Electromagnetic Coil/Inductance-Based Nondestructive Methods for Locating Distal Screw-Holes of an Intramedullary Interlocking-Nail

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ABSTRACT

We report an electromagnetic inductance/coil-based non-destructive method to target distal screw-holes in an intramedullary interlocking-nail surgical operation for fixing a long-bone fracture. The method is a radiation-free approach addressing the over-exposure issue of radioactivity caused by the typical X-ray-imaging approach. According to the method, we fabricate a targeting-system consisting of an internal inductance, external coil, guiding-mechanism, and driving/measurement electronics. When a voltage is applied to the internal inductance embedded in one of the distal screw-holes of a nail inserted in a bone, a directional magnetic flux is generated by the internal inductance due to the electromagnetic induction. Subsequently, the directional magnetic flux penetrates the nail and bone. When the external coil outside the bone scans along the axial and angular directions of the nail/bone, different amount of the generated magnetic flux is detected by the coil and consequently corresponding voltage response is induced in the coil due to the electromagnetic induction. In contrast to the magnetic flux generated and detected by the inductance and coil, respectively, we also investigate the reverse physics-behavior of the flux transmission (i.e., flux generated and detected by the coil and inductance) in order to improve the approach. Finally, by correlating the induced-voltage responses with the scanned axial-locations along the nail/bone, correlation curves are plotted. Through analyzing the curves, a criterion for predicting the location of the screw-holes of the nail is established. When compared the predicted location with the actual location of the screw-hole, the maximum targeting error is 2 mm for locating a screw-hole with a diameter of 5 mm. The result shows the targeting-method is accurate, fast, and easy for the surgeons and significantly simplifies the existed interlocking-nail surgical procedures.

Keywords: Electromagnetic, Induction, Coil, Screw Hole, Intramedullary, Interlocking Nail, Bone-Fracture, Surgery

1. INTRODUCTION

Nowadays, surgeons frequently use the intramedullary interlocking-nail in the surgical operation for the treatment of a long-bone fracture. However, surgeons have a difficulty to locate the distal screw-holes of the nail after the nail is inserted into the medullary canal of the long-bone. That is, the distal screw-holes cannot be observed by naked eye. To address this issue, surgeons utilize X-ray imaging methods to locate the screw-holes [1]. Although the X-ray imaging methods help surgeons locate the screw-holes accurately, patients have to suffer the over-exposure radiation. Due to this, a radiation-free targeting approach is needed. Recently, researches demonstrated several radiation-free approaches such as ultrasonic, fiber-optic, magnetic, and mechanical targeting-methods [2-12]. However, all of the approaches have drawbacks such as complicated, expensive, and/or inaccurate. Due to the drawbacks, researchers still search for a better approach. Hence, in this paper, we provide a novel electromagnetic inductance/coil-based non-destructive method which is a radiation-free, easy, cheap, and accurate approach.

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2. APPROACH/DESIGNS

The approach is illustrated in figure 1. There are two main designs derived from the approach: The first design (design I): magnetic flux generated and received by the internal inductance and external coil, respectively, as shown in figure 2(a). Another design (design II): magnetic flux generated and received by the external coil and internal inductance, respectively, as shown in figure 2(b)).

For design I, when an alternative current is applied to the internal inductance embedded in one of the distal screw-holes of a nail inserted in a bone, a directional magnetic flux is generated by the internal inductance due to the electromagnetic induction. The generated directional magnetic flux penetrates the nail and bone. When the external coil outside the bone scans along the axial directions of the nail/bone, different amount of the generated magnetic flux is received by the external coil and subsequently converted to different induced-voltage response due to the electromagnetic induction, as shown in figure 2(a). In contract, for design II, the directional magnetic flux is generated by the external coil and received by the internal inductance, as shown in figure 2(b). By correlating the induced-voltage responses with the scanned axial location along the nail/bone, the correlation curves are plotted. Through analyzing the curves, a criterion for predicting the location of the distal screw-holes of the nail is established. When compared the predicted and actual location of the screw-hole, the maximum targeting-error for locating a screw-hole is obtained.

