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Near field imaging system for orthopedic prosthesis

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Abstract

We propose in this study a novel diagnostic tool, in the form of a magnetic imaging system, to monitor the kinematics of a knee orthopedic prosthesis. The system operates in near field, in the LF band (50 kHz), and can be used for every type of knee prosthesis provided that they are made of metal. The current system made of 20 inductive coils allows extracting the orientation around the yaw rotation axis of a femoral shield and was validated by practical measurements.

1. Introduction

Every year, more and more knee prosthesis are implanted worldwide due to the growing population and aging as well as the increase in obesity. It is estimated that for 20% to 30% of patients having a knee prosthesis, there is pain felt even though routine examinations are normal. Typically X-ray radiography is used for diagnosis but it only gives a static 2D image of the implanted prosthesis which is not enough to build an accurate diagnostic. Fluoroscopy is one of the few examinations that allow to see the kinematics of the knee prosthesis [1]. Moreover, this is always a cumbersome, costly, and ionizing solution.

The scientific literature shows a growing interest in alternative solutions to these constraining examinations. Two approaches are being studied. The first one consists in modifying a knee prosthesis to integrate an electronic or passive device [2,3]. Although the results obtained are promising, modifying a prosthesis is not trivial from a regulatory point of view, and the proposed solutions cannot be applied to existing prosthesis. On the other hand, there are systems that do not require prosthesis modification. For example, CT (Computed Tomography) allows to observe the movement of a prosthesis on a 2D plane from numerous X-ray images. This very expensive and ionizing device requires a complex calibration phase that does not allow universal use of the system in all radiography centers.

The work described here presents an innovative, low-cost, highly integrable, non-ionizing and non-invasive solution that has the potential to address the diagnostic gaps described above with the possibility to display the 3D kinematics of the knee prosthesis. We propose a new 3D imaging device operating in near field, in the LF band (50 kHz) and allowing to follow the movement of a standard unmodified knee prosthesis. The principle is based on the use of a planar inductance matrix allowing to perform an inductive measurement of the moving prosthesis.

The rest of this paper is organized as follow. In section 2, we introduce the basic principle and the design of the novel imaging system. We propose a 2D magnetic map to visualize the prosthesis position according to experiment result of self-inductance in section 3 and another map according to transmission parameters in section 4. Lastly, concluding remarks and future work are given in section 5.

2. Basic principle and design of the system

Knee prosthesis are made of metal and are implanted in a biological environment mainly composed of skin, muscle, bone, fat, biological liquid, and cartilage with a rather low conductivity [4]. They therefore offer a significant conductivity contrast with their environment to be detected.

The principle of the measurement is as follow (see Figure 1): the emission of a primary magnetic field by a coil induces eddy currents on the metal prosthesis. These currents generate a secondary magnetic field which opposes to the primary field and thus modifies the values of the self-inductances and mutual inductances between two detectors. Self-inductances values or mutual-inductances values are combined to display an image of prosthesis

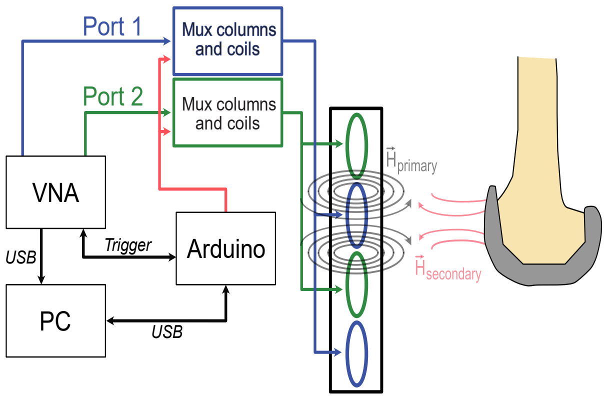

Figure 1. Principle of detection of the prosthesis.

The imaging system shown in Figure 2 is composed of a control board and five detector boards. Each detector board is based on 4 coils arranged in an arc around the prosthesis. All the detectors have the same geometry. It is based on a concentric circular coil made of 43 turns. The external diameter is 36.6 mm and internal diameter is 2.4 mm. The separation between each turn is 0.4 mm. This geometry allows generating a homogeneous magnetic field and features a self-inductance value close to 71 µH. It is to be noted that all measurements are performed at 50 kHz to comply with the European regulation authorities [5]. The measurement set-up shown in Figure 2 was realized to detect the orientation of a femoral shield (upper part of a total knee prosthesis) fixed on the axis of a stepper motor (NEMA 17). This setup allows measuring the inductances values of all detectors as a function of the orientation of the prosthesis from 0 to 180° (steps of 9°) according to the yaw rotation axis. For initial orientation (0°), the front of the prosthesis is close to the detectors and centered in the arc. Then the prosthesis rotates in clockwise direction up to 180°.

