From "MEC '08 Measuring Success in Upper Limb Prosthetics," Proceedings of the 2008 MyoElectric Controls/Powered Prosthetics Symposium, held in Fredericton, New Brunswick, Canada, August 13–15, 2008.

CONTROL OF PROSTHETIC ARM ROTATION BY SENSING ROTATION OF RESIDUAL ARM BONE

Todd A. Kuiken, Guanglin Li, Elliott Rouse, and David Nahlik
Neural Engineering Center for Artificial Limbs, Rehabilitation Institute of Chicago, Chicago, IL, USA

ABSTRACT

Arm rotation is very useful for unilateral amputees and essential for bilateral amputees to perform tasks of daily living. We propose a new approach for improving the control of prosthetic arm rotation in amputees. This new approach involves inserting a small permanent magnet into the distal end of the residual bone of subjects with upper limb amputations. When a subject rotates the residual arm, the magnet will rotate with the residual bone, causing a change in magnetic field distribution. This field change can be detected by magnetic sensors in the prosthetic socket, from which information on the residual bone rotation is derived and used as an input signal to control a powered prosthetic rotator. Proprioception remains intact for residual limb skeletal structures, thus this control approach should be natural and easy to use. Studies have been conducted in both simulation and physical experimental models to assess the feasibility and performance of sensing the voluntary rotation of the residual bone with an implanted magnet. The results from the studies are encouraging, suggesting potential clinical applications to improve the control of powered prostheses with preservation of physiological proprioceptive feedback.

INTRODUCTION

Internal and external rotations of the arm are very useful for upper limb amputees [1, 2]. Most commercially available upper limb prostheses only provide passive arm rotators using a friction turntable incorporated into the prosthesis. Thus, control of current rotators is cumbersome, slow, unintuitive, and lacks proprioceptive feedback. One approach to improve voluntary control of artificial arm rotation is to physically couple it to the rotation of the bones remaining in the residual arm. Two interfacing mechanisms, osseointegration [3] and artificial epicondyles [4], have been developed to create physical connections between the residual humerus and the prosthesis for control of prosthesis rotation. These approaches are promising, but have drawbacks: Direct skeletal attachment is challenged by infections at the skin interface, and loading of the skin over artificial epicondyles can cause skin breakdown, in addition, there is potential for loosening of the implants.

In this study, we have proposed an alternative approach for improving the rotational control of artificial limbs. This new approach involves inserting a small permanent magnet into the distal end of the residual bone of subjects with upper limb amputations (Figure 1). The permanent magnet generates a magnetostatic field, and when the amputee rotates the residual bone, the magnet rotates relative to the surface of the arm. This rotation causes a change in the magnetic field distribution around the surface of the arm that can be detected by magnetic sensors fixed within the prosthetic

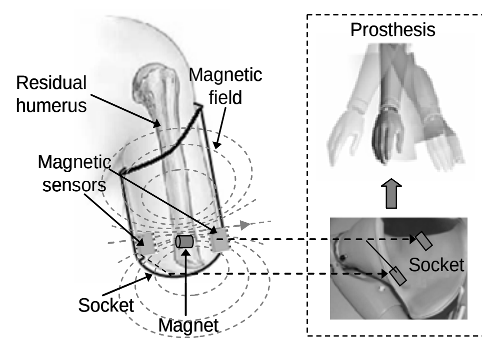

Figure 1: *Proposed implementation of implanted magnet for control of prosthesis rotation; sensing rotation of residual limb bone*

From "MEC '08 Measuring Success in Upper Limb Prosthetics," Proceedings of the 2008 MyoElectric Controls/Powered Prosthetics Symposium, held in Fredericton, New Brunswick, Canada, August 13–15, 2008.

socket. Information on residual bone rotation is therefore derived and used as an input signal to control a powered rotator.

A potential advantage of this approach is the preservation of some inherent proprioceptive awareness of arm rotation. Proprioception of rotation would come from the intact proximal joint including the muscle, tendons and joint capsule where the primary proprioceptive afferent nerve fibers are located [5]. Thus, this control approach to arm rotation should be easier and more intuitive than traditional electromyogram (EMG) methods [6] or even recently proposed EMG pattern recognition control methods [7] which rely heavily on visual feedback for the amputees to know how their arm is positioned.

Both simulation and physical experimental studies have been conducted to evaluate the feasibility and performance of this new interfacing approach. Although what is presented here considers the above elbow amputee, the concept would find similar application in control of wrist rotation for a transradial amputee.

