MRI–compatible Fluid-Powered Medical Devices

By JUN UEDA* *Mechanical Engineering, Georgia Institute of Technology* • **DAVID B. COMBER** *Mechanical Engineering, Vanderbilt University* • **JONATHON SLIGHTAM** *Rapid Prototyping Center, Milwaukee School of Engineering* • **MELIH TURKSEVEN** *Mechanical Engineering, Georgia Institute of Technology* • **VITO GERVASI** *Rapid Prototyping Center, Milwaukee School of Engineering* • **ROBERT J. WEBSTER III** *Mechanical Engineering, Vanderbilt University* • **ERIC J. BARTH** *Mechanical Engineering, Vanderbilt University*

**corresponding author*

This article introduces recent developments and challenges related to magnetic resonance imaging (MRI)-compatible medical devices. Recent advances in fluid-powered medical devices are described, including a needle steering robot for neurosurgery and a haptic device for hemiplegia rehabilitation. Recent 3-dimensional printing technologies for fabricating integrated fluid-powered robots are also reported.

MRI is a diagnostic technology enabling high-quality imaging of organs and soft tissues by using a strong magnetic field and sensor array. The tight space within the closed-bore scanner limits clinician access to the patient as well as the available actions that could be performed under MRI guidance. The capabilities of MRI can be extended beyond diagnostics by using teleoperated robots, which are able to provide high precision and enhanced dexterity. MRI-guided robotic surgery, where a surgeon performs an operation based on real-time MRI images, has the potential to play a key role in the expanding field of interventional radiology by enabling operational procedures that are more accurate and less invasive. Functional MRI (fMRI) is a newer technology that can provide brain activity images, and fMRI-compatible robotic technologies enable research on a wide variety of rehabilitation research. For example, neuroplasticity after stroke, somatosensory and motor functions, and sympathetic nerve activity during motor task learning.

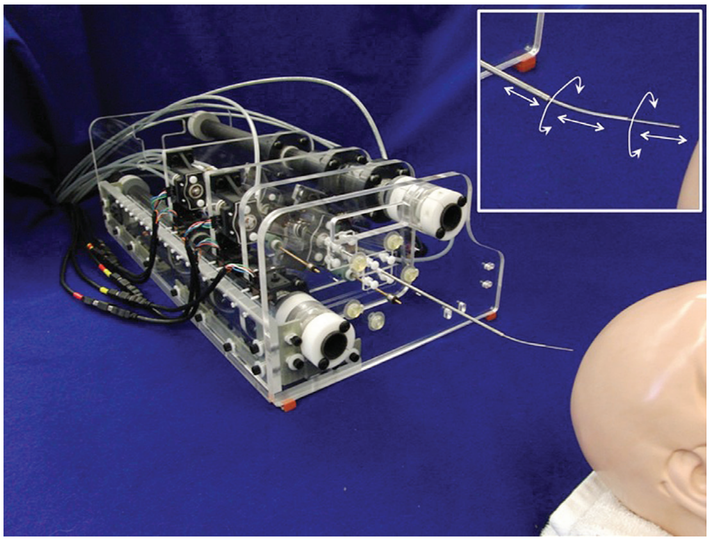


FIGURE 1 **Pneumatic needle steering robot for epilepsy therapy**[11].

The use of robotic devices in MRI/fMRI requires developing actuators and mechanisms that are able to work in strong magnetic fields and do not distort or otherwise interfere with imaging. These design requirements impose the challenging limitation that only materials within a certain range of the magnetic susceptibility spectrum can be used. Traditional electromagnetic actuators fail and may cause artifacts, especially intense magnetic fields, therefore making fluid power useful. Development of MRI-compatible devices began during the 1990s, with the first robotic platform reported in 1995 by a team of researchers at the University of Tokyo and Tokyo Women's Medical College[1]. Using six piezoelectric motors, the robot positioned a needle for stereotactic neurosurgery, but the motors substantially degraded the MRI image quality. In the years that followed, designs for non-magnetic robots attempted to avoid this problem by locating the piezoelectric motors outside the imaging volume, but many of these devices still produced unacceptable levels of signal noise, as described in a 2007 review study[2].

