2007 IEEE International Conference on
Robotics and Automation
Roma, Italy, 10-14 April 2007

Design, Control and Human Testing of an Active Knee Rehabilitation Orthotic Device

Weinberg B. [A], Nikitczuk J. [A], Patel S. [A,B], Patritti B. [B], Mavroidis C. [A,1], Bonato P. [B] and Canavan P. [C]

[A] Department of Mechanical & Industrial Engineering
375 Snell Engineering Center,
Northeastern University
360 Huntington Avenue, Boston MA 02115
Tel: 617-373-4121, Fax: 617-373-2921
Email: mavro@coe.neu.edu
Webpage: http://www.coe.neu.edu/~mavro

[B] Department of Physical Medicine and Rehabilitation
Harvard Medical School,
Spaulding Rehabilitation Hospital,
125 Nashua Street , Boston MA 02114
Tel: 617-573-2745, Fax: 617-573-2769
Email: pbonato@partners.org
Webpage: http://spauldingrehab.org/mal

[C] Department of Physical Therapy, Northeastern University
6 Robinson Hall, Boston, MA 02115
Tel: 617-373-5428, Fax: 617-373-3161, Email: p.canavan@neu.edu

[1] Author for Correspondence

***Abstract* – This paper presents a novel, smart and portable Active Knee Rehabilitation Orthotic Device (AKROD) designed to train stroke patients to correct knee hyperextension during stance and stiff-legged gait (defined as reduced knee flexion during swing). The knee brace provides variable damping controlled in ways that foster motor recovery in stroke patients. A resistive, variable damper, electro-rheological fluid (ERF) based component is used to facilitate knee flexion during stance by providing resistance to knee buckling. Furthermore, the knee brace is used to assist in knee control during swing, i.e. to allow patients to achieve adequate knee flexion for toe clearance and adequate knee extension in preparation to heel strike. The detailed design of AKROD, the first prototype built, closed loop control results and initial human testing are presented here.**

Index Terms* – *Electro-Rheological Fluids, Rehabilitation Robotics

I. INTRODUCTION

Stroke is a leading cause of permanent disability in the Unites States. According to the National Stroke Association, each year about 730,300 people suffer a stroke, and approximately two-thirds of these individuals survive and require rehabilitation [1]. Approximately 80% of stroke survivors present an early motor deficit, with 50% having chronic deficits. Impairments such as spasticity, muscle weakness, loss of range of motion, and impaired force generation create deficits in motor control that affect the stroke survivor's capacity for independent living. Robotic and mechatronic technologies that can be integrated into portable devices and can be used by patients in the home setting are particularly attractive in the above-discussed context because they have the potential of providing tools to facilitate functional recovery, reducing cost of treatment and providing patients with adequate level of independence.

Many ambulatory stroke survivors have substantial alterations of their gait patterns as a result of the hemiparesis. Compromised motor control and force generation frequently lead to limited knee flexion and stiff-legged gait, defined as limited knee flexion during swing and typically associated with limited hip flexion and limited or absent ankle dorsiflexion. These gait patterns cause substantial reduction in gait velocity and efficiency, and can increase the likelihood of falls. In some patients, knee hyperextension develops as a mechanism to increase stability during stance. Unfortunately, knee hyperextension can cause pain, and is believed to lead to premature degenerative joint disease of the knee in these individuals. Conventional treatments largely focus on the use of ankle-foot orthoses (AFO) to provide ankle stability and correct knee gait abnormalities. Little emphasis is generally aimed at addressing knee movement abnormalities via a knee orthosis. This is because currently available knee orthoses are bulky and rather make it difficult to achieve functional use of the knee. The development of an intelligent, actuated knee orthosis has the potential to address these issues. Two objectives could be pursued with the proposed AKROD: (1) enhancing gait retraining, and (2) improving orthotic intervention in the home and community settings.

For many patients, a programmable actuated knee orthosis could guide and facilitate the recovery of a more efficient and clinically desirable gait pattern via retraining sessions. Current clinical practice is generally restricted to brief periods of less than 1 hour of gait training and provided a few times per week. In between these sessions, patients continue to walk using their typical gait pattern, and reinforce compensatory patterns of gait. Lower-extremity robotic devices for gait retraining (e.g. Lokomat ®) have been developed to provide the opportunity for intense rehabilitation, but their use is limited to the clinical setting for relatively brief training sessions. A wearable training orthosis could be used by patients throughout daily activities, with constant reinforcement of the targeted gait pattern. This constant reinforcement of gait retraining in a real-world environment has the potential to provide more effective gait retraining, improving one's ability to ambulate.

