A Touch Probe Method of Operating an Implantable RFID Tag for Orthopedic Implant Identification

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***Abstract*— The major problem in operating an implantable RFID tag embedded on an orthopedic implant is low efficiency because of metallic interference. To improve the efficiency, this paper proposes a method of operating an implantable passive RFID tag using a touch probe at 13.56 MHz. This technology relies on the electric field interaction between two pairs of electrodes, one being a part of the touch probe placed on the surface of tissue and the other being a part of the tag installed under the tissue. Compared with using a conventional RFID antenna such as a loop antenna, this method has a better performance in the near field operation range to reduce interference with the orthopedic implant. Properly matching the touch probe and the tag to the tissue and the implant reduces signal attenuation and increases the overall system efficiency. The experiments have shown that this method has a great performance in the near field transcutaneous operation and can be used for orthopedic implant identification.**

***Index Terms*— Electrodes, touch probe, orthopedic implant identification, RFID tag, transcutaneous**

I. Introduction

ORTHOPEDIC implants are a type of joint implant such as knee and hip implant to replace the severely injured or diseased joints for people who suffer from joint problems and bring those people back to a normal life. The total number of knee and hip replacement surgeries per year in US keeps increasing in the recent years and will hit 3.48 million in 20 years [1]. However, once the implant replacement surgery is finished, doctors and surgeons have difficulty to observe and obtain the detailed information of the implant. Existing methods for implant identification suffer from several drawbacks. First, the information is not stored on the implant but somewhere else, which can raise the risk of data loss or counterfeiting. Second, most hospitals use paper based archives to keep the patient history whose management is a huge cost. Third, it takes much time to search for the implant and patient information, which does not only increase the risk of mistakes but also increases the cost. Aiming at providing an efficient and accurate way for orthopedic implant identification to reduce time and cost, a method of using RFID technology, a wireless radio frequency communication technology, for orthopedic implant identification has been proposed. The proposed solution is to attach a battery free implantable RFID tag on the orthopedic implant (Fig. 1). There are several reasons to use RFID for implant identification. First, an RFID tag has a rewritable memory large enough for not only an implant ID but also a complete patient registry including patient details, operation details and implant details. Second, the average period for reading an RFID tag is only a few seconds, a lot less than searching a paper based record. Third, the information is always kept on the implant, so there will be no worry about data loss or counterfeiting. Fourth, the RFID tag can be used as a server to drive a biosensor for monitoring the status of the implant to help diagnosis, which is a popular research topic at present and will have huge potential applications in the future.

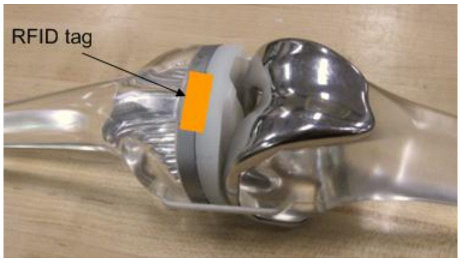

Fig. 1. RFID tag on an orthopedic implant.

A typical RFID system includes a reader with a transmitting antenna and a tag with a receiving antenna. Powering the tag for transcutaneous operation is usually based on the inductive coupling of the two resonating antennas [2]-[5]. However, most of the orthopedic implants are made of metal, causing interference with the RF signal, thus, the existing RFID antennas suffer from low efficiency [6], [7]. Because a passive RFID tag operates without a battery and relies only on the power received from the reader, efficiency is then critical to a

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successful operation and a large operation range. The current solutions are to increase the size of the antennas and re-tune the antennas [8]; however, this will be impractical in two aspects. First, there is limited space for the RFID tag and no big antennas can fit; second, increasing the antenna size at the reader side also increases the radiation area around human body, thus increasing the chance of interference between the RFID system with other medical devices in the body such as a pacemaker, which can cause a fatal malfunction of the medical device [9]. The proposed method in this paper using the touch probe is to address the above issues.