Fluid power actuators are considered the best solution for MRI compatibility because they can completely eliminate electric and magnetic presences from the scanner room[3]. The creators of INNOMOTION, an MR-compatible robotic system commercially available in Europe, used piezoelectric motors in an early version of the robot. However, reduction in image quality and the risk of inductive heating led the team to an improved design with pneumatic piston-cylinders, engineered for safety and controllability through high dynamic and low static friction characteristics[4]. In other research efforts, pneumatic piston-cylinders have been used in several MRI-guided needle placement robots designed for diagnosis and treatment of cancers of the prostate and breast[5-6]. Robots employing intrinsically fail-safe pneumatic stepper mechanisms have demonstrated successful image-guided interventions in pig abdomens and canine prostate[7]. Pneumatic actuators, particularly, have the compliance necessary for safety in devices interacting with humans. However, the use of fluid-driven systems, without compromising performance, is a challenging task due to the higher order dynamics those systems require and the time-delay problems associated with their tele-operation.

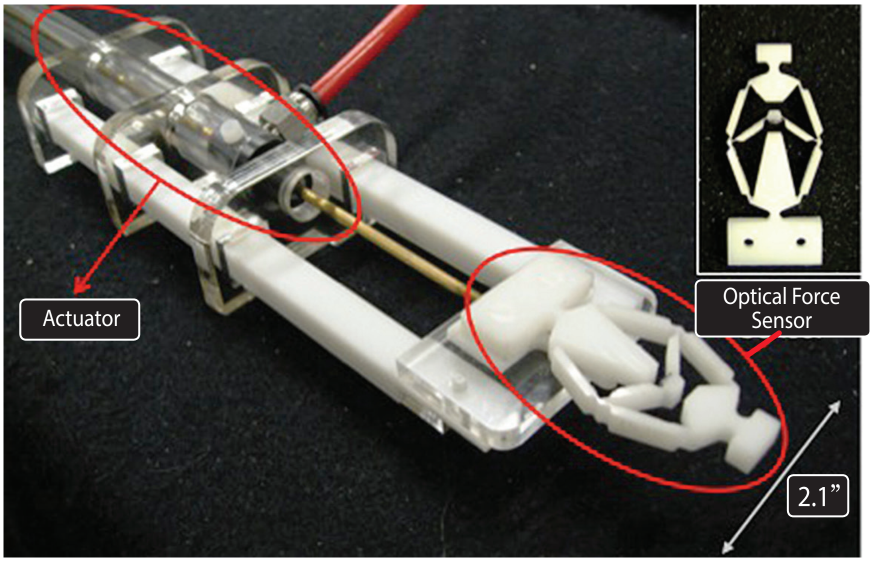


FIGURE 2 Pneumatic haptic device for hemiplegia rehabilitation[18].

FLUID-POWERED NEEDLE STEERING ROBOT FOR EPILEPSY THERAPY

One half to one percent of the population in North America and 50 million patients worldwide are affected by epilepsy with a 7 to 17 percent chance of sudden unexplained death if left untreated[8-9]. In the majority of temporal lobe epilepsy cases, seizures are caused by the hippocampus, and 60 to 70 percent of patients who undergo surgical removal of the hippocampus become seizure free for at least two years[10].

Mechanical engineers at Vanderbilt University have created the first fully pneumatic robot to be designed for neurosurgical interventions as shown in **Figure 1**[11]. The idea is that this robot could be used to position a needle at the hippocampus to deliver thermal energy (e.g. via a laser, acoustic ablator or other ablation technology) that would achieve the same goal as surgical removal of the hippocampus. We do note that thermal ablation in the brain is an experimental procedure, meaning that much testing will be required to verify that heat can accomplish the same goal as surgery. However, the potential benefit to patients of replacing open brain surgery with a needle insertion in terms of trauma and complication risk is vast if we are ultimately successful.