An intelligent programmable actuated knee orthosis could be used as an alternative to currently available mechanically-passive braces. Existing options for control of pathologic knee movement during gait include the use of short-leg braces (AFO's), long-leg braces (KAFO's), and stand-alone knee braces (KO's). AFO's provide some stabilization of knee movement and partially resist knee hyperextension. However, many patients find that AFO's are not effective in controlling abnormal knee movements and frequently adopt maladaptive gait patterns. KAFO's are more effective at preventing knee hyperextension, but do not assist with knee flexion, and provide a "hard stop" for knee hyperextension, rather than providing a graded resistive force to this movement. The size and weight of KAFO's interfere with their acceptance by patients. KO's are similarly unable to assist with knee flexion, and also provide an abrupt check on knee hyperextension. Long-term use of KO's by patients with stiff-legged gait and hyperextension is the exception. These devices lack variable-damping and torque-actuator characteristics that we see as essential to restore mobility in stroke patients. The proposed knee brace would provide such characteristics thus allowing a significant improvement over existing orthotic interventions.

In this paper, we present the design, control and testing of a novel, smart and portable Active Knee Rehabilitation Orthotic Device (AKROD), shown in Figure 1. The main torque generation component of the device is a resistive variable damper that is the key to foster training of more efficient and clinically desirable knee biomechanical patterns in stroke patients. This component will be relied upon in order to avoid knee hyperextension and foster re-learning of a knee flexion pattern during stance. Also, it will be relied upon to correct stiff-legged pattern, defined as limited knee flexion during swing.

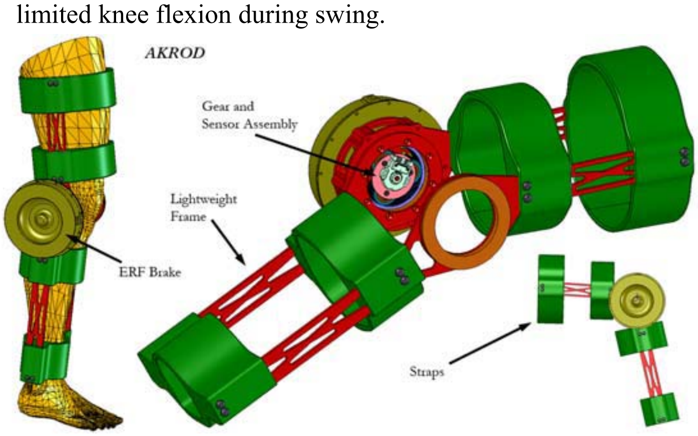


Figure 1: *Active Knee Rehabilitation Orthotic Device.*

The AKROD is composed of straps and rigid components for attachment to the leg, with a central hinge mechanism where a gear system is connected. The key features of the proposed AKROD include: a compact, lightweight design with highly tunable resistive torque capabilities, and sensors (encoder and torque), and real-time capabilities for closed loop computer control for optimizing gait retraining. The controllable variable resistance is achieved through an electro-rheological fluid (ERF) element that connects to the output of the gear system. Using the electrically controlled rheological properties of ERFs, compact brakes capable of supplying high resistive and controllable torques, have been developed. Concentric cylinders, acting as electrodes supply the necessary electric field to activate the fluid. Simultaneously, these plates, when charged and rotating, act as surfaces upon which the activated fluid creates a shear force in response to rotation. This paper presents the detailed design, closed loop control and initial human testing of AKROD.

II. Background

An orthotic by strict definition is a specialized mechanical device that supports or supplements weakened or abnormal joints or limbs [2]. The Sports Medicine Committee of the American Academy of Orthopedic Surgeons has classified knee braces into four categories: prophylactic, rehabilitative, functional and patellofemoral. The majority of these devices can be considered passive devices. They provide stability, apply precise pressure, or help maintain alignment of the joints. Improved technology has allowed for advancements where these devices can be designed to apply a form of tension to resist motion of the joint. These devices induce quicker recovery and are more effective at restoring proper biomechanics and improving muscle function. These may employ torsion springs, pistons and simple mechanical devices to make them "semi-active", rather than passive orthotics.

