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Identification of widely applicable configurations for the electrostimulative total hip revision system*

Ulf Zimmermann and Ursula van Rienen, *Member, IEEE*

***Abstract*— Since the 1980s electrostimulation is used to accelerate the healing of fractures and bone defects. In prior works this effect has been implemented in a numerical model of an electrostimulative hip revision cup which was optimized using a multi-objective evolutionary algorithm. The aim of our simulations is to design an implant which provides optimal electric fields in the acetabular region enhancing the reconstruction of the pelvic bone in such way as to improve the fixation of the prosthesis in the surrounding bone. In the present work we will show that this multi-objective algorithm can also be used to identify a small amount of configurations of the implant that will be able to stimulate a wide range of pelvic bones with different acetabular defects.**

I. Introduction

The accelerating effect of electromagnetic fields on the development of bone was characterized by Bassett et al. in 1974 [1]. Since then numerous studies have proven that exposure to electrical and electromagnetic energy enhances the regeneration and the growth of the stimulated bone [2, 3]. Although the underlying biological mechanisms are only partially understood electrostimulation is increasingly used in modern orthopedics to treat a wide range of fractures and bone defects [4].

Between 1990 and 2002 the number of total hip arthroplasty (THA) revisions doubled in the United States [5]. Within 15 years 27.4 % of these revisions have to be revised again mostly due to aseptic implant loosening [6]. For this reason we develop an electrostimulative prosthesis which will be able to enhance the bone recovery leading to an improved mechanical stability of the implant [7, 8].

Basing on the method of Kraus [9] we use an inductively coupled system. A primary coil is placed around the patient's hip generating an oscillating (20 Hz) magnetic field to transfer energy to an arrangement of stimulation elements which are placed on the acetabular cup as shown in Fig. 1. This field induces a voltage between the electrodes which are connected by secondary coils inside the stimulation elements. Our main focus is at the optimal positioning of the stimulation electrodes on the cup which is primarily affected by the stimulation goals.

Generally the most efficient stimulation is assumed to be a homogenous field around the cup which causes an evenly distributed electrostimulation of the surrounding bone and thus the fixation of the implant on all sides. Yet most THA revisions are necessary because of aseptic loosening. This often leaves a defective pelvic bone as it was classified by Paprosky et al. [10] (see Fig. 2). For this reason the stimulation elements have to be arranged to enhance the regeneration of this defective bone as well.

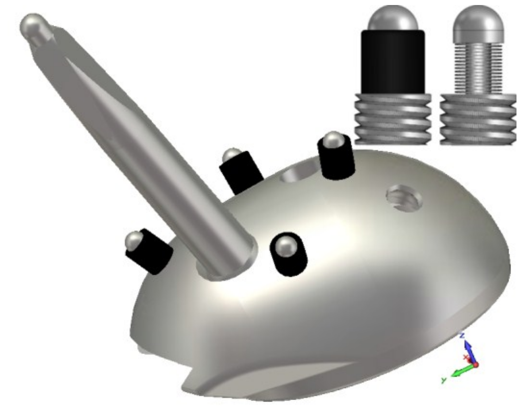

Figure 1. Simulation model of the acetabular revision cup with anchorage cone and four stimulation elements

The number of stimulation elements used on this implant is limited since each of them has to be placed into the bone during the surgery. In consequence an optimal configuration has to be found numerically depending on the anatomy of the specific pelvic bone. Our simulation method enables us to arrange the stimulation electrodes for the individual needs of every patient. But with regard to the production effort of the implant, we are also interested in a small number of electrode configurations providing a sufficient stimulation for most of the defective situations.

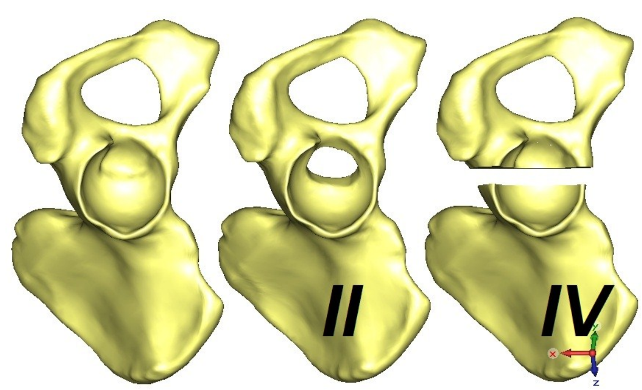

Figure 2. Simulation models of the same pelvic bone. Healthy (left), Type II: central cavitary defect (middle) and Type IV: pelvic discontinuity (right). Here the type II and IV models were artificially generated from the healthy bone for better comparison.