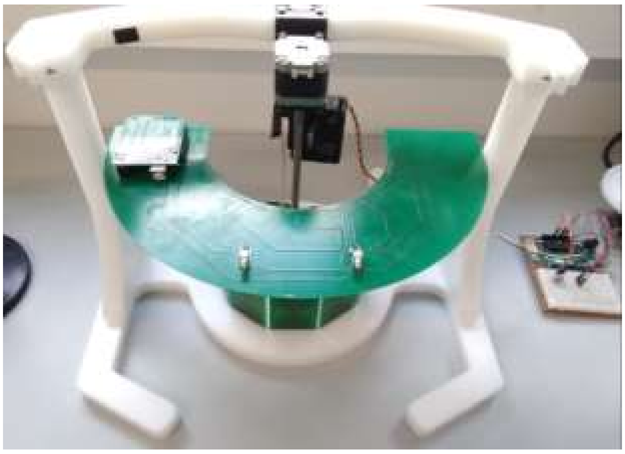

Figure 2. Imaging system (front view).

Measurement of inductance values are performed with a two ports vector network analyzer (VNA) Keysight E5061B. A multiplexer allows the routing of port 1 of VNA to even-numbered detectors ranging 2 to 20, whereas a second multiplexer connect port 2 to the odd-numbered detectors ranging from 1 to 19. The detectors are positioned around the prosthesis to be imaged as shown in Figure 2. Self-inductances values are extracted from measurement of S11 et S22 parameters, and transmission coefficients values (correlated with mutual inductances) are extracted from S21 or S12 parameters. The configuration of both multiplexers to measure a specific self-inductance or transmission coefficient is done by an Arduino board which is also in charge of triggering the record of the waveform on the VNA by generating pulse on its external input trigger.

3. Self-inductance measurement for a given coil

For each new measurement round, we first perform a no-load measurement (without the prosthesis) of all inductances. For this empty measurement, the recorded values are shown in Figure 3. The range of values is between 71.29 µH and 73.85 µH. We then place the prosthesis in the center of the arc formed by the detector boards and we observe the inductance variations as a function of the orientation.

71.38 µH (1)	72.76 µH (2)	71.79 µH (3)	73.38 µH (4)	71.61 µH (5)
71.29 µH (6)	72.45 µH (7)	71.57 µH (8)	73.32 µH (9)	71.51 µH (10)
71.34 µH (11)	72.62 µH (12)	71.51 µH (13)	73.32 µH (14)	71.51 µH (15)
71.68 µH (16)	72.98 µH (17)	71.87 µH (18)	73.85 µH (19)	71.87 µH (20)

Port 1 (white) *Port 2* (green)

Figure 3. Measurement of the coils with numbering (without the prosthesis).

As shown in Figure 4, we observed that among the 20 sensors of the system, the largest variations are obtained for those closest to the surface of the prosthesis.

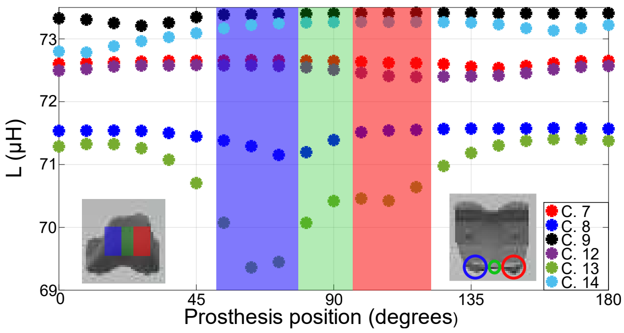

Figure 4. Variation of self-inductances according to the position of the prosthesis (9° steps) at less than 2 cm.

Since detector noted 13 is the closest one, we obtain the largest variation of the order of 2.15 µH. The shape of the curve seems to show a good correlation with the geometry of the prosthesis in the horizontal plane. Indeed, the asymmetry of the prosthesis corresponding to blue and red areas in Figure 4 can be detected based on the analysis of the curves. The trochlea (a kind of trench that allows the movement of the patella in the alignment of the femur) corresponding to the green area on figure 4 can also be seen.
With the help of all the self-inductances, a mapping is made. The objective is to associate a magnetic image to a

