Guest Editorial
Introduction to the Focused Section on Healthcare Mechatronics

I. Introduction

A RECENT U.S. National Academy of Engineering and Institute of Medicine study (*Building a Better Delivery System: A New Engineering/Health Care Partnership*, National Academy Press, 2005) advocated the applications of system engineering tools and information/communication technologies to improve the quality and productivity of the healthcare system. Mechatronics design principle provides a synergistic integration of information, computation, and electromechanical device and systems, which plays an important role in advancing healthcare at both the device and system levels.

In this "Focused Section on Healthcare Mechatronics" of the IEEE/ASME Transactions on Mechatronics, we solicited articles that summarize recent development in employing mechatronics approach to the design of healthcare systems and devices to improve quality of care or efficiency and productivity of healthcare delivery. In this editorial, we will highlight articles related to this topic published in previous issues of this Transactions as well as introduce the six articles published in this Focused Section.

II. Related Articles Published in the Past Five Years in IEEE/ASME Transactions on Mechatronics

During the past five years, there were numbers of papers and Focused Sections related to healthcare mechatronics that were published in the IEEE/ASME Transactions on Mechatronics. The majority of these papers are related to robotics or assisted rehabilitation, surgery, and prosthesis.

A. Rehabilitation

In 2006, a series of papers were published that discussed the design of exoskeleton for rehabilitation. Gupta and O'Malley [1] summarized the space, weight, and kinematic constraints as well as workspace and performance requirements for a haptic arm exoskeleton used for robot-assisted rehabilitation and training. Their paper described the design and control of a five-degree-of-freedom (5-DOF) haptic arm exoskeleton that was capable of providing kinesthetic feedback to the lower arm joints and wrist of the patient. The weight and volume limitations were also discussed in Kong and Jeon's work [2] on the development of a tendon-driven power assistive exoskeleton designed for the elderly. The exoskeleton for patients and the old by Sogang University (EXPOS) is a caster walker that used tendon-connecting motors and pulley at the hip and knee joints to generate the necessary assistive power. Mori *et al.* [3] developed a robotic assistive device to provide mobility for a patient with leg disability. The device consisted of a pair of telescopic crutches, a powered lower extremity orthosis, and a pair of mobile platforms. A motion strategy was proposed to coordinate the use of the three modules to assist the patient to stand up from a sitting position, walk, and ascend a flight of stairs. In 2007, Perry *et al.* [4] presented the design of an anthropomorphic, 7-DOF cable-actuated dexterous exoskeleton for neurorehabilitation (CADEN-7). The novel placement of the motors (proximal) and cable-pulley (distal) led to a low inertia, high stiffness, zero backlash, and back-drivable powered upper-limb-assistive device. Masia *et al.* [5] presented the design and characterization of a hand robot that completed the development of an upper extremity robot that can be used for neurorehabilitation of the upper-extremity motor functions. A novel dual-rotor statorless motor was the key component in the design.

Assisted gait and posture rehabilitation had also received attention. Using subsensory electrical stimulation with visual-audio feedback, a foot pressure sensory compensation system was developed by Lee *et al.* [6]. Experiments demonstrated the effectiveness of the proposed system used in conjunction with visual-auditory feedback in compensating sensory loss and improving posture control for amputees. Kong and Tomizuka [7] developed a gait monitoring system based on air pressure sensors embedded in between the cushion pad and the sole in shoes. The design employed fuzzy logic to detect gait phases from measuring ground contact force. Using vector and kinematic analysis, both normal and abnormal gaits can be identified. To *et al.* [8] designed a variable constraint hip mechanism for a hybrid neuro-prosthesis. The mechanism was designed to provide posture stability for paraplegic patient while maintaining uninhibited hip rotation. A hydraulic system was designed to provide the necessary structure coupling for posture stability while minimizing the passive resistance during hip rotation.

Zhang *et al.* [9] used extremum-seeking control to find the velocity setpoint for developing the optimal velocity trajectory to maximize the user's power output for an exercise machine. Based on the availability to measure the user's torque input, two different controllers were designed to ensure acceptable trajectory tracking and passivity. Treating the human motion control as a feedback-control system, Kong and Tomizuka [10] modeled the human controller as a set of fixed algorithms amplified by a fictitious gain (FG). The FG can be adjusted to compensate for changes in the human control loop, such as physical impairment or load variation. An exoskeleton controller that realized the FG was developed and experimentally verified.

