \( v = 20 \text{ mm/s} \) and \( d = 8 \text{ mm} \), failed count is two times of three times as shown in Table 1. One of that causes is what \( S/N \) rate of the searching signal is small. We should choose \( v \) bigger than 20 mm/s. As the other solution approach, we propose a new screw hole position locating method in the next chapter.

### 3. HOLE POSITION LOCATING METHOD

Figure 9 shows the flowchart of the proposed method. In this method, the shape of the nail is identified by using the waveform of the EC searching signal. First, the end position of the nail is determined. Second, all waves are extracted in the waveform by selecting local minimum values. Finally, two screw hole positions are identified by selecting two positions in the extracted waves.
Figure 6. Model waveform of searching signal.

(a) Large signal  
(b) Small signal

Figure 7. Real searching signal.

Table 1. Comparison results of changing speed and distance.

<table>
<thead>
<tr>
<th></th>
<th>Hole</th>
<th>error</th>
<th>SD</th>
<th>faild count</th>
<th>Hole</th>
<th>error</th>
<th>SD</th>
<th>faild count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case A</td>
<td>v=5</td>
<td>15.98</td>
<td>2.78</td>
<td>0.08</td>
<td>1</td>
<td>38.90</td>
<td>1.90</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>10.89</td>
<td>1.11</td>
<td>0.00</td>
<td>0</td>
<td>34.80</td>
<td>2.23</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>12.10</td>
<td>0.10</td>
<td>0.08</td>
<td>0</td>
<td>36.80</td>
<td>0.20</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>13.29</td>
<td>1.29</td>
<td>1.26</td>
<td>0</td>
<td>37.73</td>
<td>0.73</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>13.06</td>
<td>1.06</td>
<td>0.08</td>
<td>0</td>
<td>37.05</td>
<td>0.05</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>11.00</td>
<td>1.00</td>
<td>0.00</td>
<td>0</td>
<td>30.83</td>
<td>1.16</td>
<td>0.00</td>
</tr>
<tr>
<td>Case B</td>
<td>d=6</td>
<td>13.73</td>
<td>1.73</td>
<td>0.13</td>
<td>1</td>
<td>38.47</td>
<td>1.47</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>12.67</td>
<td>0.67</td>
<td>0.13</td>
<td>2</td>
<td>39.53</td>
<td>2.53</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
First, we determine Wave A, which expresses the end position of the nail, in the obtained searching signal. In Figure 6, the shape of the nail is indicated by aspect from the side. The distance between the probe and the position of the nail changes by the position of the nail. Since the distance between the probe and the end position of the nail is larger than the distance $d$ between the nail and the probe, the amplitude of Wave A is smaller than that of the other waves. We define the position with the maximum amplitude in the wave A as the position of Wave A, so the position of Wave A is determined by finding the position with the maximum amplitude in the wave A. When the amplitude of the searching signal becomes smaller, Wave A is barely detectable. A zone in which the amplitude remains negative exists for a certain time behind Wave A, as shown in Figure 10. Thus, we define the zone containing a negative value for $t_{zone}$ as the negative zone, and a position $t_{WA}$ with the maximal amplitude between 0 s and the first negative zone as the position of Wave A.

Second, we extract all waves including these waves (i.e., Wave B, Wave C, Wave C, Wave D, and Wave D). All of the peaks of these waves have the local maximum value and minimum value in the searching signal. Local maximum positions in the searching signal are determined by calculating local maximum values in our previous study [6]. However, as the distance $d$ increases, local maximum values mightly decreases as shown in Figure 7 (a) ($d = 4\, \text{mm}$) and (b) ($d = 8\, \text{mm}$). Therefore, we determine local minimum positions as the waves. This procedure is described as follows.

We change all values that are greater than zero to zero in the obtained searching signal to make easily to find the local minimum values. The searching signal below zero has a contiguity of non-smooth values as shown in Figure 11. Non-sooth values are caused by noise. Because the local minimum value cannot be determined due to the non-smooth values, a moving average of this searching signal is calculated, and the waveform is smoothed. The moving average is calculated by Eq. (2):
\[ m(t) = \frac{\sum_{i=0}^{2n} y(i)}{2n+1} \]  

(2)

where \( y(i) \) denotes the amplitude value at \( i \), and \( n \) denotes the length of the moving average. For this experiment, the value of \( n \) is 10. Next, the local minimum position on the waveform is selected for applying a moving average process. The local minimum position is located between two positions whose amplitudes are zero. We use threshold \( th \) to cut out noise, and determine only such local minimum positions whose amplitude are below \( th \) as local minimum positions hereafter. The determined the local minimum positions are shown in Figure 12. In Figure 12, \( th \) is 0.06.

Finally, the two screw hole positions are determined in the local minimum positions. The two screw hole positions, \( H1_s \) and \( H2_s \), are assumed to have the following characteristics:

- \( H1_s \): the start of Hole 1 is determined as second local minimum position.
- \( H2_s \): the start of Hole 2 is determined as the local minimum position with maximum \( f \), which expresses distance between \( H1_E \) and \( H2_S \).