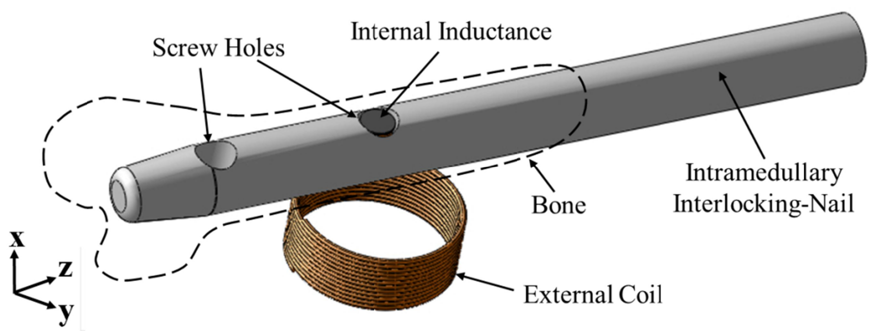

Figure 1. The illustration of the targeting approach.

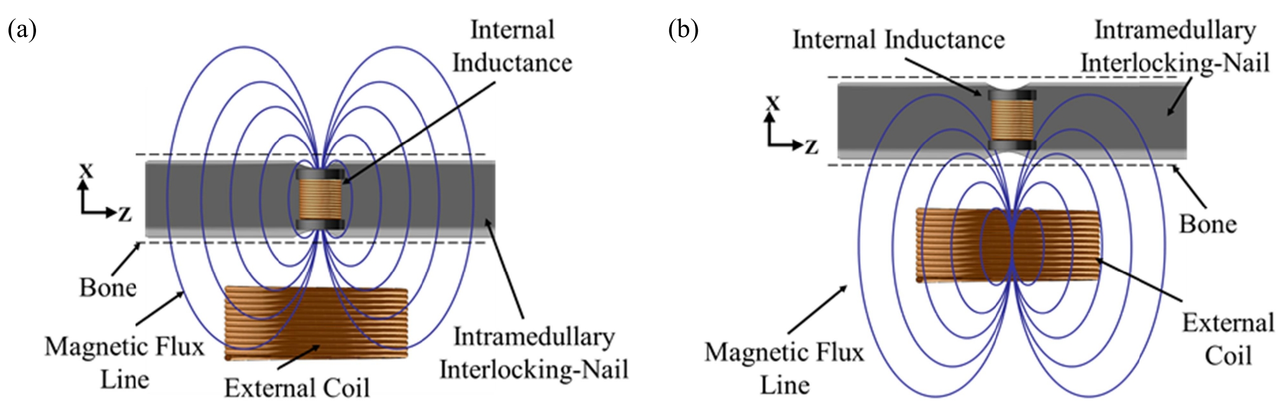

Figure 2. (a) design I: magnetic flux generated and received by the internal inductance and external coil, respectively. (b) design II: magnetic flux generated and received by the external coil and internal inductance, respectively.

3. FABRICATION

According to the approach/design, the screw-hole targeting system is fabricated. The system consists of (I) an internal inductance embedded in one of the distal screw-holes of an intramedullary interlocking-nail, (II) external coil and holder, and (III) guiding mechanism (linear stage). Figure 3 (a) and 3(b) is the photograph showing the front and top view of the inductance, respectively. The inductance (diameter × height: 5 mm × 4 mm) consists of an iron core and enameled-wire welded to the connecting wire, as shown in figure 3(c). The inductance with connecting wire is embedded inside one of the distal screw-holes of the nail (nail: Smith & Nephew R-T Tibial Interlocking-Nail 12-2131, diameter × length: 1.2 cm × 40 cm) without causing a damage to the structure of the nail (i.e., non-destructive), shown in figure 3(f). For the second part, the external coil is made by winding 100-turns of an enameled-wire (diameter × height: 2.5 cm × 6 mm, diameter of the wire: 0.15 mm). After the coil is fabricated, the coil is fixed on the holder. A photograph of the coil and holder is shown in figure 3(d) and 3(e), respectively. For the third part, the guiding mechanism is modified from a commercial linear-stage, as shown in figure 3(g). The nail with the embedded internal inductance is clamped on the guiding mechanism for testing.