Some of the more innovative designs allow the torsion to be adjusted; giving some variety and even further improvements in efficiency over a simple passive device. However, their shortcoming is in their inability to be adjusted in real-time, which is the most ideal form of a device for rehabilitation. This introduces a second class of devices beyond passive orthotics. It is comprised of "active" or powered devices, and although more complicated in designs, they are definitely the most versatile. An active or powered orthotic, usually employs some type of actuator(s). These types of devices are ideal for providing additional support to the knee, due to their unique ability to adjust in real-time. The actuator aspects of these devices allow them to perform augmentations and enhancements on the human muscles. Examples of work recently performed in this line of research are the ones described in [3,4]. Both groups have explored the use of advanced robotics and innovative actuators to improve the functional use of ankle-foot-orthoses. Unfortunately, advances in active orthotics have generally been limited only to assistance and enhancement. Very little and close to no work is evident where active components are added to orthotics specifically for the purposes of rehabilitation (i.e. gait retraining) as it is proposed in this application. Besides, it is worth mentioning that previous work concerning the active control of orthotics has been limited, to our knowledge, to ankle-foot-orthoses. No knee orthosis as advanced as the one herein proposed has ever been developed and tested in retraining gait patterns in stroke patients.

Innovative actuators and force-feedback robotic devices that provide controlled resistivity and operability that can be used for patient rehabilitation training and human muscle enhancement and augmentation have been studied by the PI's team [5-7]. The developed novel robotic devices are designed to support and train the human knee, elbow and fingers. The mechanisms are designed to provide controlled resistance, force and torque at high dexterity and rapid response using novel elements that produce controlled stiffness and actuators. For this purpose, the property of electro-rheological fluids (ERF) to change the viscosity in response to an electric field allowing to produce virtually zero resistance when idle and to provide high resistivity when stimulated electrically has been exploited.

A key to the above stated innovative robotic device ability to provide resistivity as well as to operate on-demand is the property of Electro-Rheological Fluid (ERF) to increase the viscosity in the presence of an electric field. Winslow [8] was the first to explain the effect in the 1940's using oil dispersions of fine powders. These fluids are made from suspensions of an insulating base fluid and particles having a size on the order of 0.01 to 0.1 μm and volume fraction of the particles between 20% and 60% [9,10]. The electro-rheological effect arises from the difference in the dielectric constants of the fluid and particles. In the presence of an electric field, the particles, due to an induced dipole moment, form chains along the field lines. The induced structure changes the ERF's viscosity, yield stress, and other properties, allowing the ERF to change consistency from that of a liquid to something that is viscoelastic (such as a gel) at response time on the order of milliseconds. ERF properties of high yield stress, low current density, and fast response (less than 1 ms) offer essential characteristics for the construction of rehabilitation devices. ERFs can apply very high electrically controlled resistive forces while their size (weight and geometric parameters) can be very small. ERFs are not abrasive, non-toxic, and non-polluting (meet health and safety regulations).

Control over a fluid's rheological properties offers the promise of many possibilities in engineering for control of mechanical motion. The use of ERFs for tactile sensing in robotic fingers was proposed in [11]. Based on that work, several researchers proposed the use of ERFs in tactile arrays used to interact with virtual environments [12] and also as assistive devices for the blind to read the Braille system [13]. A 5x5 ERF tactile array was developed in [14]. An ERF-based planar force-feedback manipulator system that interacts with a virtual environment was studied in [15]. An ERF-based force-feedback joystick has been developed in the Fraunhofer-Institut in Germany [16]. The use of ERF resistive elements and brakes in rehabilitation has been very limited. The few rehabilitations devices employing ERF elements that have been developed so far were fixed based, non-portable, non-wearable systems [17-19].

Very similar to ERFs are the Magneto-Rheological Fluids (MRFs) whose rheological properties change with variations of a magnetic field instead of an electric field. Several MRF based haptic / force resistive systems have been described in [20-23]. Lower limb prosthetic systems using MRF brakes have been developed [24-26]. Some rehabilitation devices using MRF brake / damper systems have also been proposed [27, 28].