METHODS

Simulation Model: A computer simulation study was conducted using finite element (FE) to model the upper arm as a cylinder (Figure 2). The radius of the cylindrical model was 50 mm (corresponding to the average mid upper arm circumference of approximately 300 mm for adults [8]), and the length was 300 mm [9]. All tissue (bone, muscle, fat and skin) of the upper arm model were considered magnetically homogeneous, with the approximate magnetic permeability of free space [10], and were therefore assigned identical magnetic permeability with a relative permeability of $\mu_r = 1$. A smaller cylinder was inserted into the arm model to represent the permanent magnet. The cylindrical magnet model was placed with its axis perpendicular to the arm axis and was centered with respect to a cross-section 30 mm from the distal end of the arm model. The magnet was modeled with a radius of 5 mm and a length of 20 mm to approximate a magnet that might be placed in the humerus, much like a large orthopedic screw. A magnet with a residual flux density, B_r, of 11 Kilogauss (KG) was used in the model to approximate a rare earth neodymium iron boron (NdFeB) magnet of similar size. The arm-magnet model was meshed into about 25,000 tetrahedral elements using FEMLAB[1]. The model had about 4,700 nodes. Given the pre-magnetization of the permanent magnet, the magnetic flux density vector at each node was computed by the partial differential equation (PDE) coefficient application mode of FEMLAB.

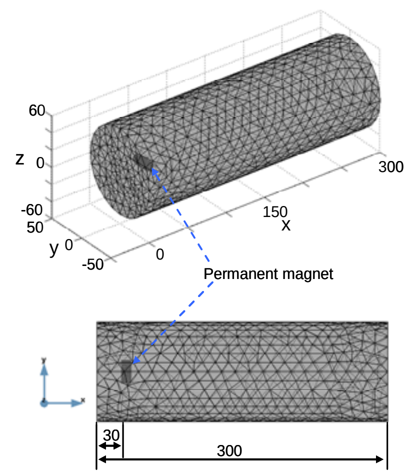

Figure 2: *FE model of upper arm with an inserted permanent magnet*

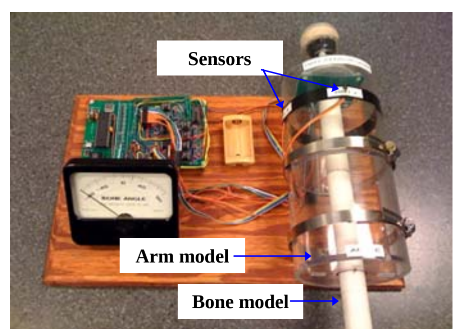

Figure 3*: Physical experimental model*

Physical Experimental Model: A physical experimental model (Figure 3) was constructed to further investigate the feasibility of this newly proposed approach. An acrylic tube, 6 mm thick

[1] FEMLAB Electromagnetics Module (version 2.3), 2002, COMSOL AB, Stockholm, Sweden

with an inner radius of 50 mm, was used to represent the surface of the residual arm. A nylon rod with a radius of 12.5 mm was settled in the center of the acrylic tube to represent the bone in a residual arm. A cylindrical NdFeB (B_r = 13.2 K*G*, N42) magnet with a radius of 6 mm and a length of 20 mm was inserted perpendicular to the axis of the nylon bone, 10 mm distal to the face of the bone. Magnetic sensors were placed (1) on the surface of the acrylic tube, in-plane with the magnet and (2) 20 mm in front of the magnet along the axis of the nylon bone in order to measure the magnetic field.

RESULTS AND DISCUSSION

Distribution of the Simulated Magnetic Field on the Surface of the Arm: Thirty-six surface nodes on the circumference of a transverse cross-section of the FE arm model were chosen as the observation points of the magnetic field. These nodes were equally spaced around the circumference at 10-degree intervals. The transverse cross-section was in the plane of the implanted magnet. The simulated field ($\vec{B}$) magnitude and its two components (B_y and B_z) at these nodes are shown in Figure 4. It can be observed from Figure 4 that the field magnitude and its two components in the *y* and *z* directions oscillate around the arm. The peak-to-peak magnetic field strength (Figures 4(b) and (c)) was about 35 *G* over 90 degrees. This provided a positioning resolution of about 0.39 *G* per degree rotation of the residual humerus model. Suitably placed magnetic sensors in the prosthetic socket would be able to detect these magnetic fields allowing the rotation angle of the residual humerus to be measured and used to control powered humeral rotation of the prosthesis.

Results from Physical Experimental Model: Two pairs of Hall effect[2] sensors, located along the axis of the bone, were used in the control mechanism for the prosthetic rotator. Each pair of sensors was subtracted differentially, with a gain of 10. The sensors gave a measure of the components of magnetic field perpendicular to the axis of the bone. To determine the angle of humeral rotation, the inverse tangent was taken of the components shown in Figure 5. The angle of the prosthetic rotator was then matched to the angle of the bone successfully.