Actuated by five non-magnetic pneumatic piston-cylinders, the steerable needle robot rests on the MRI scanner bed just above the patient’s head. Long lines of tubing tether the cylinders to remotely located pressure sensors and valves, which position the pistons to sub-millimeter precision using a robust, nonlinear controller.

A five degree-of-freedom needle has been designed to target the hippocampus, an anatomical structure about 1 cm across and 4 cm long, located deep within the temporal lobe. The needle comprises a stiff outer tube and two tubes of a super-elastic memory metal called nitinol. Telescoping and rotating the tubes with respect to each other, the pneumatic robot steers the needle along a desired path in the patient’s brain. Before the procedure, the front end of one nitinol tube is set to a curved shape, and during the procedure the tube returns to this shape as it telescopes beyond the outer stiff, straight tube. At its tip the needle carries an MRI-compatible thermal ablator. The MRI scanner provides real-time feedback of the needle location as well as real-time thermal dose monitoring using MR thermometry.

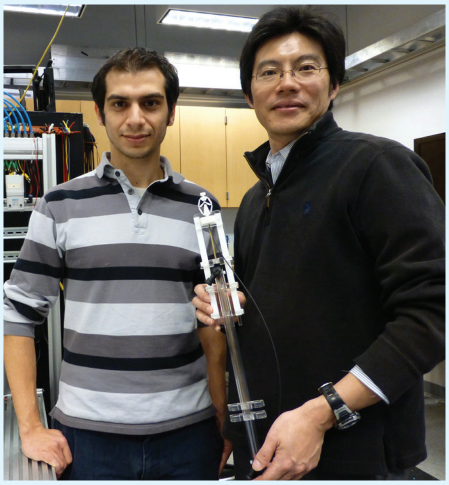
FLUID-POWERED HAPTIC INTERFACE FOR HEMIPLEGIA REHABILITATION

Hemiplegia, a paralysis of one side of the body, is widely observed in the 700,000 people who survive strokes in the U.S. every year, and it often restricts their ability to perform normal daily activities[12]. Recent studies indicate rehabilitation exercise

ABOUT THE AUTHORS

JUN UEDA received the B.S., M.S., and Ph.D. degrees from Kyoto University, Japan, in 1994, 1996, and 2002 all in Mechanical Engineering. He was an Assistant Professor at Nara Institute of Science and Technology, Japan, from 2002 to 2008. During 2005-2008, he was a visiting scholar and lecturer in the Department of Mechanical Engineering, Massachusetts Institute of Technology. Since 2008, he has been with the Woodruff School of Mechanical Engineering at Georgia Institute of Technology as an Assistant Professor. He is a co-recipient of the 2009 IEEE Robotics and Automation Society Early Academic Career Award.

DAVID COMBER received his B.S. degree with honors in electrical engineering from Pennsylvania State University, University Park, in 2009. Currently a Ph.D. candidate in the Department of Mechanical Engineering at Vanderbilt University, Nashville, TN, he is a graduate research assistant in the Laboratory for the Design and Control of Energetic Systems and the Medical and Electromechanical Design Laboratory. His research interests include MR-compatible interventional devices and the design and control of precision pneumatic actuators.



Melih Turkseven (left) and Jun Ueda.

JONATHON SLIGHTAM is currently a graduate student and research personnel at MSOE’s Rapid Prototyping Research (RPR) laboratory and received his B.S. in mechanical engineering in February 2012 at MSOE. His research interests are in additive manufacturing, robotics, controls and alternative energy. He was recognized for excellence in the use of additive manufacturing at the 2012 Additive Manufacturing User’s Conference (AMUG). He is presently working on his M.S. in engineering focusing on fluid power and robotics and plans to pursue his Ph.D. after graduation.