The proposed method is based on the fact that ionic fluids within biological tissues are capable of conducting electrical current which, when intentionally manipulated, can be used to transmit information and energy [10]. If two pairs of electrodes one internally and the other externally are both attached to the tissue, energy transfer will occur by capacitive coupling between the two pairs (Fig. 2). The existing systems using capacitive coupling for a biomedical device include transmitting signal along tissue [11], transmitting signal through tissue [12] and transmitting power through tissue [13]; however, none of the existing systems have used RFID devices. Furthermore, none of the existing systems have studied the interference with metal when capacitive coupling is applied. This paper establishes a platform using a touch probe method to operate an implantable passive RFID device on a metallic implant. The next part of this paper discusses how metal degrades the efficiency in signal reception with an experiment platform using a saline container. The third to the fifth sections of this paper discuss the design and optimization of the system with experiments using pig skin. The prototype system has shown that the proposed method can achieve a good operation range for near field transcutaneous operations while uses a probe much smaller than any antennas used in the existing RFID systems.

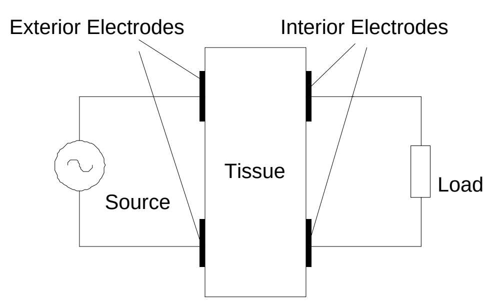


Fig. 2. The two pairs of electrodes coupling with each other for energy transfer.

II. The Metal Effect

Signal attenuation occurs when the RF signal is going through biological tissue. To study how metal affects signal reception, experiments on signal attenuation have been conducted with two cases: a metal plated being placed behind the interior electrodes and no metal insertion.

A. Experiment Platform

The experiment uses saline solution with 0.18% NaCl concentration, recommended in [14] to mimic biological tissue in the measurement. A saline container is built with two holes drilled through the center of the front side so that the exterior electrodes can be fastened to the inner surface of the front wall using screws. The two exterior electrodes are selected to be 40 mm in diameter with 50 mm between each center so that the RF signal can distribute in a large area in the saline. A movable panel with a slot is used to hold the interior electrodes and to adjust the distance between the interior electrodes and the exterior electrodes. The interior electrodes are aligned with the exterior electrodes in such a manner that their flat surfaces are in parallel and they have the same height to the bottom of the saline container from their centers. A 50mm by 80mm stainless steel plate with 5 mm thickness is attached between the movable panel and the interior electrodes as the object causing interference (Fig. 3). A sine wave at 13.56 MHz is added to the exterior electrodes, and the voltages across the exterior electrodes and the interior electrodes are measured.

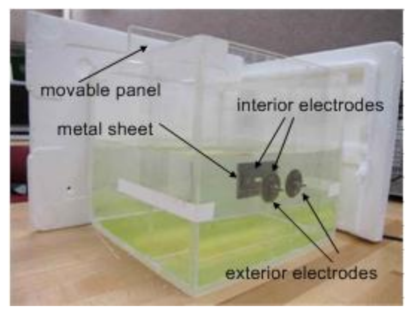


Fig. 3. The saline container with electrodes.

The signal attenuation is then calculated from (1):

$$A = 20\log_{10}\left(\frac{V_{\mathrm{EX}}}{V_{\mathrm{IN}}}\right), \tag{1}$$

where V_{EX} and V_{IN} are the voltages measured across the exterior electrodes and the interior electrodes.

B. Signal Attenuation

The signal attenuation with and without the metal plate is shown in Fig. 4. In Fig. 4, L represents the distance between the interior electrodes and D represents the diameter of the interior electrodes. The average signal attenuation increase with the metal plate is 2.38 dB, indicating an equivalent 24% loss in voltage efficiency caused by the interference. Considering that this study is the worst case in that the size of the metal plate is greater than the metallic surface of most orthopedic implants and the interior electrodes are placed right at the center of the plate, it is believed that the efficiency loss by a real implant is much less and will not cause a failure in the operation of a tag.