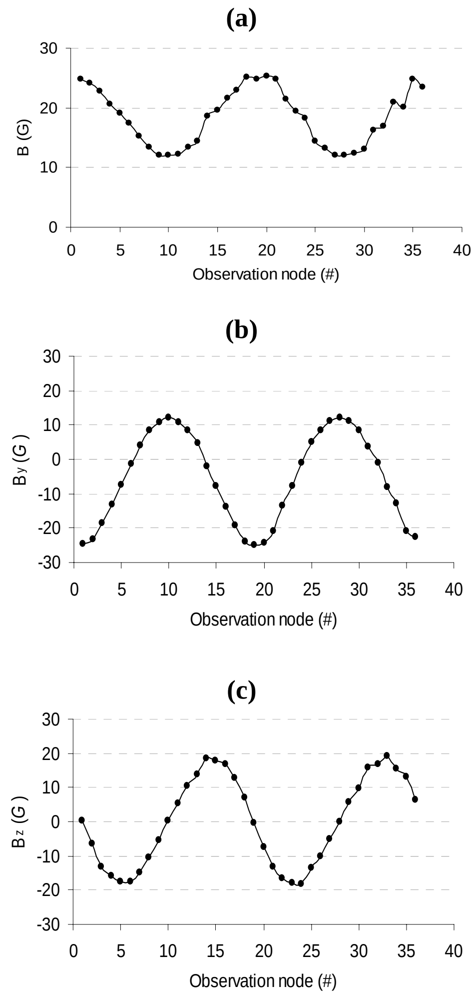

Figure 4: *Magnitudes of simulated magnetic density and its two components (B_y, B_z) over 36 observation nodes: (a) B magnitude; (b) B_y component; (c) B_z component.*

[2] Allegro A3515 radiometric linear hall effect sensors, sensitivity of 5V/1000G

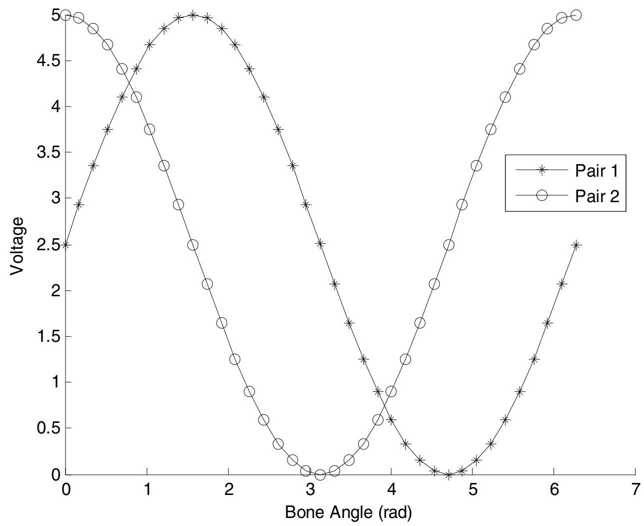

Figure 5: *Example of sensor voltage readings displaying components of magnetic field*

CONCLUSIONS

This exploration suggests that the newly proposed implanted magnet approach provides a means to sense the rotation of the residual humerus for control of a powered humeral rotator in an arm prosthesis. The results from both simulation and physical experimental studies show potential clinical applications to improve the control of powered prostheses with preservation of physiological proprioceptive feedback of rotation. This study provides important guidelines for developing a practical humeral rotation control system and implies that this technique may also be beneficial for transradial amputees.

ACKNOWLEDGEMENT

We thank Blair Lock and Aimee Schultz for their assistance in the preparation of this paper.

REFERENCES

1. C. Taylor, "The biomechanics of the normal and of the amputated upper extremity," *Klopsteg PE, Wilson PD [eds.] In: Human Limbs and Their Substitutes*, New York: McGraw-Hill, pp.169-221, 1954.
2. D. J. Atkins, D. C. Y. Heard, and W. H. Donovan, "Epidemiologic overview of individuals with upper-limb loss and their reported research priorities," *JPO.*, vol. 8, pp. 2-11, 1996.
3. R. Bloebaum, "International Symposium on Osseointegration," *32nd Academy Annual Meeting and Scientific Symposium, Chicago, IL*, 2006.
4. E. WitsØ, T. Kristensen, P. L. Benum, S. Sivertsen, L. Persen, A. Funderud, T. Magne, H. P. Aursand, and A. Aamodt, "Improved comfort and function of arm prosthesis after implantation of a Humerus-T-Prosthesis in trans-humeral amputees," *Prosthet. Orthot. Int.*, vol. 30, pp.270-278, 2006.
5. V. Dietz, "Proprioception and locomotor disorders," *Nature Rev. NeuroSci.*, vol. 3, pp.781-790, 2002.
6. P. A. Parker and R.N. Scott, "Myoelectric control of prostheses," *Crit Rev Biomed Eng.*, vol. 13, pp. 283-310, 1986.
7. B. Hudgins, P. A. Parker, and R. N. Scott, "A new strategy for multifunction myoelectric control," *IEEE Trans Biomed Eng.*, vol. 40, pp. 82-94, 1993.
8. Merck Manual, "Introduction: Undernutrition", *Merck Manual Online Medical Library* at http://www.merck.com/mmpe/print/sec01/ch002/ch002a.html.
9. M. M. Lowery, N. S. Stoykov, A. Taflove, and T. A. Kuiken, "A multiple-layer finite-element model of the surface EMG signal", *IEEE Trans on BME*, vol. 49, pp. 446-454, 2002.
10. P. Stavroulakis, "Biological Effects of Electromagnetic Fields" Springer-Verlag, 2003.