In this paper we present a novel ERF based active knee rehabilitation orthotic device that presents high portability and offers very accurate computer control and monitoring of resistive torque and motion.

III. AKROD DESIGN AND PROTOTYPE

AKROD is composed of the following main components: a) ERF-based brake; b) brace and gear assembly and c) sensors. To set the design goals for the knee device, peak torque during extension in isometric exercises was used as the benchmark. This has been shown to be on average, 172 Nm for healthy men and 112 Nm for healthy women [29]. Since the torques necessary for walking are less than these maximum capabilities, 172 Nm at 5 kV was set as the designed torque output for the knee device (Note: 5kV is the maximum output voltage from the power supply that is used). Therefore, for an operating maximum voltage of the ERF at 3kV, the torque capabilities of the AKROD are equal to 78 Nm. With the knee moment assumed to be 75 Nm/kg, AKROD is able to support an individual of 104 kg (approximately 229 lbs). This is sufficient to be used with most of the stroke population. Below we provide design details for AKROD's components and we present the first prototype developed.

ERF – Brake

The ERF brake uses a resistive smart fluid element (RSFE) to modulate the device resistive torque. The RSFE consists of sets of aluminum electrodes, one fixed and one rotating, which are configured as concentric cylinders (Figure 2). The electrodes are separated by a narrow gap (~1mm) that is filled with ERF. Applying a voltage across this gap generates an electric field that then alters the properties of the ERF, more specifically, the yield stress is increased. When the rotating cylinder is in motion, the higher yield stress corresponds to increased shear forces on the electrode surface that then translates into increased resistance. By manipulating the strength of the electric field applied to the fluid, the torque can be easily controlled, turning this simple concept into a highly tunable brake. Shear forces are directly proportional to the surface area of the electrodes. To maximize the torque/force output, multiple sets of concentric rotating cylindrical electrodes are used as shown in Figure 2. This allows for maximum shearing surface area while maintaining a compact overall volume for the device. The general design and performance characteristics of the knee orthosis are listed in Table 1. The ERF brake was filled with the 3365S fluid, from Smart Technology LTD (http://www.smarttec.co.uk/). All tests throughout this work were performed using the same fluid.

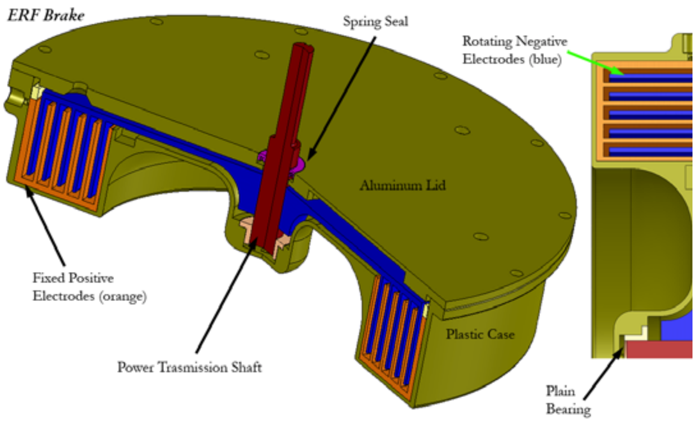


***Figure 2:** ERF Brake.*

***Table 1:** System Characteristics of AKROD*

ERF Brake Parameters:	
Number of concentric cylinders	5
Gap between cylinders	1.27 [mm]
Brake torque (at 3 kV)	12.6 [N m]
Overall Device Parameters	
Gear ratio	6.2:1
Degrees of rotation	Continuous
Device resistive torque (at 3 kV)	78 [N m]
Device resistive torque (at 5 kV)	172 [N m]

Brace and Gear Assembly

A detailed description of the brace components can be found in Figure 3. The resistive brake torque is multiplied using a planetary gear system that also serves as the foundation for the sensor sub-system. Velcro straps are padded by foam, which forms to the patient's leg helping to prevent brace migration. The hinge design is the same on both sides of the brace. This allows one to switch the side that the knee orthosis is on; so the knee brace can be used on either leg. Force is transmitted from the wearer through the straps and frame and leads to a torque at the hinge. Contained in the exterior hinge is the planetary gear system that multiply torque by 6.2:1. Two compression sensors are mounted between the ring gear (largest gear) and the frame preventing the ring gear from moving. When a torque is supplied to the hinge, the ring gear pushes on one of the sensors (which one depends on the direction of motion). This force measure is combined with known dimensional values to calculate the torque. An optical encoder is included to precisely measure joint motion. Migration of the orthosis is minimized through the use of an AFO that is attached to the lower brace arms of the device. This supports the weight of the orthosis while maintaining its position on the leg. If needed, additional constraints will be added through suspension from an additional pelvic brace. The orthosis does not interfere with electrode placement because of the foam padding used as an interface between the brace and the patient. The padding allows for thin electrodes to be used without any alterations to the design or attachments.