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B. Surgery and Intervention Procedures

Kode and Cavusoglu [11] realized local actuation at the end-effector of a laparoscopic needle driver through a series connection of a dc micromotor and a shape memory alloy (SMA) actuator. Their approach avoided the DOF limitation due to power transmission associated with an external actuator pack that is common in existing robotic tools for minimally invasive surgery. Liu *et al.* [12] investigated methods to improve the positional accuracy of a neurosurgical robot. The use of a back-propagation neural network to compensate the joint transmission error of the robot was proposed and verified through a robot-assisted neurosurgery using a phantom. The achievable positioning accuracy is within the target registration error of the phantom. To provide realistic feedback for surgeons during robot-assisted surgery, Tholey and Desai [13] developed a 7-DOF haptic device that was able to provide 4-DOF force feedback and 7-DOF position feedback. Force feedback was provided by a spatial mechanism through a universal joint located at the grasping mechanism. Friction estimation was employed to improve the fidelity of the position feedback and force display.

High fidelity and stable force feedback is a key challenge in robot-assisted surgery. Zemiti *et al.* [14] presented the design of a compact and lightweight robot that allowed for measuring manipulation force during minimally invasive surgeries (MIS). The device used a regular force senor attached to a trocar external to the patient and provided uninterrupted force measurement and removed the need for integrating miniature force sensor into surgical instruments. Mitsuishi *et al.* [15] presented an augmented force-feedback algorithm to improve force perception in laparoscopic MIS. The approach identified several force augmentation modes associated with laparoscopic surgery. An algorithm was developed to switch among different modes based on position and force measurements. A proportional-integral (PI) gain-scheduling force feedback controller is used to provide stable force control.

The June 2008 issue of the TRANSACTIONS included a "Focused Section on Mechatronic Systems for MRI Applications." Most of the papers in the Focused Section discussed the MR compatibility of actuators, sensors, and systems. We will highlight four of the papers that described system level integration of surgical procedures. Greer *et al.* [16] outlined the development of the human–machine interface of a telerobotic surgical system. The interface combined haptic surgical interface with audio feedback and steroscopic imaging device to incorporate 3-D MR image manipulation. Zemiti *et al.* [17] presented image segmentation and registration algorithms as well as the position control needed to register and localize a puncture robot on computer tomography (CT) or MR images for image guided intervention. MRI guided surgical procedure requires the compatibility of material as well as the component under high magnetic field (1.5 T or greater). Ultrasonic, pneumatic, and hydraulic motors are viable actuators in an MRI environment. Goldenberg *et al.* [18] presented a robotic system using ultrasonic motor for an MRI-guided ablation. Fischer *et al.* [19] presented a similar system using pneumatic servo. Phantom studies had verified the proposed workflow and the accuracy of the visualization and targeting of the system.

C. Prosthesis

Hand prosthesis has received the most attention in the past five years. Zollo *et al.* [20] reported the design and control of a three-finger (thumb, index, and middle finger) anthropomorphic hand. Design optimizations were performed to limit the number of actuators and DOFs to achieve the required size and weight constraints for hand prosthesis. The corresponding control system was developed to track reference trajectories that were obtained from neuroscience literature. The same research group subsequently developed a soft compliant tactile microsensor (SCTM) [21]. Using a cumulative summation algorithm, the SCTM was able to detect slip event with adequate response that met neurophysiological requirements while maintaining adequate toughness needed for a tactile sensor. Recently, researcher at Vanderbilt University designed a 16-joint anthropomorphic hand prosthesis intended for myoelectric interface [22]. Five independent actuators were used to generate a set of eight canonical hand postures. The speed and force capacity of the prosthesis were experimental characterized.

Myoelectric signal is the most common interface for lower arm prosthesis. In the June 2007 "Focused Section on Advanced Integrated Mechatronics," two different pattern recognition approaches were proposed to extract essential information from electromyographic (EMG) signals. Liu *et al.* [23] used a cascade kernel learning machine (CKLM) to classify EMG features extracted from autoregressive models and EMG histograms. Two learning kernels, generalized discriminant analysis and support vector machine were employed in sequence. The proposed algorithm was implemented in a DSP and achieved 93.54% recognition rate. Chu *et al.* [24] proposed the use of linear discriminant analysis (LDA) in linear supervised feature projection of EMG signals. EMG feature vectors were extracted using a wavelet packet transformation followed by LDA-based dimensional reduction. A multilayer perceptron classifier was used to recognize nine hand motions. The proposed approach achieved a 97.4% recognition accuracy. Using a different modality, Carrozza *et al.* [25] demonstrated the feasibility of using foot movement as a viable biometric interface. The signal pick up mechanism is similar to that of Kong and Tomizuka [7] using the insole of a shoe. Biomechanical analyses of the foot anatomy and joint kinematics were used in developing the interface. The proposed interface was experimentally verified in the control of a prosthetic hand.