In the waveform shown in Figure 6, Wave \( C_s \), which is the second wave, expresses \( H1_e \). The notation \( f \) denotes the distance between two adjacent local minimum positions. Distance between \( H1_e \) and \( H2_e \) is the longest in the other distances between two adjacent local minimum positions in the shape of the nail. However, in this experiment, local minimum positions are not stable between two zero positions because the searching signal has the lower S/N ratio, and thereby, the waveform is different shape from the model case. Thus, we employ zero positions instead of local minimum positions when calculating \( f \) because zero positions are hardly changed. Zero positions mean that the probe starts locating on the screw hole. Changing of current is bigger in the case that the probe starts locating on the start or end position of the hole than the case of the probe starts locating on the center of the hole. If a zero position which is in front of the local minimum position indicates \( z_1 \), and a zero position which follows the local minimum position indicates \( z_2 \), the \( f \) is determined as the distance between two adjacent \( z_1 \)s.

4. EXPERIMENTAL RESULTS

We have conducted experiments with three cases by obtaining the searching signal and applying our proposed method in three cases. In Case A, the target object was the bare nail, the distance \( d \), which represents the distance between the nail and the probe, was 8 mm. In Case B, the target object was the nail with a swine bone with thickness of 8 mm, which was put on the nail, and the distance \( d \) was 8 mm. In Case C, the target object was the bare nail, and the distance \( d \) was 4 mm. The velocity, \( v \), which represents the scanning speed of the probe, was 25 mm/s in three cases. Experimental results in three cases are shown in Table 2. We obtained the searching signals through four trials for each case. Hole 1 and Hole 2 represent the distance between the end position of the nail and \( H1_s \) or \( H2_s \), which were determined by the proposed method and represented by time \( t \) in seconds. Then, time \( t \) is converted into Euclidean distance \( x \) (mm) by:

\[ \text{Hole 1} = (t_{h1} - t_{WA}) \cdot v \]  

(3)

\[ \text{Hole 2} = (t_{h2} - t_{WA}) \cdot v \]  

(4)

where \( t_{WA} \) denotes the end position of the nail and \( t_{h1} \) denotes \( H1_s \), and the average error of four trials. True value of the Hole 1 and Hole 2 are 12 mm and 37 mm, respectively. Error represents difference between the true value and the calculated value.

Comparison results between Case A and Case B establish that our proposed system is valid for finding the holes in bone. As the result, both results show similar directions. The errors of Hole 2 were lower than that of Hole 1 in Case A and Case B, and among the errors of Hole 2, the level of error in Case A was especially greater than that reported when ultrasound was used [4], which gave an accuracy of 1.43 mm. Our proposed system was successfully inserting a screw to Hole 2 in this accuracy.

Comparison results between Case A and Case C establish that our proposed system is valid the situation in which the distance becomes long up to 8 mm. Failed counts are zero in all cases of Table 2.
Table 2. Experimental results of three cases.

<table>
<thead>
<tr>
<th></th>
<th>Hole 1 (mm)</th>
<th>error (mm)</th>
<th>SD (mm)</th>
<th>Hole 2 (mm)</th>
<th>error (mm)</th>
<th>SD (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case A</td>
<td>14.69</td>
<td>2.69</td>
<td>0.64</td>
<td>37.99</td>
<td>0.99</td>
<td>0.68</td>
</tr>
<tr>
<td>Case B</td>
<td>13.94</td>
<td>2.17</td>
<td>1.09</td>
<td>37.13</td>
<td>1.49</td>
<td>1.34</td>
</tr>
<tr>
<td>Case C</td>
<td>10.78</td>
<td>1.22</td>
<td>0.17</td>
<td>34.48</td>
<td>2.52</td>
<td>0.19</td>
</tr>
</tbody>
</table>

In our previous study shown in Table 1, we did not locate the hole position for the distance $d$ is 8 mm.

EC system was used in different situation from US system because two systems have different advantages and disadvantages. In ref. [4], distance between US probe and the nail is over 20 mm, and nail is set in the water because ultrasonic wave is attenuated by air. We should use EC system if we can provide good situation for EC system, which is shorter distance between the probe and the nail less than 8 mm.

5. CONCLUSIONS
This study focused on a method to identify the screw hole position on the intramedullary nail for fracture repair in orthopedic surgery. A new EC system was proposed that located an invisible object in bone such as an intramedullary nail with minimally invasion and good hygiene. As the target object, we used the intramedullary nail under a swine bone, whose thickness was 8 mm, instead of the one in human bone. Since the thickness of cortical bone in the femur ranges from 5 to 10 mm, this experimental environment fulfills some of practical situations. In our proposed method, the screw hole position was identified successfully with smallest error of 0.99 mm by focusing on the waveform and amplitude of a searching signal obtained by the EC system.

This study would be basis for establishing a locating system of these holes over the skin of the leg. As the future works, it remains to locate the screw hole with longer distance between the probe and the nail. To overcome the problem, we should consider not only a software solution but also a solution by using new hardware approach. The most appropriate candidate would be a pulsed Eddy Current [7]. The system [7] has robustness for attenuation with respect to the distance.

Many EC systems have been applied to industrial situation [8]-[10], or treatment equipment by heat evolution. However, no study has been done by using a sensor for finding implants in bone. Our study including Ref. [6] is the first one in a new area of biomedical EC system.

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