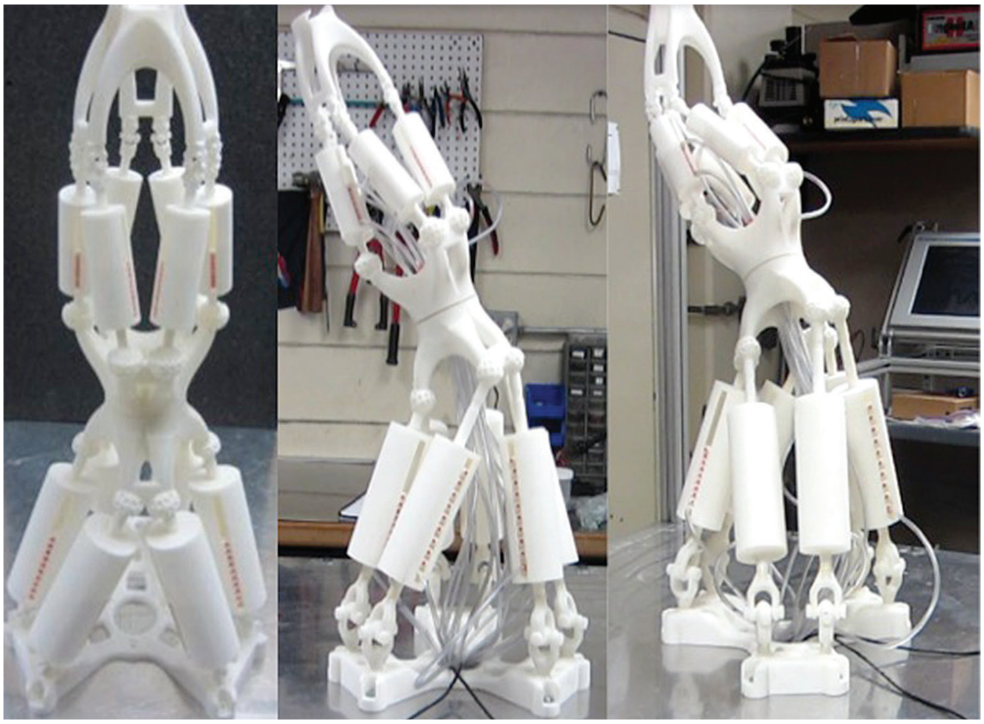


FIGURE 3 Non-assembly pneumatic robotic system[20].

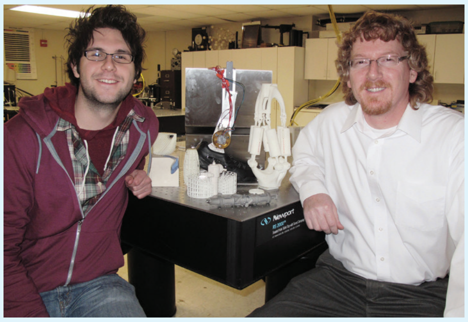
could shape subsequent reorganization in the adjacent intact cortex[13]. Robotic systems can be well-suited for rehabilitation, improving the efficiency of the health-care system as well as providing researchers with valuable data about the brain's involvement in physical tasks[14]. Research indicates that fMRI can be an effective tool for evaluating functional recovery, providing direct evidence of the efficacy of rehabilitation[15]. Thus, fMRI compatible robotic systems have been introduced where the strong magnetic field prevents a therapist from performing the exercise[13, 16].

Given the magnetic operating environment in the MRI room and the tight space inside the scanner-bore; compact, non-magnetic, low-noise, accurate robotic (i.e. force feedback) interfaces are required[17-18]. Fluid driven systems are often preferred since they satisfy the challenging compatibility requirements. Gassert et al. developed a tele-operated robotic system that interacts with the patient inside the MRI room[19]. A hydraulic connection was utilized to transmit force and motion produced by magnetic components that operate outside the magnetic shield of the MRI room.