D. Diagnosis and Others

To improve the maneuverability of capsule-type endoscopes in the gastrointestinal tract, Kim *et al.* [26] developed a locomotion mechanism for endoscopic capsules that consisted of a pair of clamping devices and a pair of shape memory alloy spring-based linear actuators. Experiments verified the effectiveness of the mechanism to improve locomotion efficiency of the capsule under sequential control. Quirini *et al.* [27] took a different approach by designing a set of four super-elastic legs actuated by a brushless mini-motor. The legged capsule can achieve a typical speed between 10 and 40 mm/min.

Koizumi *et al.* [28] presented an impedance controller for a master-slave-type remote ultrasonic diagnostic system. The paper proposed a trajectory-tracking controller to maintain position tracking of the master and slave manipulators as well as maintaining the desired contact force between the ultrasound probe and the affected area. The path control performance of the proposed controller was experimentally verified.

Sensor encapsulated within orthopedic implants can provide *in vivo* diagnostic information of the potential abnormality or impending failure that is critical to the well-being of the patient. For these intelligent implants, power is always the main limiting factor. Platt *et al.* [29] proposed the use of piezo-ceramics (PZT) to generate *in vivo* electric energy during normal physical activities. The feasibility of the proposed approach was tested on a total knee replacement implant.

Li and Xu [30] presented the design and control of a translational parallel manipulator for assisting chest compression in cardiopulmonary resuscitation (CPR). Design analyses were conducted to achieve the desired workspace. Dynamic models were developed and a computed torque control algorithm was employed to achieve the desired performance. A design prototype was used in the experimental validation.

III. Highlights of the Focused Section

This Focused Section collected six papers that represent a sample of current developments in healthcare mechatronics. A majority (two-thirds) of the papers received was in the areas of robot-assisted rehabilitation and prosthesis.

The first paper introduces a novel hybrid locomotion design of a miniature endoscopic capsule. The proposed hybrid approach combines an on-board legged actuation mechanism [27] with an external magnetic field that guides the capsule motion through a permanent magnet embedded in the device. The legged mechanism is employed to modify the capsule profile and generate adequate force to dislodge the device from collapsed regions of the gastrointestinal tracts to enable external magnetic guided locomotion. The device and associated wireless control were verified through *ex vivo*, *in vivo*, and *in-vitro* experiments.

The second paper describes the design of an intelligent trunk corset using pneumatic artificial rubber muscle to support the rollover movement of cancer bone metastasis patients. The intention of the patient is derived by processing EMG signal with a neural network. Based on the signal, the artificial muscle is controlled to provide the necessary support and restrict the motion of the trunk. The device was experimentally verified and was able to reduce the discomfort of the patient while providing similar level of support as compared with existing hard corset.

The remaining four papers are related to rehabilitation therapy using robotic devices or sensor integrated vibrotactile feedback. The first of these four papers discusses a novel control algorithm to realize joint torque and motion profiles to be exerted by an exoskeleton during rehabilitation exercises to reproduce equivalent buoyancy and drag forces associated with aquatic therapy. The approach uses ground contact force measurements to determine appropriate motion phases that are used to compute the desired joint torque and motion profile. The proposed algorithm was confirmed through human subject experiments. The second rehabilitation paper presents a 6-DOF robot that provides gait rehabilitation to patients and allows velocity update as well as synchronous motion between upper and lower limbs. The proposed device and therapy is an integration of robotics and virtual reality technology. The algorithms for trajectories generation as well as walking interaction control for upper and lower limb connections were proposed, simulated and tested. It allows patients to update their walking velocity on various terrain types and to navigate in virtual environments through upper and lower limb connections. The third rehabilitation paper addresses the feasibility of using specially designed exoskeleton and training paradigms to adjust the gait of healthy individuals. A 7-DOF actively controlled leg exoskeleton is paired with force-field control to deliver the appropriate interaction force between the subject and the orthosis for effective gait training. Human subject testing demonstrated effective gait alteration for healthy subjects in less then an hour. The last paper proposes a system that provides real-time feedback during postural training using vibrotactile actuators and a triaxial inertial sensor. In addition to visual and auditory feedback, the proposed system adds another approach for the clinician to use in posture or balance training for patients with visual or auditory perception issues following stroke or other injuries. Preliminary human subject testing showed promising results.

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