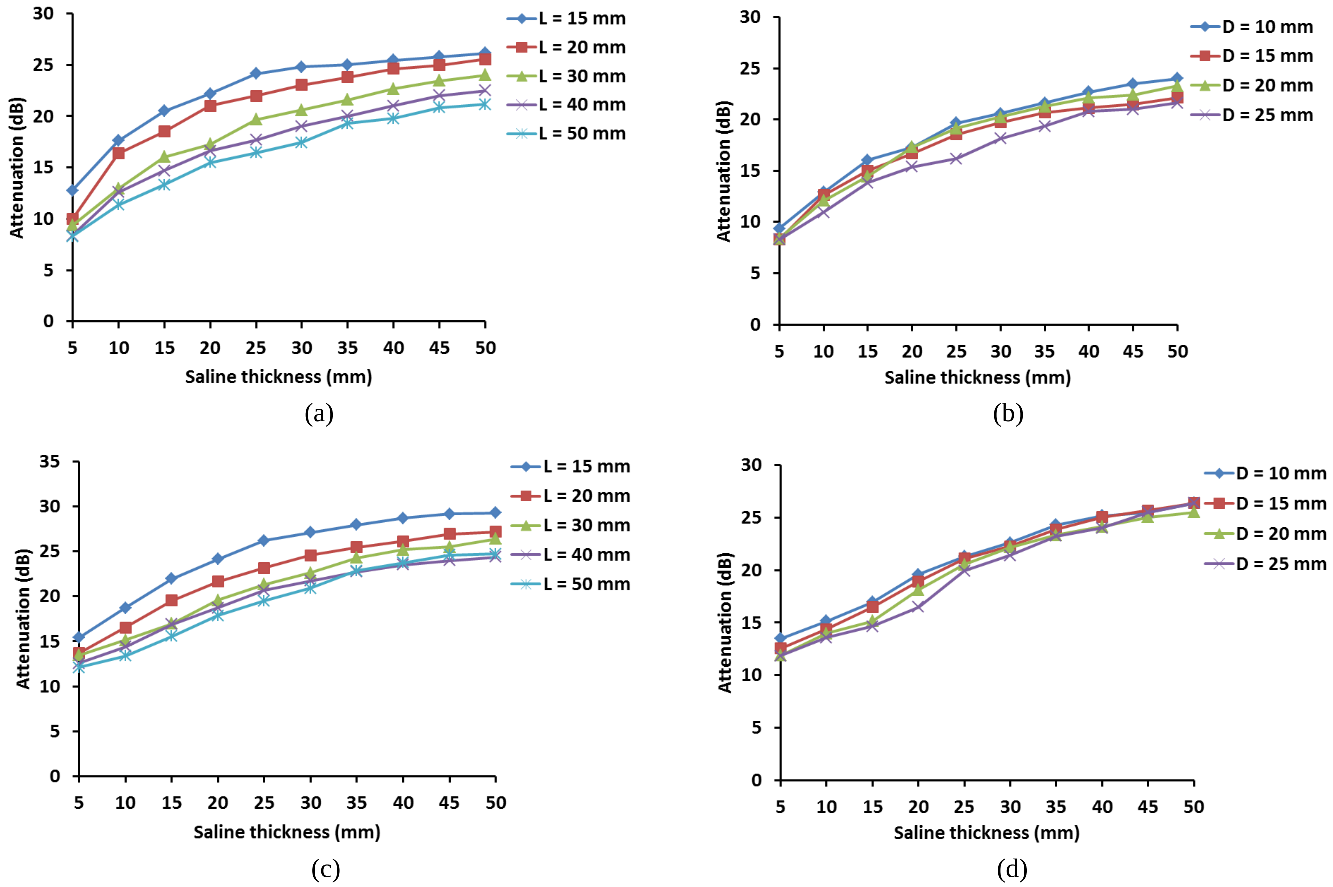


Fig. 4. (a) signal attenuation without the metal plate: D is fixed to be 10 mm; (b) signal attenuation without the metal plate: L is fixed to be 30 mm; (c) signal attenuation with the metal plate: D is fixed to be 10 mm; (d) signal attenuation with the metal plate: L is fixed to be 30 mm. Letter "D" represents the diameter of the interior electrodes and "L" represents the distance between the interior electrodes.

III. System Design

The proposed RFID system using the touch probe method is in Fig. 5, where two pairs of electrodes, one placed on the surface of tissue at the external side and the other attached under the tissue, are used for communication. Two matching circuits are added: one matching the exterior electrodes to the reader and the other matching the interior electrodes to the RFID chip. The touch probe consists of the exterior electrodes and its matching circuit and the implantable tag consists of the interior electrodes, its matching circuit and the RFID chip.