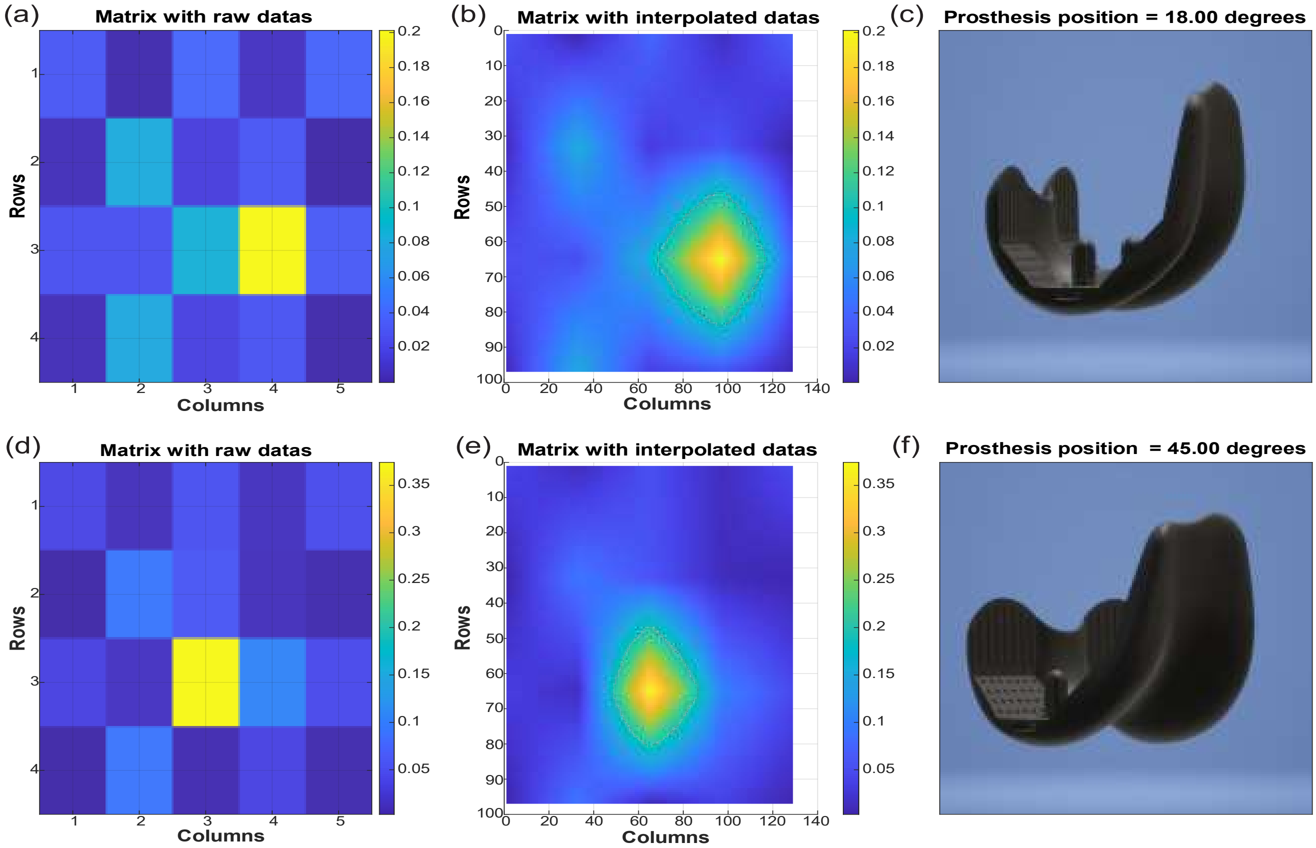

Figure 5. Measured self-inductance 2D map (a) based on RAW values, (b) and after interpolation for the femoral shield orientated at 18° as shown in (c). Figures (d) to (f) are similar to (a) to (c) but when the femoral shield is orientation at 45°.

position of the prosthesis. Several steps are necessary to achieve this image. The first step is to make a measurement of the 20 self-inductances without the prosthesis. For each self-inductance, a pixel is attributed on a raster image representing the real placement of the physical system (see figure 3).

Then, a measurement of the 20 self-inductances is made for each position of the prosthesis. For each position, the no-load measurement is subtracted to obtain only the variations due to the presence of the prosthesis. We thus obtain a raw matrix of 20 pixels (4x5), this is the raw magnetic image of the prosthesis (see figure 5).

A last step allows us to obtain the interpolated magnetic image of the prosthesis. The interpolation of the raw matrix makes the variations on the magnetic image more visible by artificially increasing the number of pixels. Indeed, the interpolating step increase the number of pixels by a factor of 32 on each dimension so that we obtain finally an image based on 96x128 pixels.

We can clearly see that the most important variation among the 20 coils moves in the same direction as the prosthesis, from right to left (see figure 5) passing from self-inductance 14 to self-inductance 13 (see figure 3). But also, a decrease of the variations for the inductance 7 and 17 between the two positions of the prosthesis because the back part of the prosthesis moves away from the coils during the rotation. Even though the preliminary results are promising and prove that the designed system allows to extract a rough estimation of the prothesis orientation, the detection range is limited to less than three centimeters in our case so that the system cannot be used for each patient having a knee prosthesis due to great morphological differences.