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U. Zimmermann and U. van Rienen are with the Faculty of Computer Science and Electrical Engineering, University of Rostock, 18059 Rostock, Germany (corresponding author; phone: +49 381 498 7078; fax: +49 381 498 7081; e-mail: ulf.zimmermann@uni-rostock.de).

II. METHODS

A. Simulation and optimization

Basing on the works of Potratz et al. [11], we use the Finite Integration Technique program CST EM Studio® to simulate the field distribution within the pelvic bone. The bone models were based on computer tomography scans which were modified afterwards to generate a layered structure as shown in Fig. 3 with different electric properties. The tissue properties as they can be seen in Table I. were gathered from literature [12] and our own research [13]. The model of the acetabular revision cup was extracted from computer-aided design (CAD) datasets and amended by stimulation elements.

Because of the linear behavior of the materials it is possible to separate the simulation from the optimization process using the principle of superposition. In this way the time for the actual optimization is remarkably reduced since there is no need to simulate each possible arrangement for the comparison. Instead of this one stimulation element is simulated at 468 equidistant distributed positions on the implant with a voltage of 1 V. The electric field distribution in a surface plane just above the implant is saved for every simulated position.

In the beginning of the optimization the optimization goals have to be defined as well as the number of stimulation elements to achieve these objectives. Thereby the number of optimization goals is irrelevant. One optimization goal can for example be that the electric field is kept below 70 V/m while the other demands a field above 5 V/m. Since these goals are most improbable to be reached with for example four stimulation elements, there has to be a tradeoff between both objectives.

For this reason the optimization is done with the help of an evolutionary algorithm. In the beginning the initial population which is a set of randomly chosen electrode arrangements is generated. For every arrangement the field distribution ($\mathbf{E}_{sup}$) in the area of interest is calculated by multiplying the extracted field distribution from the single-electrode simulations ($\mathbf{E}_i$) with a scaling factor (w_i) for each of the four stimulation elements used before superposing them. This scaling factor is proportional to the magnetic flux through the secondary coil in each stimulation element.

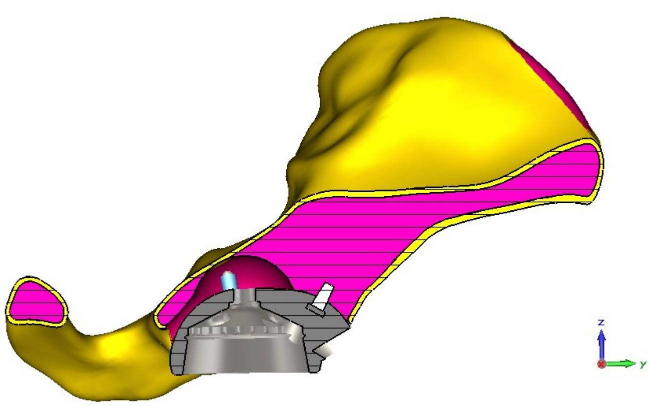

Figure 3. Simulation model of the layered pelvic bone with central defect and electrostimulative acetabular cup

TABLE I. ELECTRIC MATERIAL PROPERTIES

material	conductivity σ [S/m]	rel. permittivity ε_r
cancellous bone	0.08	4 020 200
cortical bone	0.02	25 119
blood[a]	0.7	5 260
fat[a]	0.015	5 032 800
background material	0.01	10 000 000

a. Possible tissues inside the defect (worst case)

$$\mathbf{E}_{sup} = \Sigma\, w_i\, \mathbf{E}_i \tag{1}$$

The evolutionary algorithm evaluates the calculated electric field distribution of the initial population with respect to the optimization goals. The best arrangements are used again in the following population. In addition, modifications of the best arrangements as well as of randomly selected other arrangements are attached to the following population to be evaluated again. This so called tournament is repeated until a final population is reached. If more than one optimization goal has been defined this final population provides several electrode arrangements from which any one can be selected. Fig. 4 shows the electric field 3 mm above the implant of such an arrangement. This surface represents our stimulation area.