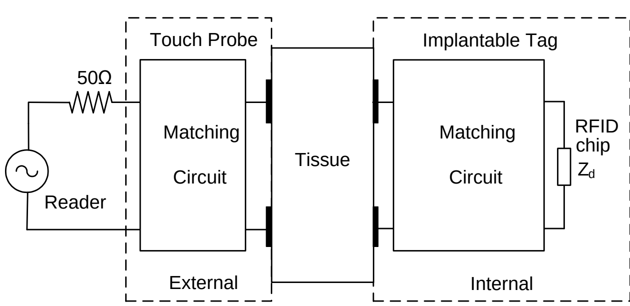


Fig. 5. The proposed RFID system.

In general, the power transmission efficiency from the reader to the RFID chip can be expressed as [15]

$$\frac{P_D}{P_R} = \tau_R C \tau_D, \tag{2}$$

where P_R is the output power from the reader, τ_R and τ_D are impedance matching coefficient at the reader side and the tag side respectively. C is the coupling coefficient (the power transmission loss) between the two pairs of electrodes. An optimized system should have a maximized coupling coefficient (minimum transmission loss) with matching coefficients at both sides being equal to 1.

The main factors that can affect the coupling include:

- Touch probe and tag geometries;
- The thickness of tissue;
- Touch probe and tag alignment.

To increase coupling for better signal reception at the internal side, we assume in the rest part of this paper, the exterior and interior electrodes are well-aligned so that they are in parallel and their perpendicular symmetric axes overlap. The coupling between the electrodes through tissue can be illustrated further using the circuit in Fig. 6. Z_E is the equivalent impedance representing the energy exchange between the exterior electrodes, without interference with the interior electrodes; Z_{EI} and Z'_{EI} represents the impedances caused by the interaction between the exterior electrodes and the interior electrodes; Z_I is the impedance representing its interference with the implant.

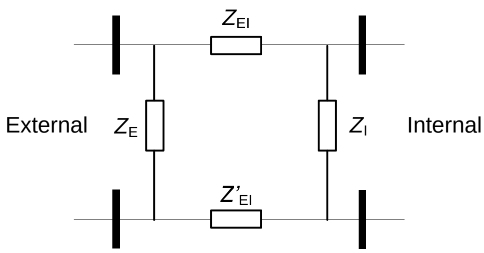


Fig. 6. The equivalent circuit of tissue using the touch probe method.

The coupling varies with the change of the above impedances. If the thickness of tissue is given as a constant, the change of the impedances is mainly controlled by changing the shape, size and location of the electrodes. However, the impedances are difficult to define and calculate in tissue; we use the following method to optimize the coupling in simulation.

We first assume the external side matched and keep the power going into the tissue $P_R\tau_R$ constant. The next step is to perform a finite element analysis using ANSYS/HFSS to solve the fields. We then calculate the open circuit voltage at the internal side V_{OP} by integrating the $\boldsymbol{E}$ field along a path linking the electrodes and the short circuit current I_{SH} by integrating the $\boldsymbol{H}$ field along a path around one electrode. According to the basic circuit laws and the maximum power transfer theorem, the equivalent impedance seen from the internal side is

$$Z_{IEQ} = \frac{V_{OP}}{I_{SH}}, \qquad (3)$$

and the power going into a perfect matched load is

$$P_{Match} = \frac{|V_{OP}|^2}{4\,\mathrm{Re}[Z_{IEQ}]}. \qquad (4)$$

Because equation (4) is the power with τ_D=1 and the input $P_R\tau_R$ is set constant at the beginning, from equation (2), the coupling is proportional to P_{Match}, and therefore maximizing equation (4) also maximizes the coupling. For small changes in the geometry of the interior electrodes close to its optimum, Re[Z_{IEQ}] is approximately proportional to $|Z_{IEQ}|$, as closer electrodes results in smaller resistance (Re[Z_{IEQ}]) but also reduces the reactance (Im[Z_{IEQ}]) and vice verse. Therefore, with an affordable difference, we use $|Z_{IEQ}|$ instead of Re[Z_{IEQ}] in equation (4) to reduce computation complexity, and the function to optimize is simplified to $|V_{OP}I_{SH}|$.