Engineers at Georgia Institute of Technology have developed a fiber-optic force sensor and encoder made from polyoxymethylene and acrylonitrile butadiene styrene (ABS) for a pneumatic haptic interface[18]. The team invented a new design method based on the distribution of strain energy. The newly designed force amplification mechanism

MELIH TURKSEVEN received a B.S. degree in mechanical engineering from Bogazici University, Istanbul, Turkey, in 2010. He is currently working towards an M.S. degree at Georgia Institute of Technology. His current research interests include mechanical design, control of dynamical systems, bio-inspired robotics and medical robotics.

VITO R. GERVASI earned his B.S. in manufacturing engineering technology and M.S. in mechanical engineering (materials science) from Milwaukee School of Engineering in 1996 and 2003 respectively. Mr. Gervasi joined the research staff as an undergraduate research assistant in 1993 and now directs Rapid Prototyping Research. He has been involved in additive manufacturing for 19 years and has been awarded a number of patents related to additive manufacturing of lattice structures, harsh environment components and molecular models. He is an experimentalist at heart with interest in additive manufacturing (including zero G), alternative energy and NPD.



Jonathan Slightam (left) and Vito Gervasi.

ROBERT J. WEBSTER III received his B.S. degree in electrical engineering from Clemson University in 2002 and his M.S. and Ph.D. degrees in mechanical engineering from Johns Hopkins

REFERENCES

1 Masamune, K., et al, 1995, "Development of an MRI-Compatible Needle Insertion Manipulator for Stereotactic Neurosurgery," *J. Image Guid. Surg.*, 1, pp. 242-248.

2 Tsekos, N., et al, 2007, "Magnetic Resonance-Compatible Robotic and Mechatronics Systems for Image-Guided Interventions and Rehabilitation: A Review Study," *Annu. Rev. Biomed. Eng.*, 9, pp. 351-387.

3 Su, H., Cole, G. A., and Fischer, G. S., 2011, "High-field MRI-Compatible Needle Placement Robots for Prostate Interventions: Pneumatic and Piezoelectric Approaches," *Advances in Robotics and Virtual Reality*, eds. Gulrez, T., and Hassanien, A., Springer-Verlag, Chap. 1.

4 Melzer, A., et al, 2008, "INNOMOTION for Percutaneous Image-Guided Interventions: Principles and Evaluation of this MR- and CT-Compatible Robotic System," *IEEE Eng. Med. Biol. Mag.*, pp. 66-73.

5 Fischer, G. S., et al, 2008, "MRI-Compatible Pneumatic Robot for Transperineal Prostate Needle Placement," *IEEE/ASME Trans. Mechatronics*, 13(3), pp. 295-305.

6 Yang, B., et al, 2011, "Design and Implementation of a Pneumatically-Actuated Robot for Breast Biopsy under Continuous MRI," *IEEE Int. Conf. Robot. Autom., Shanghai*, pp. 674-679.

7 Zemiti, N., et al, 2008, "LPR: A CT and MR-Compatible Puncture Robot to Enhance Accuracy and Safety of Image-Guided Interventions," *IEEE/ASME Trans. Mechatronics*, 13(3), pp. 306-315.

8 Wiebe, S., et al, 2001, "A Randomized, Controlled Trial of Surgery for Temporal-Lobe Epilepsy," *N. Engl. J. Med.*, 345(5), pp. 311-318.

9 Sperling, M. R., 2001, "Sudden Unexplained Death in Epilepsy," *Epilepsy Currents*, 1(1), pp. 21-23.

10 Berkovic, S. F., 1995, "Preoperative MRI Predicts Outcome of Temporal Lobectomy: An Actuarial Analysis," *J. Neurol.*, 45, pp. 1358-1363.

11 Comber, D. B., Cardona, D., Webster, R. J., III, and Barth, E. J., 2012, "Sliding Mode Control of an MRI-Compatible Pneumatically Actuated Robot." *Bath/ASME Symp. Fluid Power & Motion Control*, eds. Johnston, D. N., and Plummer, A. R., Centre for Power Transmission & Motion Control, University of Bath, UK, pp. 283-293.