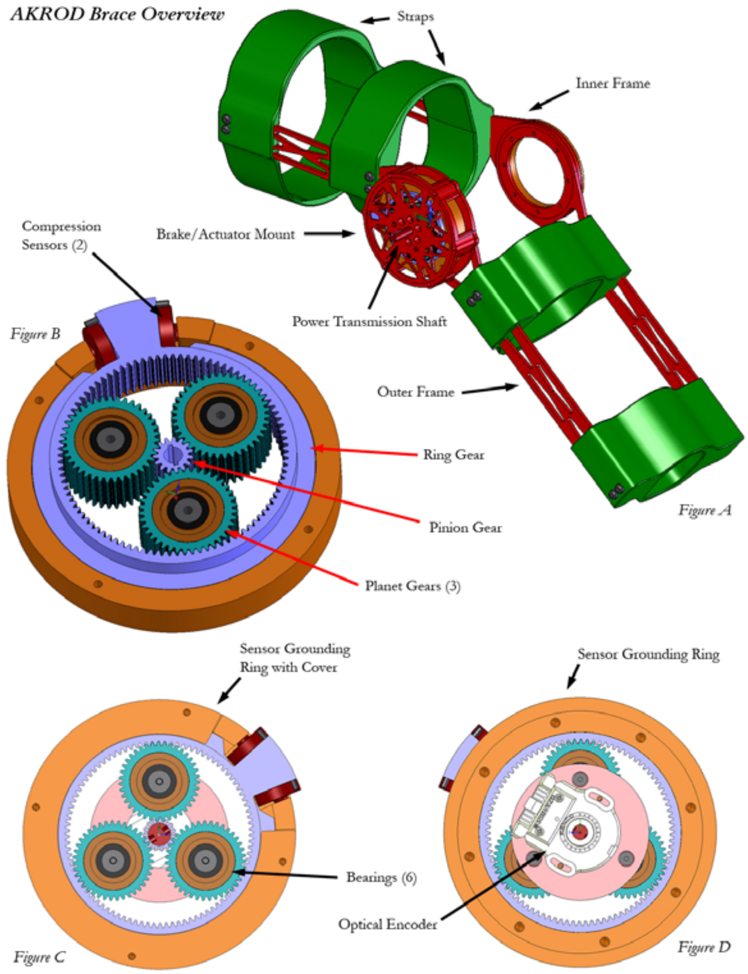


***Figure 3:** AKROD Brace: A- Brace Detail; B - Sensor Detail; C - Hinge Exterior; D - Hinge Interior.*

Sensors

Two primary sensors are implemented into the device design. The first is an optical encoder (Figure 3D) to measure angle, velocity, and acceleration of the knee. The second sensor is a torque sensor for measuring the torque developed by the patient and for closed-loop control of the device. Two miniature compressor sensors (Figure 3B) are arranged in opposite directions to measure torque via a force from a moment arm in both flexion and extension. Currently, electrical power to the orthosis is provided using a tether for off-the-wall power acquisition. A Trek model 610C high voltage power supply was used to amplify the input voltage to the levels needed to activate the ERF brake. In the future, a fully portable power supply / high voltage amplifier system will be developed and implemented.

Prototype

A prototype for AKROD, has been developed. Figure 4 shows the assembled prototype and views of its components. The final weight of the device is approximately 7 pounds (3.18 Kg). Preliminary tests were performed with the AKROD being worn by a human as shown in Figure 5 where a subject is wearing AKROD in both legs. The test performed was a level ground walking test over the Gait Mat II walkway system. The purpose of these tests was to study, from a first point of view, the comfort level while wearing AKROD.