IV. Electrode Design

A. Touch Probe Electrodes

The major consideration to design the touch probe electrodes is the size. The touch probe should have a proper size so that it can fit onto the knee area of an adult person. The size of the electrodes also affects the field distribution in tissue and therefore affects the performance of the system in that the area of the field around the touch probe is proportional to the size. Because bigger electrodes have a field distributed in a larger area causing larger interference with the upper knee while smaller electrodes focus the field within a smaller area reducing the coupling with the tag, the selection of the size is to balance between these two extremes. With the help of HFSS, the electrodes of the touch probe are selected to be 20 mm in diameter with 30 mm between each electrode center, making an overall dimension of the touch probe be 50 mm by 20 mm. This yields a field distribution within an area of approximately 75 mm by 50 mm around the electrodes, sufficient to have good coupling with the tag but does not have any interference with the upper knee (Fig. 7). The electrodes are then connected to a pair of thin copper bars so that the distance between them can be adjustable by bending the copper bars to fit people with different knee sizes.

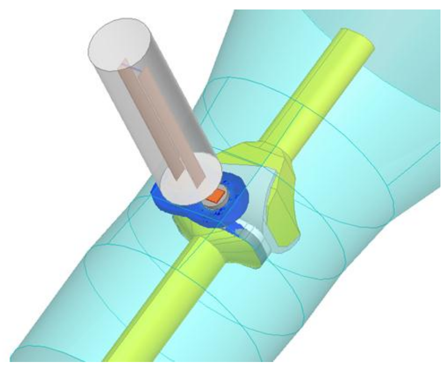


Fig. 7. The field distribution by the touch probe. The simulation is performed using ANSYS/HFSS on a knee implant model.

B. Tag Electrodes

The design of the electrodes on the tag is of significant importance to the coupling coefficient and the power transmission efficiency. One concern for tag mounting on the implant is that the bending of the tag should be minimized so that the tag maintains a good coupling with the touch probe. Another concern is to reduce the motion and abrasion of the tag for which the lower knee is the better place. A good place for the tag is the front surface of the lower knee as in Fig. 1, where the surface is nearly flat. According to [10], different patterns of electrodes including round, rectangular, triangular and ring electrodes have been studied to compare the power transmission efficiency with conclusion that round and rectangular electrodes are more efficient than the other two. In this paper, electrodes are shaped as shown in Fig. 8, which combines the advantages of round and rectangular electrodes. The tag size is limited within a rectangular area of W by H.

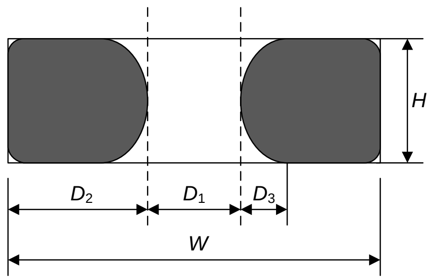


Fig. 8. The design of the electrodes on the tag. D1, D2 and D3 are the control parameters to determine the performance.

As from the experiment results in Fig. 4, larger electrodes with a larger distance between them have a less signal attenuation and in turn a larger coupling coefficient. With the limited space on a knee implant, the problem is to find the optimal point to balance the tradeoff between the electrode size and the distance between the electrodes. Therefore, the outer border uses rectangular shape to increase the electrode area and the inner border uses round shape to increase the effective distance between the electrodes. Three parameters D_1, D_2 and D_3 are the control parameters that determine the distance between the electrodes, the size and the shape of electrodes respectively. The design of the electrodes then becomes an optimization problem with constraints defined in the following equation. The objective function to be maximized is the power received by the interior electrodes which, in this paper, is the multiplication of the open circuit voltage and the short circuit current as discussed previously. The constraint is the total size for the tag being equal to the specified size.

$$\begin{aligned} &\underset{D_1,D_2,D_3}{\mathrm{MAX}} \quad \{|V_{OP} I_{SH}|\} \\ &\text{s.b.} \quad D_1 + 2D_2 = W \text{ and } D_3 \le D_2. \end{aligned} \tag{5}$$

In the optimization process, interior electrodes are fixed to a rectangular area of 30 mm by 10 mm considering the available space on the front surface of a knee implant. D_1 is optimized within a range from 6 mm to 14 mm, with 0.5 mm increment. D_3 ranges from 0 to D_2 to adjust the shape and the equivalent distance between the electrodes. With each set of D_1, D_2 and D_3, the dimension of the tag model is adjusted and a simulation is performed to analyze the field around the tag with $|V_{OP}I_{SH}|$ being calculated. The results are shown in Fig. 9. As D_3 increases from 0 to 5 mm, the inner border changes from rectangular to round; as D_3 continues increasing, the shape changes from round to triangular which is inefficient from [10]. The optimized parameters of D_1, D_2 and D_3 are found to be 9 mm, 10.5 mm and 5 mm separately.