12 Roger, V.L., Go, A.S., Lloyd-Jones, D.M., Benjamin, E.J., Berry, J.D., Borden, W.B., et al., 2012, "Heart disease and stroke statistics—2012 update: a report from the American Heart Association," *Circulation*, 125(1):e2–220.

13 Dancause, N., 2006, "Vicarious Function of Remote Cortex following Stroke: Recent Evidence from Human and Animal," *The Nueroscientist*, 12(6), pp. 489-499.

14 Krebs, H. I., Volpe, B. T., Aisen, M. L., Hogan, N., 2000, "Increasing productivity

improves the resolution of force sensing, and obtains a force resolution of 0.06N by effectively reducing the hysteresis due to plastic deformation. **Figure 2** shows a prototype haptic interface. A force feedback controller has been implemented on an integrated haptic device. The team has been investigating the pneumatic line dynamics and delay. This study is expected to produce sufficient understanding of key technologies for the development of a clinically usable integrated device.

EMERGING ADDITIVE MANUFACTURING TECHNOLOGIES FOR FUTURE MEDICAL DEVICES

The emerging technology of Additive Manufacturing (AM) may prove to be a disruptive technology when applied to the aforementioned robotic devices. With the limited space in an MRI machine any device is required to be significantly tethered or inherently compact. To achieve necessary compactness, the aforementioned robotic devices could potentially be manufactured as integrated devices rather than a collection of discrete components. Additive manufacturing allows for the integration of discrete components (e.g., with fluid power systems actuators, sensors, joints, fluidic channels and structural members) to be manufactured simultaneously and optimized for compactness in a fully functional surgical robot[20].

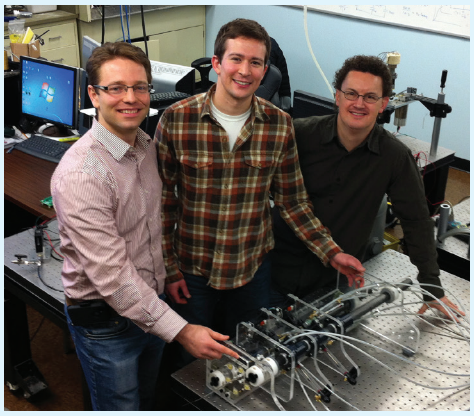
AM is believed to be the next "leap-forward" technology in MRI-Compatible robots by leveraging methods of fabricating components in a layer-wise manner. This layer-wise method of fabrication allows complex geometries to be achieved as opposed to conventional manufacturing, that is subtractive in nature[21]. AM allows for the fabrication of "non-assembly" mechanisms where components that are typically assembled after fabrication, e.g. a hub and a shaft, are fabricated simultaneously such that they are embedded into one-another, and fully functional once fabrication is complete. Non-assembly mechanisms are best enabled with the use of polymer based powder bed fusion processes, e.g. Selective Laser Sintering (SLS), which also allows for the inclusion of embedded fluid powered bellows. The addition of embedded actuation classifies non-assembly mechanisms as non-assembly robotic systems. **Figure 3** illustrates an example of the achievable complexity in non-assembly robotic systems, where each Gough-Stewart platform in the two-level system was manufactured simultaneously as a single entity. This work highlights the potential of additive technologies to manufacture compliant, customized, compact, integrated fluid power systems[20].