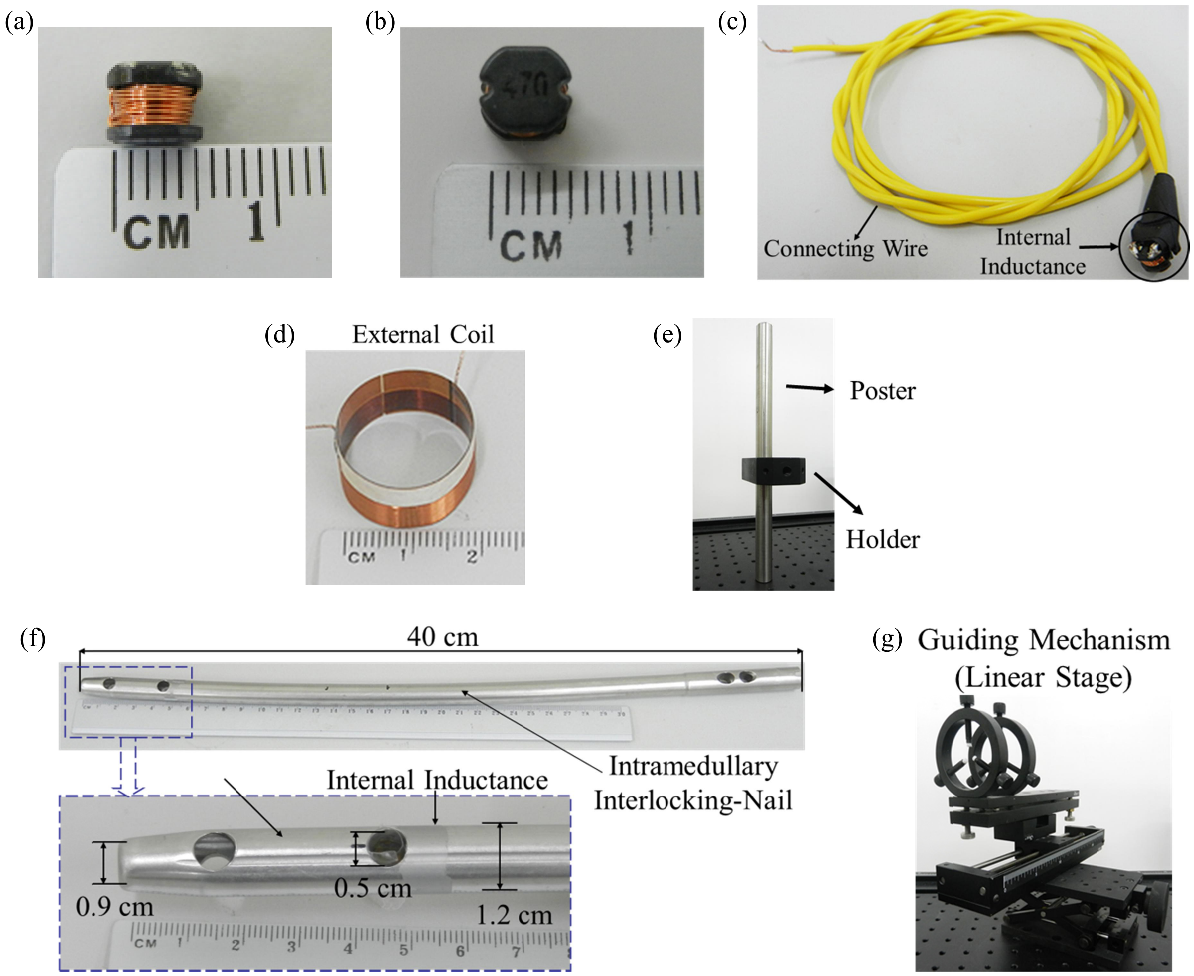

Figure 3. The photograph of the (a) front view and (b) top view of the inductance. (c) the internal inductance with connecting wire, (d) the external coil, (e) the holder for external coil, (f) the intramedullary interlocking-nail with the embedded internal inductance, and (g) guiding mechanism (linear stage).