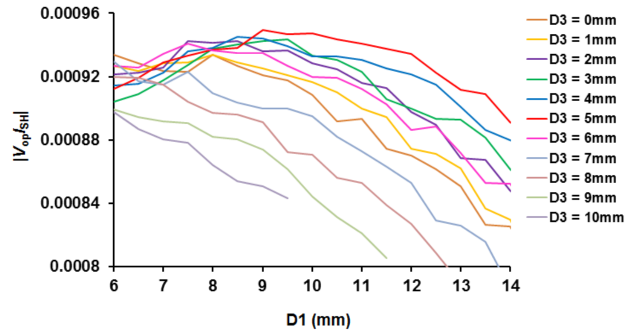


Fig. 9. The received power ($|V_{OP}I_{SH}|$) with different D_1 and D_3.

V. MATCHING

The matching networks are designed so that the impedance from both the exterior side and the interior side of the system can be matched to the desired value for maximum power delivery [16]. According to the maximum power transfer theorem, the optimal efficiency occurs when the touch probe is matched to 50 ohm and the RFID chip is matched to the complex conjugate impedance observed at the electrodes on the tag. To match the touch probe to the 50 ohm reader resistance, an LC circuit is connected between the touch probe and the reader. Because the impedance across the touch probe is measured to be greater than 50 ohm, an inductor (L_0) is connected in parallel with the touch probe electrodes and a capacitor (C_0) is connected in series with the inductor and the electrodes as in Fig. 10.

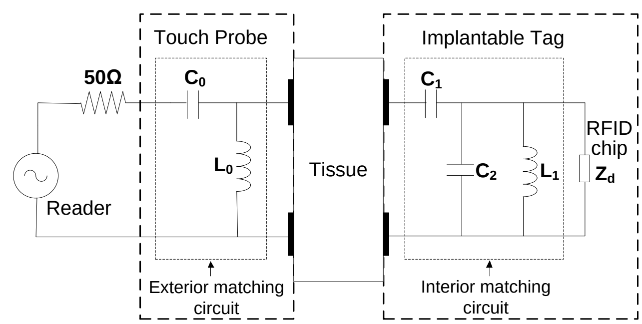


Fig. 10. The proposed matching circuits.

By setting the resistance through the matching circuit to the 50 ohm reader resistance (equation (6)), the LC values can be calculated from equation (7) in which R_S and X_S are the resistance and the reactance of the impedance observed across the touch probe electrodes and ω is the angular frequency of the 13.56 MHz RFID system.

$$-j\frac{1}{\omega C_0} + \frac{(R_S + jX_S)(j\omega L_0)}{R_S + jX_S + j\omega L_0} = 50 \tag{6}$$

$$\begin{cases} L_0 = \dfrac{5\sqrt{2}\sqrt{R_S^3 - 50R_S^2 + R_S X_S^2} + 50X_S}{\omega(R_S - 50)} \\ C_0 = \dfrac{R_S}{5\sqrt{2}\omega\sqrt{R_S^3 - 50R_S^2 + R_S X_S^2}} \end{cases}. \quad (7)$$

The RFID chip has a small rated capacitance and therefore has a larger impedance than that across the electrodes of the tag. Its matching circuit has C_1 in series and L_1 in parallel with the electrodes. Because the small capacitance of the chip requires a large inductance for matching, usually too large to be embedded on the tag, a capacitor C_2 is added in parallel with L_1 to reduce its value so that a small surface mount on-tag inductor can be used. Considering the availability of parts in discrete unit in the market, in the matching process, the value of L_1 is selected at the beginning and the problem then becomes solving for C_1 and C_2. Assuming $Z_C = R_C + jX_C$ is the combined parallel impedance of L_1 and the RFID chip Z_d and $Z_L = R_L + jX_L$ is the impedance measured across the electrodes of the tag, the matched condition is then equation (8) and its solution can be calculated from equation (9) where the item $\sqrt{R_C^2 - R_L R_C + X_C^2}$ is always satisfactory based on measurement using fresh pig skin.