The use of additive manufacturing conjoined with modern digital imaging techniques allow for the customization of components, a trait that is generally needed in medical implants and devices[21]. Furthermore, the materials that are available in additive processes allow for direct end-use production of customized components and devices. In addition, the polymer-based materials have an inherently low permeability, allowing for use in a MRI environment while not causing imaging interference. Presently, SLS, Stereolithography, and extrusion processes illustrate and suggest that they offer the greatest promise in MRI compatible end-use components[23]. Future work is aimed at using AM to develop inherently safe, compact, MRI compatible medical devices. ■

ABOUT THE AUTHORS

University, Baltimore, MD, in 2004 and 2007, respectively. In 2008, he joined the Faculty of Vanderbilt University, as an Assistant Professor of mechanical engineering, where he currently directs the Medical & Electromechanical Design Laboratory. His current research interests include medical robotics, image–guided surgery, and continuum robotics. Prof. Webster received the IEEE Volz award for PhD thesis impact as well as the NSF CAREER Award in 2011.

ERIC J. BARTH received his B.S. in engineering physics from the University of California at Berkeley, and M.S. and Ph.D. degrees from the Georgia Institute of Technology in mechanical engineering in 1994, 1996, and 2000 respectively. He is currently an associate professor of mechanical engineering at Vanderbilt University. As the director of the Laboratory for the Design and Control of Energetic Systems, his research interests include the design, modeling and control of mechatronic and fluid power systems, MRI compatible pneumatic robots, energy harvesting devices, free-piston internal combustion and free-piston Stirling engines, power supply and actuation for autonomous robots, and applied non-linear control.



LEFT TO RIGHT: *Robert Webster, David Comber, and Eric Barth*

REFERENCES

and quality of care: robot-aided neuro-rehabilitation," *Journal of Rehabilitation Research and Development*, 37(6), pg. 639.

15 Carey, J.R., Kimberley, T.J., Lewis, S.M., Auerbach, E.J., Dorsey, L., Rundquist, P., Ugurbil, K., 2002, "Analysis of fMRI and finger tracking training in subjects with chronic stroke," *Brain*, 125, pp. 773–788.

16 Cramer, S.C., Nelles, G., Benson, R.R., Kaplan, J.D., Parker, R.A., Kwong, K.K., Kennedy, D.N., Finklestein, S.P., and Rosen, B.R., 1997, "A functional MRI study of subjects recovered from hemiparetic stroke," *Stroke*, 28(12), pp. 2518-2527.

17 Gassert, R., Chapuis, D., Bleuler, H., Burdet, E., 2008, "Sensors for Applications in Magnetic Resonance Environments", *IEEE/ASME Transactions on Mechatronics*, 13(3), pp. 335- 344.

18 Turkseven, M., and Ueda, J., 2011, "Design of an MRI Compatible Haptic Interface," *IEEE International Conference on Intelligent Robots and Systems (IROS 2011)*, pp. 2139 - 2144.

19 Gassert, R., Moser, R., Burdet, E., Bleuler, H., 2006, "MRI/fMRI-compatible robotic system with force feedback for interaction with human motion," *IEEE/ASME Transactions on Mechatronics*, 11(2), pp. 216-224.

20 Slightam, J., Gervasi, V., 2012, "Novel Integrated Fluid-Power Actuators for Functional End-Use Components and Systems via Selective Laser Sintering Nylon 12," *Proceedings of the 2012 Solid Freeform Fabrications Symposium*, pp. 197-211.

21 Gibson, I., Rosen, D. W., Stucker, B., 2010, "Additive manufacturing technologies rapid prototyping to direct digital manufacturing," New York: Springer.

22 Webb, P., 2000, "A review of rapid prototyping (RP) techniques in the medical and biomedical sector," *Journal of Medical Engineering & Technology* Vol. 24 No. 4, pp. 149-153.

23 Faustini, M., Neptune, R., Crawford, R., Stanhope, S., 2008, "Manufacture of Passive Dynamic Ankle-Foot Orthoses Using Selective Laser Sintering," *IEEE Transactions on Biomedical Engineering*. Vol. 55. No. 2. pp. 784-789.

ACKNOWLEDGEMENTS

The authors would like to thank the National Science Foundation Engineering Center for Compact and Efficient Fluid Power (CCEFP) for the sponsorship of this work under grant EEC-0540834.