4. TESTING

An illustration and photograph of the testing setup of the distal screw-holes targeting of an intramedullary interlocking-nail inside a bone is shown in figure 4(a) and 4(b), respectively. The guiding mechanism (i.e., linear stage) enables a location-targeting of the screw-holes along the axial direction of the nail. Utilizing the guiding mechanism, the nail with the bone is translated to pass by the external coil in a scanning/guiding direction along the nail's axial direction from the distal to the central section of the nail. For design I [i.e., magnetic flux generated and received by the internal inductance and external coil, respectively, as shown in figure 2(a)]. The function generator is used to provide an alternating current to the internal inductance to generate an AC magnetic field/flux. The magnetic flux is received by the external coil connected with an oscilloscope in order to record the induced voltage-response. The peak-to-peak magnitude of the induced voltage-response at different scanned location is analyzed to establish a criterion to predict the actual location of the distal screw-holes of the nail.

Because the design II [i.e., magnetic flux generated and received by the external coil and internal inductance, respectively, as shown in figure 2(b)] is to investigate the reversal physics-behavior of the magnetic-flux transmission of the design I, therefore the testing setup of the design II is similar as the design I. The only difference between the testing setup of design I and II is the exchanging of the function and oscilloscope, as shown in figure 4(a).

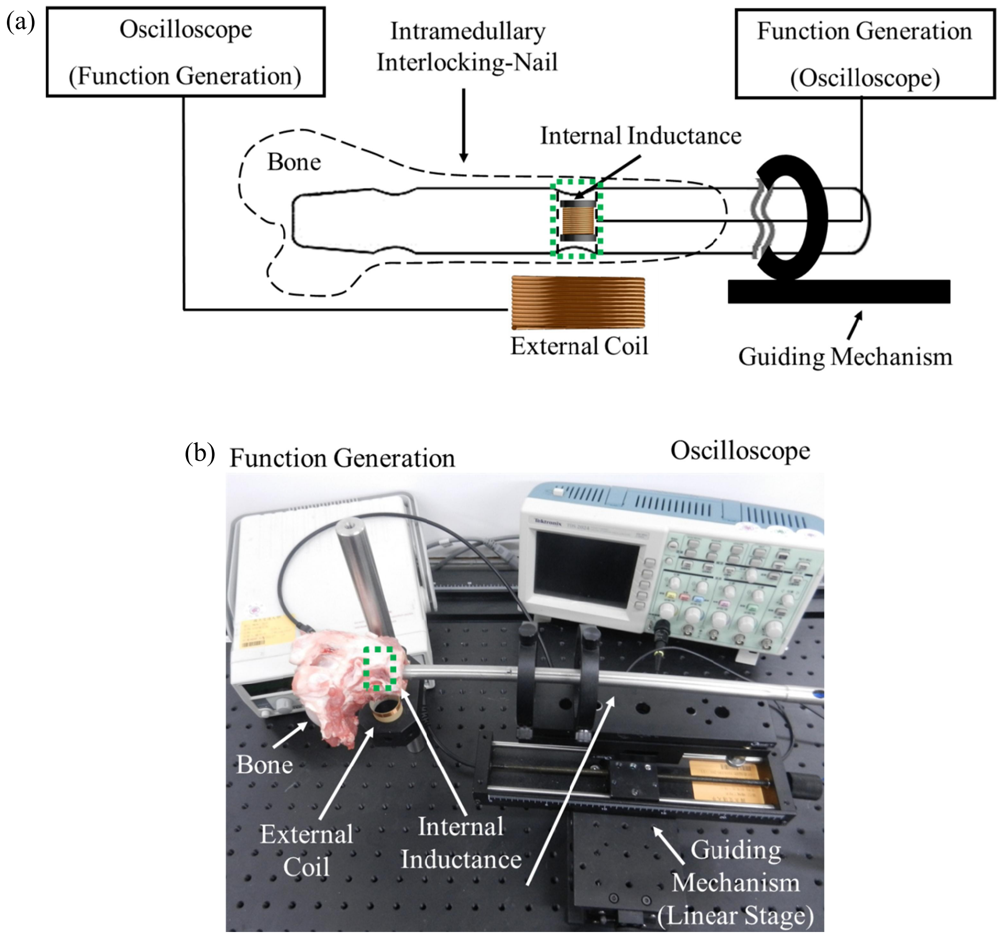

Figure 4. (a) The illustration and (b) the photograph of the testing setup for the location-targeting of the distal screw-holes of the intramedullary interlocking-nail in the bone. The location of the distal screw-holes of the nail inside the bone is approximately within the green-dash-line boxed region in (b).

5. RESULTS AND DISCUSSION

The test results of the location targeting of the distal screw-holes along the nail's axial direction is shown in figure 5. Utilizing the guiding mechanism (i.e., linear stage), the nail with bone is translated to pass by the external coil with a scanning direction along the nail's axial direction from the distal to the central section of the nail. The peak-to-peak magnitude of the induced voltage-response with the scanned location is plotted in figure 5(b) and 5(d) for design I and II, respectively. After the induced voltage-response is obtained, we compare the scanned location in figure 5(b) and 5(d) with the actual location of the nail in figure 5(a). That is, we correlate the critical locations (point A and B) in figure 5(b), 5(d), and 5(a). The voltage pattern at the locations nearby the most critical location point A (i.e., as the green-dash-line boxed region in figure 5(b) and 5(d)) is enlarged as shown in figure 5(c) and 5(e), respectively.