$$Z_L^* = -j\frac{1}{\omega C_1} + \frac{Z_C\left(-j\dfrac{1}{\omega C_2}\right)}{Z_C - j\dfrac{1}{\omega C_2}} \quad (8)$$

$$\begin{cases} C_1 = \left\{\omega\left[X_L + \sqrt{\dfrac{R_L}{R_C}\left(R_C^2 - R_L R_C + X_C^2\right)}\right]\right\}^{-1} \\ C_2 = \left\{\omega\dfrac{R_L X_C + \sqrt{R_L R_C\left(R_C^2 - R_L R_C + X_C^2\right)}}{R_L - R_C}\right\}^{-1} \end{cases}. \quad (9)$$

Table I lists the LC parameters in the matching circuit and the impedance of the touch probe and the tag. Note that because of the availability of parts in continuous unit and the impedance of tissue is observed to have a small change during the measurement, there is a 10% tolerance on the matched impedance compared with the desired value. Fig. 11 shows the measured S parameters of the system. The measurement is performed with 10 mm pig skin between the touch probe and the tag with a metal plate under the tag. S_{11} is the return loss of the touch probe, S_{22} is the return loss of the tag normalized to the RFID chip and S_{21} is the gain from the touch probe to the tag which is -11.8 dB at the center frequency. This gain is higher than the signal attenuation measurement in Section II where the measured gain with the metal plate is around -15 dB because the optimization of the electrodes has increased the electrode coupling and reduced the signal attenuation.

TABLE I
THE IMPEDANCE AND LC PARAMETERS IN THE MATCHING CIRCUIT

Symbol	Representation	Value
L_0	inductance of the exterior matching circuit	1.0 μH
C_0	capacitance of the exterior matching circuit	180 pF
Z_d	RFID chip impedance	531 – j1487 Ω
L_1	inductance of the interior matching circuit	1.5 μH
C_1	capacitance of the interior matching circuit	24 pF
C_2	tuning capacitor	64 pF
Z_S	impedance across the touch probe electrodes	121 – j41 Ω
Z_L	impedance across the tag electrodes	202.7 – j85.3 Ω
Z_{M1}	impedance that the touch probe is matched to	54.6 + j4.8 Ω
Z_{M2}	Impedance that the RFID chip is matched to	189 + j92 Ω

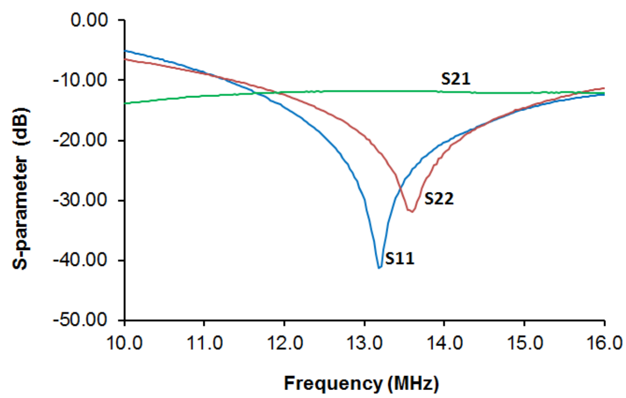
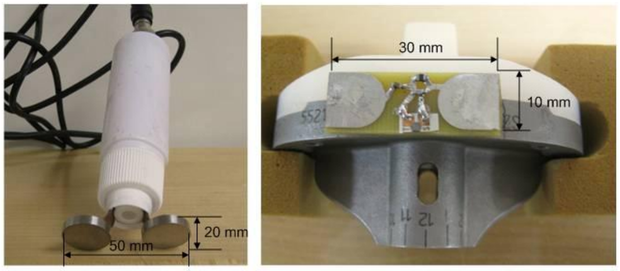


Fig. 11. The measured S parameters of the system.

VI. EXPERIMENT

Reading an implantable RFID tag through tissue is to demonstrate the operability of a tag using the proposed touch probe method as well as to study the range of operation. In this paper, fresh pig skin is used as the tissue in the experiment as the selection of tissue in [10]. Because the pig skin only has an average of 4 mm thickness, multiple layers of skin are used to increase the thickness of tissue. The number of layers of pig skin that the tag can respond through then becomes the parameter to evaluate the range of operation.