4. Transmission measurement between two coils

We focus now on transmission coefficient measurements that improve sensitivity for a wider range of detection. In addition, the amount of measured sensor data is much higher to compare with self-inductance; so potentially both the accuracy and the detection reliability could be improved. The current system allows measuring transmission values for 200 couples of coils among the 20 coils denoted 1 to 20. Figure 6 shows transmission coefficient variation for various couple of coils that showed a significant variation according to the orientation of the prosthesis. To find these values, we normalize S12 or S21 parameters by the value obtained during the empty measurement. Among the 200 couples of coils, we observed that the most sensitive ones are those close to the prosthesis as for the self-inductances. In addition, two coils closely spaced are more sensitive than those which are well separated. As for the self-inductance values, we can extract a 2D map of values for a given orientation. Figures 7 (a) and (b) show the map obtained for two different orientations (18° and 45°). One can see that the number of pixels is much higher to compare with the map obtained based on self-inductances values so we have a larger amount of data. Even though significant variations can be observed, the spatialization of the data is lost with a 2D image. Thus, the variations can no longer be explained globally but locally, and numerical method has to be applied to extract an orientation from these 2D maps.

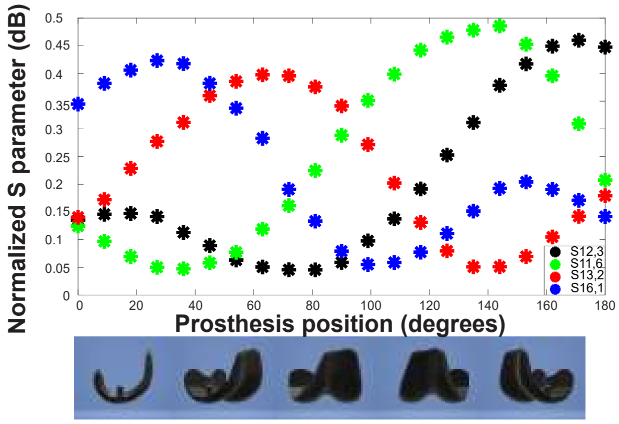

Figure 6. Variation of S-parameter according to the position of the prosthesis (9° steps) at 5 cm.

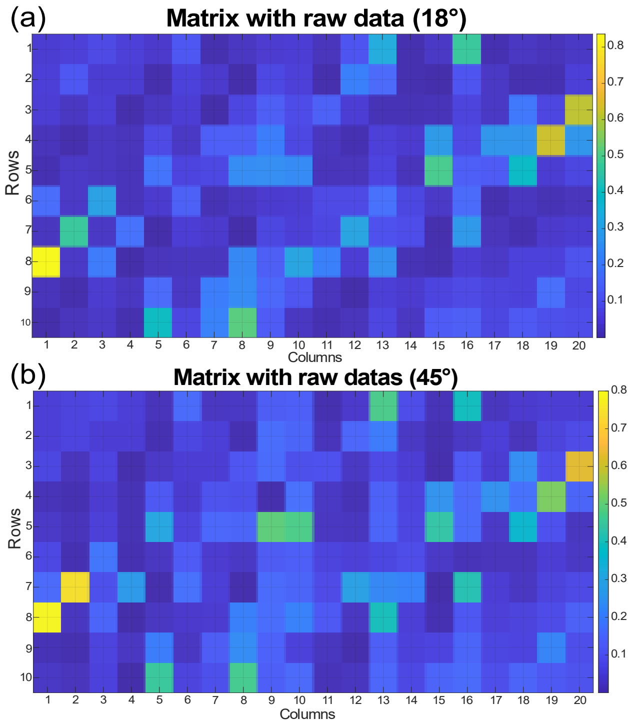

Figure 7. Raw magnetic image with S parameters for two prosthesis positions 18 ° (a) and 45° (b).

5. Conclusion

It is shown in study that the association of prosthesis position with a 2D magnetic map can be achieved using a novel low frequency magnetic based imaging system. Significant variations of self-inductances values have been measured for 20 circular coils positioned as a grid around the prosthesis. Based on these variations, a rough image has been extracted revealing hot spot whose intensity is well correlated with the distance between the detectors and the metallic surface of the prosthesis. Besides, transmissions coefficients for couples of coils revealed a good sensitivity to the orientation of the prosthesis and allowed to increase significantly the quantity of information as we rise from 20 pixels to 200 pixels. In a future work, we plan to treat the large amount of data provided by transmission coefficients in order to extract the 3D orientation of a total knee prosthesis with the help of numerical methods.

References

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