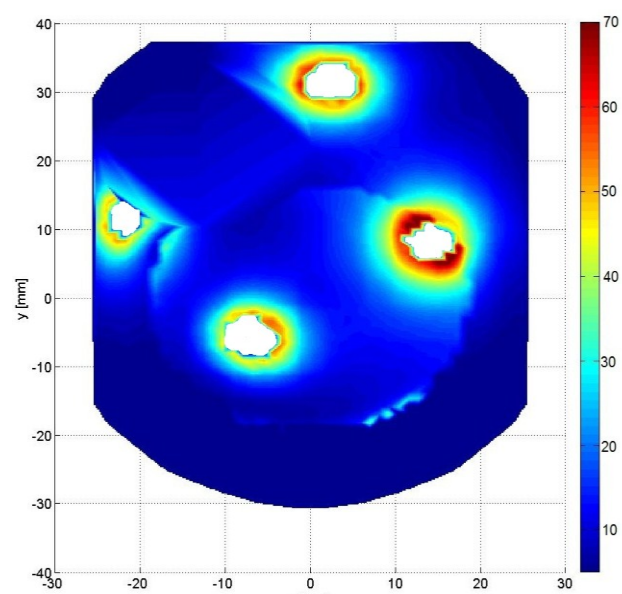

Figure 4. Absolute value of the calculated electric field [V/m] 3 mm above the acetabular cup. The color ramp is clamped between 5 V/m and 70 V/m. For this simulation, the central defect has been filled with poorly conducting fat.

B. Optimization for multiple models of the pelvic bone

The optimization algorithm is most suitable to identify the best possible electrode arrangement for the individual needs of each patient. But since all electrodes are in close proximity of the implant and since we are mostly interested in the electric fields near the implant we assume a low influence of the distant pelvic anatomy on our optimization. This assumption has been confirmed by a direct comparison between the optimized electrode arrangements of two different pelvic bones with nearly the same defective situation. As shown in Fig. 5 only in the areas where the implant is close to the edge of the bone larger deviations appear. This is because the edge differs from bone to bone.

The identification of electrode arrangements that can be generally used for the acetabular stimulation is of high interest because in this way the electrostimulative implants can be fabricated ready to use by the manufacturer and do not need to be altered in preparation of the surgery. For this reason we modified the multi-objective algorithm to be able to handle different optimization goals for different electric fields. Thus the electrode arrangements can be optimized for a multitude of CAD models of the pelvic bone. In preparation for this optimization, the single-electrode simulations have to be done for all models which is the most time consuming issue of this method. But also the optimization effort increases exponentially with the number of simulation models.

For the test of the modified multi-objective algorithm we only had two different simulation models of healthy pelvic bone available. These were remodeled by cutting out a central cavitary defect of the same size. Thus the algorithm could also be tested with four simulation models which is sufficient to serve as a proof of principle. With the help of a larger dataset we will be able to determine representative electrode arrangements.

III. Results

To compare the arrangements of the multi-model optimization with the electrode configuration of the unmodified algorithm the stimulation area was divided into two parts depending whether or not the electric field is within the stimulation interval. Since all optimizations were done with the same optimization goal to provide an electric field between 5 and 70 V/m, the percentage of the stimulated area can be used as characteristic quality feature for the electrode arrangements.

For example The electrode configuration shown in Fig. 4 which was optimized for this single model (from now it is referred to as defective bone 1) provides a sufficient stimulation at 78.02 % of the stimulation area 3 mm above the implant. For the same model this value is at 77.04 % using an arrangement optimized for both bone models with central cavitary defect.

As it can be seen in Fig. 6 most field deviations are still at the edges of our stimulation area. The variation of the electric field at the bottom electrode is also a result of this behavior because of the close proximity of the implant to the other side of the pelvic bone which can be seen in the upper left part of the implant in Fig. 3.

For the second defective bone model (defective bone 2) this arrangement provides a sufficient stimulation at 76.88 % of the stimulation area while this value is at 77.73 % using an individually optimized electrode configuration.

The result of the multi-model optimization for the unmodified models of the healthy bones shows similar results concerning the deviation, which is within the same magnitude as for the optimization of the defective bones. However, an arrangement optimized for all four models which in this case means two defective situations (healthy and central cavitary defect) provides noticeable variances

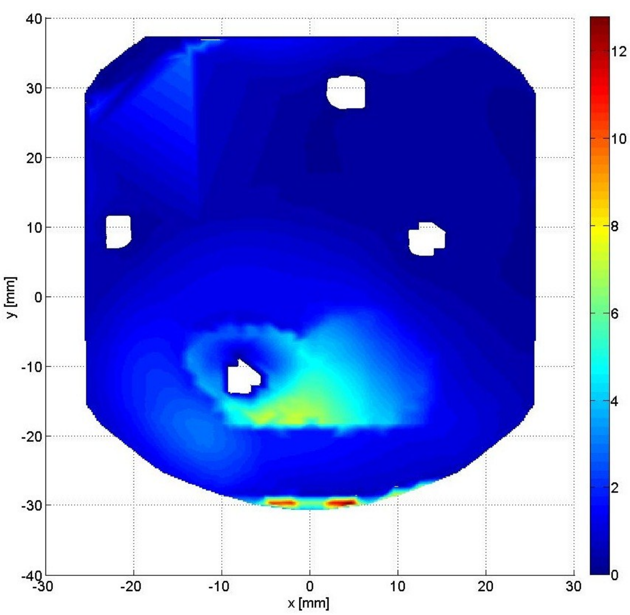

Figure 5. Relative deviation of the electric field 3 mm above the implant [%] of two different pelvic bones with the same central cavitary defect using an arrangement optimized for the first model.