The RFID system in the experiment includes an HF RFID reader with its console application, the prototype touch probe (Fig. 12(a)) and the implantable RFID tag (Fig. 12(b)). The RFID chip is with 1 KB memory and a data rate up to 96 KB/s. The experimental setup is shown in Fig. 13, where to obtain the best efficiency, the tag is placed on the center of the knee implant and the touch probe is placed on the center area of the knee on the pig skin with proper alignment. The operation status is displayed on the screen of the computer with messages indicating a successful read operation.



(a) (b)

Fig. 12. (a) the touch probe; (b) the RFID tag on a knee implant.

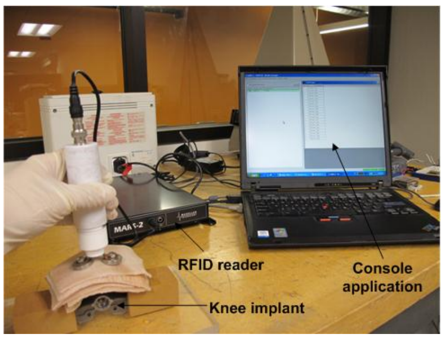


Fig. 13. Experiment on reading the tag through pig skin.

The power transfer efficiency reduces as the number of pig skin layers increases. In this paper, the read operation efficiency, defined as the ratio of number of successful operations to the number of total operations, is used to evaluate the efficiency of the proposed system through different thickness of tissue (equation (10)). One advantage to use the read operation efficiency is because it is based on statistical operation which counts the touch probe alignment and other causal factors. This can provide a more practical reference to the doctors and surgeons. The results are shown in Fig. 14 where the data are based on a total of 20 times of read operations for each layer. The unmatched system has the same setup as in Fig. 2 in which the reader is directly connected to the exterior electrodes and the RFID chip is connected to the interior electrodes without a matching circuit. The unmatched system can only operate the tag through 3 layers of pig skin while the matched one can go through 6 layers meaning that the matching circuit used in this paper is effective to double the operation range. With 6 layers of pig skin that the RF signal can go through, the operation range is close to 25 mm which is sufficient for most patients with knee implants. Therefore, the proposed system using a touch probe method is efficient to operate an implantable RFID tag to identify orthopedic implants. With a fast data rate, the operation of the tag only requires a total of a few seconds meaning that the proposed system is time efficient and cost efficient.

$$\text{Efficiency} = \frac{\text{number of successful operations}}{\text{number of total operations}} \tag{10}$$

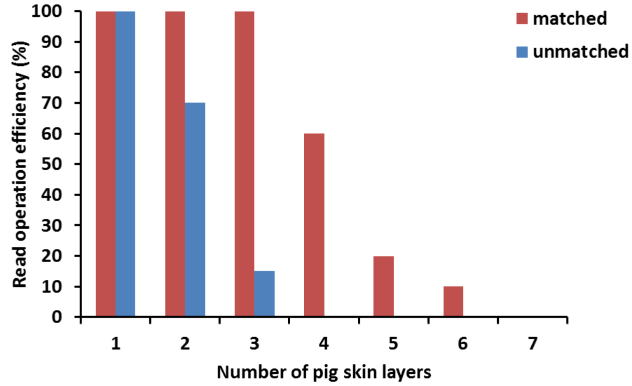


Fig. 14. The read operation efficiency with matched and unmatched system.

VII. Conclusion

This paper proposes a method of using a touch probe method to operate an implantable RFID tag that is embedded on metallic orthopedic implants. The optimization of the interior electrodes and matching the touch probe and the tag to the tissue promotes the power transmission efficiency and the read operation range through tissue. Successful operations of an implantable RFID tag through pig skin have demonstrated that the proposed touch probe method is an efficient means of communication with an implanted RFID tag embedded on orthopedic implants to reduce the interference between RF signal and the metallic implants. The operation range of 6 layers of pig skin proves that this method is capable for orthopedic implant identification with an RFID system for most patients. Compared with the existing RFID antennas and tags, the method proposed in this paper uses a much smaller touch probe and tag to obtain better transmission efficiency and is effective for orthopedic implant identification.

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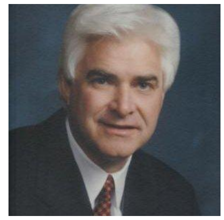

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