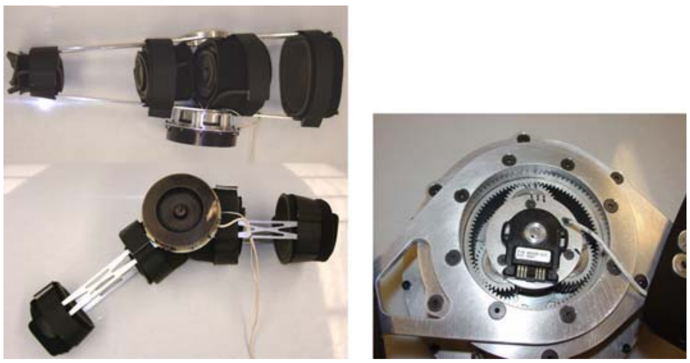


Figure 4: *AKROD - Assembled Prototype and Close-Up Views of Its Components.*

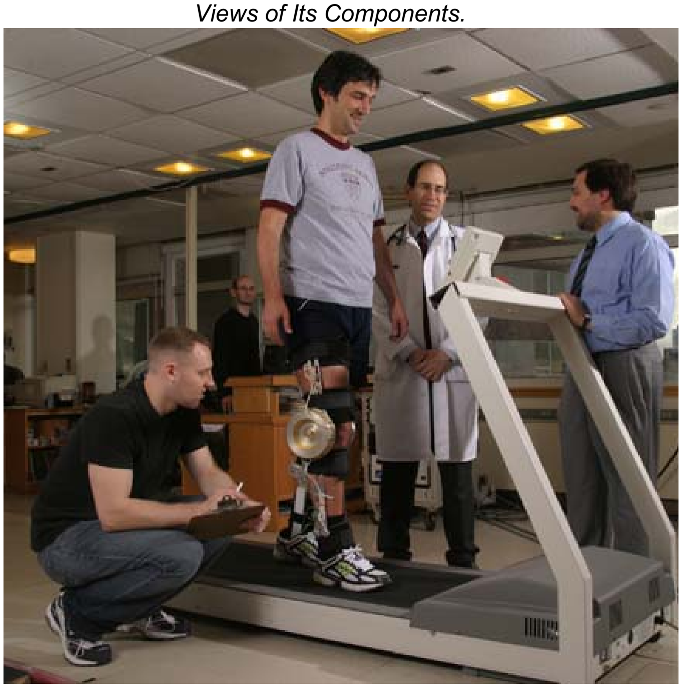


Figure 5: *AKROD Worn While Walking on Treadmill With Unactuated AKROD to Evaluate Comfort.*

IV. Closed-Loop Control

AKROD was tested in closed loop torque and velocity control experiments. In the torque control experiments, the ERF brake was asked to maintain a constant torque even if various disturbances were introduced. A hybrid (non-linear, adaptive) Proportional-Integral (PI) torque controller (shown schematically in Figure 6-TOP) was implemented to achieve this goal. A representative result is shown in Figure 6 (BOTTOM) where a very accurate torque is produced and maintained by the ERF brake. Several experiments were performed with a large number of torque values and several disturbances were introduced such as introducing unexpected external torques to the system. The controller was able to almost instantly compensate these torque disturbances and maintain very accurately the desired torque value. The details of our torque control algorithm as applied on the ERF brake can be found in our recent paper [30].

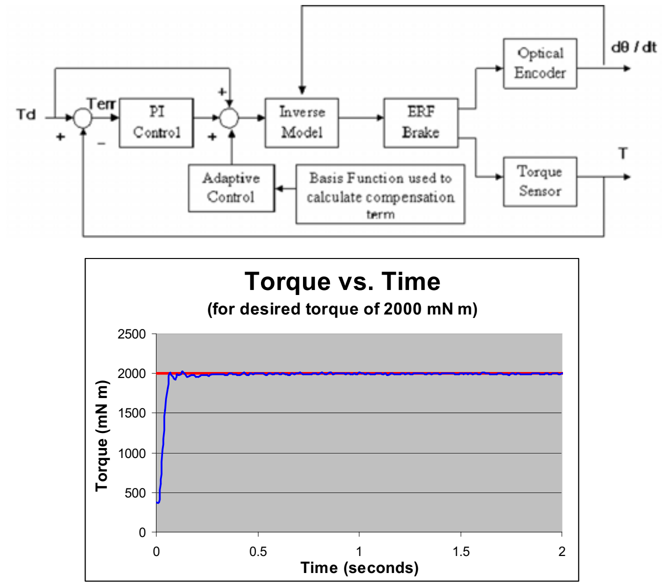
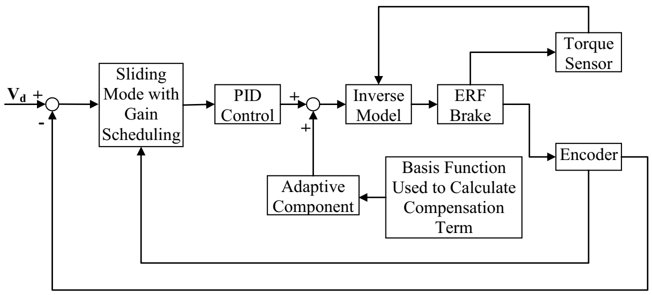