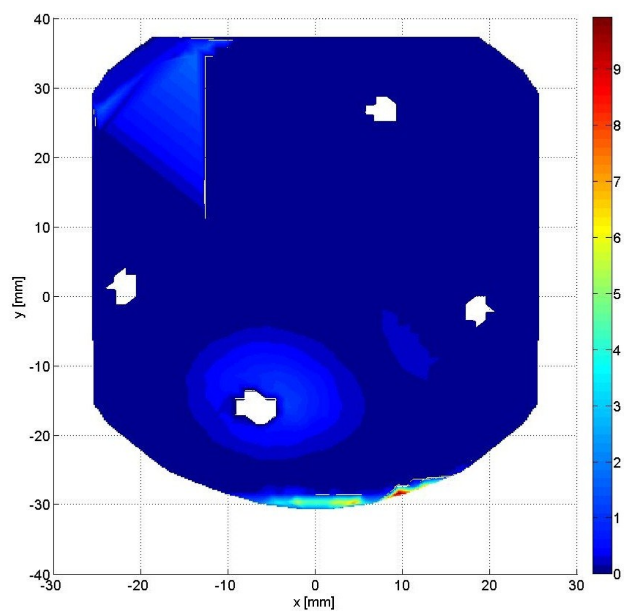

Figure 6. Relative deviation of the electric field 3 mm above the implant [%] of two different pelvic bones with the same central cavitary defect using an arrangement optimized for two bone models.

TABLE II. COMPARISON BETWEEN OPTIMIZATION METHODS

Optimization for:	**Deviation from single-model optimization of:**			
	Healthy bone 1	***Healthy bone 2***	***Defective bone 1***	***Defective bone 2***
Both healthy bone models	- 1.2 %	- 1.07 %	-	-
Both defective bone models	-	-	- 0.98 %	- 0.85 %
All four models	- 5.29 %	- 6.43 %	- 5.59 %	- 5.92 %

compared to the results of the single-model optimizations. For instance, in defective bone 1 this arrangement provides at 72.43 % of the stimulation area an electric field between 5 and 70 V/m. The particular deviations of the multi-model optimization from the individual optimizations for all models can be seen in Table II.

Here it can be seen that, as expected, all multi-model optimizations provide less stimulation in the individual model than the unmodified algorithm. In case of a multi-model optimization for the same defective situation these deviations were around one percent. Slight alterations of size and position of the central cavitary defect as they can occur in nature show only minor influences on these results.

Nevertheless it can also be seen in Table II that the arrangement optimized for all four models shows five times stronger deviations than the arrangements optimized for one defective situation. These deviations increase when further optimization goals are defined to treat the damaged area of the bone or when the stimulation interval is defined narrower (i.e. an electric field between 35 and 70 V/m).

IV. CONCLUSION

We demonstrated that the multi-model optimization is capable to generate common electrode arrangements for different models of the pelvic bone. This simple proof of principle also shows that arrangements which are optimized for more than one defective situation provide noticeable deviations from those arrangements optimized for one specific bone or a group of bones with the same defect. For this reason we aim for one electrode configuration for each defective situation of the Paprosky classification.

This is also necessary to be able to define particular optimization goals for the treatment of different bone defects. The optimizations presented in this paper have been done with a very broad stimulation interval for the whole stimulation area regarding no other goals. To meet these goals certain sections of high interest depending on the defective parts of the acetabular region have to be defined within this area. So the electrode arrangements can be optimized to apply individual electric fields within these sections.

The values of these fields are not yet well investigated. For this reason the effects of the electric field on osteoblasts, which are the cells responsible for the bone formation, are currently being investigated at the University of Rostock. The results of this research will be integrated into our optimization process.

In this way it is possible to identify one widely applicable electrode configuration for each defective situation that is able to enhance the pelvic reconstruction. To achieve this, further bone models have to be added to the dataset and related to the Paprosky classification. Nevertheless for the needs of those patients that do not fit in this classification the program can always be used to review whether the optimization goals are better met by an individual electrode arrangement.

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