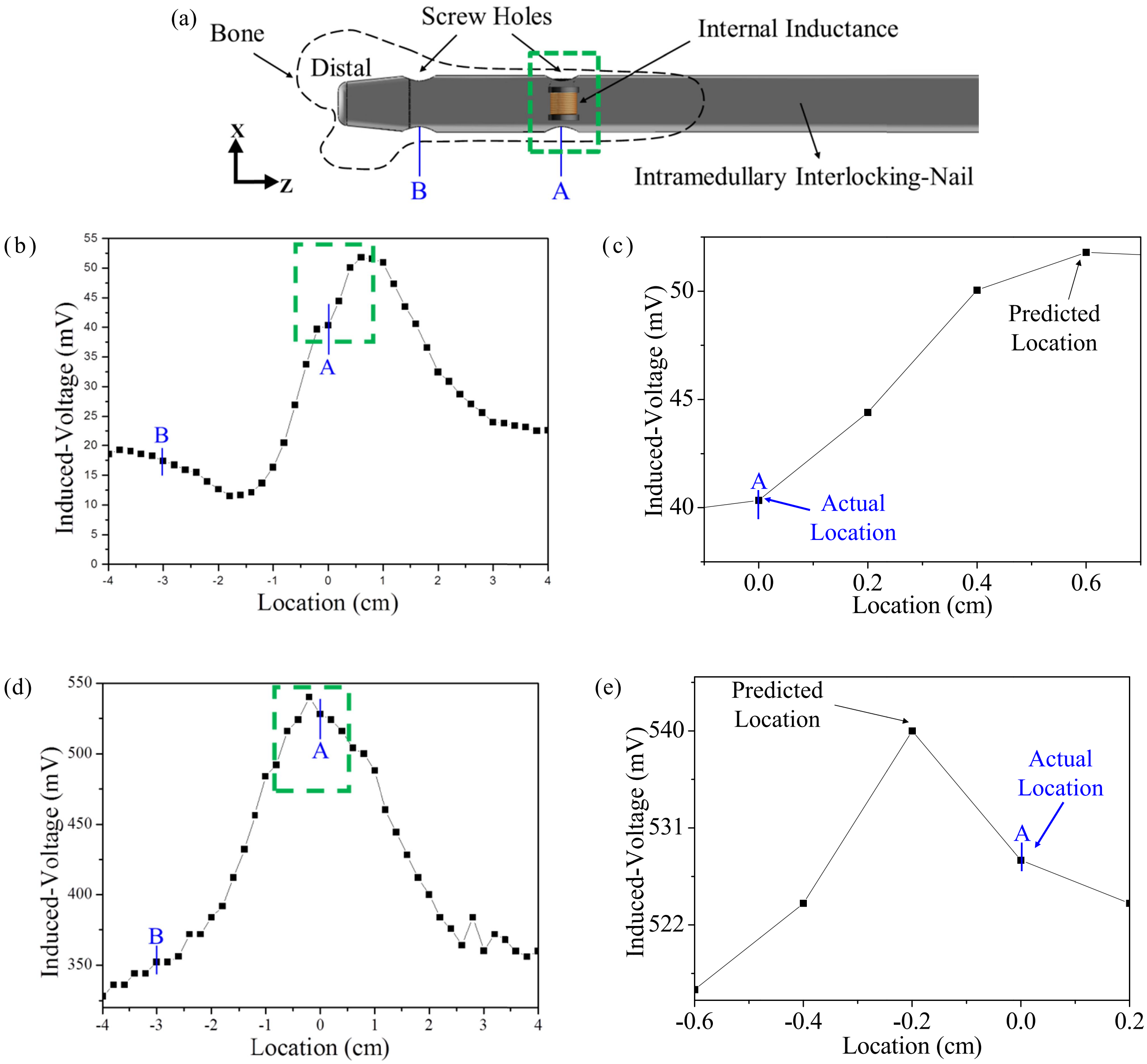

Figure 5 The test results of the location targeting of the distal screw-holes of the nail inside the bone. (a) the illustration shows the critical location A and B while scanning along the nail's axial direction. (b) the result for design I (i.e., magnetic flux generated and received by the internal inductance and external coil, respectively): the peak-to-peak magnitude of the induced voltage-response at different scanned location. (c) the voltage pattern enlarged from (b). (d) the result for design II (i.e., magnetic flux generated and received by the external coil and internal inductance, respectively): the peak-to-peak magnitude of the induced voltage-response at different scanned location. (e) the voltage pattern enlarged from (d).

According to the approach in the design section, the maximum peak-to-peak magnitude of the induced voltage-response indicates a maximum amount of the magnetic flux is received. Receiving the maximum amount of the flux only occurs while the inductance and coil are aligned coaxially during the scan. However, according to the results we obtained in the figure 5(b) and 5(d), the maximum voltage response occurs at a location slightly away from the critical location point A rather than exactly occurring at point A (note: the critical location point A represents the inductance and coil are aligned coaxially during the scan). Nevertheless, the maximum voltage response is still capable of being used to predict the location of the inductance which is embedded in one of the distal screw-hole. That is, the maximum voltage response successfully predicts one of the distal screw-hole. Furthermore, because the distance between each distal screw-hole is known when manufactured, the location of each distal screw-hole is also obtained. Finally, when we compare the predicted and actual locations of the distal screw-holes, as shown in figure 5(c) and 5(e), the targeting error of locating the screw hole with a diameter of 5 mm in design I and II is 6 mm and 2 mm, respectively. Due to this, the design II with a targeting error of 2 mm is accurate enough for the intramedullary interlocking-nail surgery.

6. CONCLUSION

We successfully fabricated an electromagnetic inductance/coil-based targeting system demonstrating a location-targeting of the distal screw-holes of a nail inside a bone for the surgical operation in intramedullary interlocking-nail surgery. From the approach utilized by the system, two designs for investigating the magnetic-flux transmission between the inductance and coil are derived in order to optimize and improve the system. Experimental results show the maximum targeting error is 2 mm for the location-targeting of a distal screw-hole with a diameter of 5mm.

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