Figure 6: *Non-linear Adaptive PI Torque Control Experiments with AKROD's ERF Resistive Actuator.*

In addition to torque control experiments, we developed closed loop velocity control algorithms. The velocity control was based on a PID (Proportional Integral Derivative) algorithm with a nearly identical adaptive scheme as the torque control. All the same steps were performed for its development with the exception of a few additional elements. These were an improved inverse model and a sliding mode with gain scheduling component. These were included to improve the accuracy of the initial control and the overall stability of the control system, especially during the transient stage. The final block diagram of the controller can be seen below in Figure 7 (TOP). A representative result is shown in Figure 7 (BOTTOM) where a very accurate velocity is produced and maintained by the ERF resistive actuator.

These excellent control results with the ERF resistive brakes are very important as they demonstrate that we have developed very efficient control algorithms so that we are able to accurately implement and control any desired resistive torque and velocity value. From the rehabilitation point of view this is very important as we are able to implement any isotonic (constant torque) and isokinetic (constant velocity) profile.

Finally, in closed loop control experiments, the knee device was worn while exercises in both extension and flexion were performed. Once AKROD activated, the Adaptive PI Torque control produced excellent results. The user's motions were resisted with what was explained as smooth and continuous force by all tested. The results can be seen graphically in Figure 8 where the user is shown going from a resting position to being resisted 10 Nm during an extension or flexion exercise. The control produced accurate resistive forces and responded well to the inconsistent forces produced by the human. This final verification of the Adaptive PI Torque control confirms its effectiveness with human-interactive AKROD.



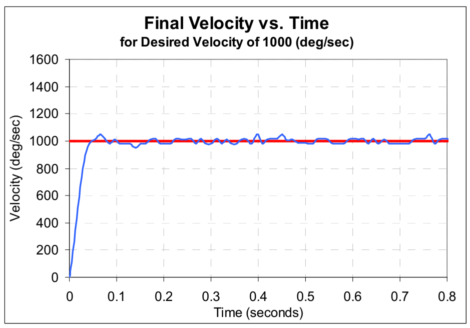


Figure 7: *Non-linear Adaptive PID Velocity Control Experiments with AKROD's ERF Resistive Actuator.*

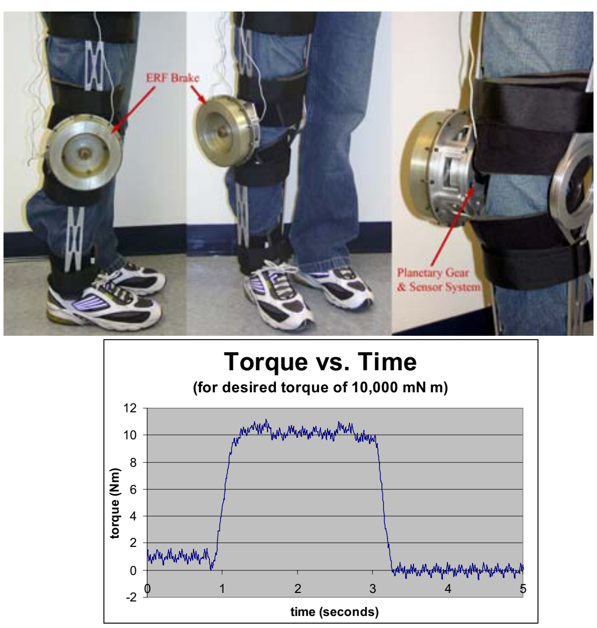


Figure 8: *AKROD Worn by a Human in a Standing Mode While Adaptive PI Torque Control has Been Activated (LEFT); The User is Shown Going from a Resting Position to Being Resisted a Desired Torque of 10 Nm During an Extension or Flexion Exercise.*

V. WALKING TESTS WITH AKROD UNACTIVATED

Furthermore, additional tests were performed in order to assess the effect of the physical characteristics of the orthosis (e.g. alignment and mass distribution) on the gait mechanics of healthy individuals. We hypothesize that when healthy subjects wear the orthosis on one leg they will demonstrate kinetic asymmetries aimed to maintain fairly symmetric gait kinematics. We further hypothesize that when healthy subjects wear the orthosis on both legs, we will observe symmetric kinematics and kinetics at the hip, knee, and ankle. We envisage the results of this study on healthy subjects will provide an insight to the control parameters necessary when testing the active orthosis on stroke patients.

In this study, we intended to quantify gait responses of healthy subjects to wearing the additional mass of the AKROD, to study the speed dependence of these responses, and to explore the development of optimal strategies to minimize the biomechanical adaptations introduced by the knee orthosis. We tested one male subject who reported no neurological or musculoskeletal problems at the time of this pilot study. We asked the subject to ambulate along a level walkway at two speeds, ~0.6 $m.s^{-1}$ and ~0.9 $m.s^{-1}$ while wearing either (1) no orthosis, (2) an orthosis uni-laterally (right lower limb), or (3) an orthosis bi-laterally (left and right lower limbs). The orthosis was secured to each leg with velcro straps attached to the proximal and distal struts. To minimize downward migration during the walking trials the orthosis was suspended proximally from a pelvic brace and supported distally with an AFO from DonJoy. The order of the orthosis conditions was mixed while the two speeds for each condition were block randomized. The subject completed 10 trials for each orthosis-speed condition.

An 8-camera motion analysis system (Vicon 512, Vicon Peak, Oxford, UK) with two force platforms (AMTI, Watertown, MA) embedded in the walkway was used to collect kinematic and kinetic data for each lower limb during the walking trials. We will only report on kinematic data. Kinematics were described from the trajectories of reflective markers attached to the lower limbs of the subject. A set of "technical" marker clusters was attached to the skin over bony landmarks of the pelvis and each foot, and the anterior aspects of each thigh and shank (Figure 9). Additional "anatomical" markers were attached to specific anterior bony landmarks of the pelvis and proximal and distal bony landmarks of each femur, tibia and fibula before each block of walking trials for the respective conditions. The technical and anatomical markers were coincidental for the feet. The relative position and orientation of the "technical" marker clusters on the segments defined by the "anatomical" markers was recorded via a static standing calibration trial. The "anatomical" markers for each thigh and shank were then removed prior to the walking trials. Translation-rotation matrices of the respective marker clusters defining each segment were used to quantify the kinematics of the hip, knee and ankle of each lower limb during the dynamic walking trials. Figure 10 shows the kinematics of sagittal motion at the hip, knee, and ankle in the three experimental conditions of level walking 1) with no orthosis, 2) with the orthosis on the right lower limb (uni-lateral), and 3) with two orthoses (bi-lateral). Data is shown for one subject walking at ~0.9 m.s-1.

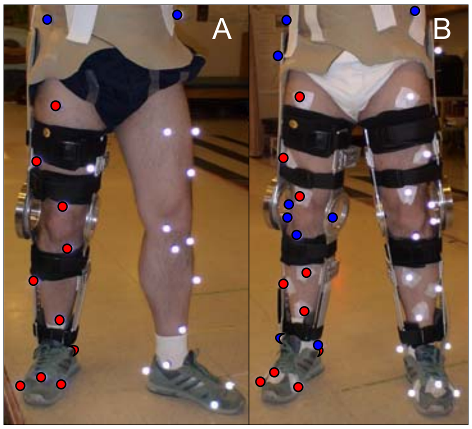


Figure 9: *Technical (Red) and Anatomical (Blue) Markers of the Right Leg for the (A) Uni-lateral Orthosis Condition, and (B) Bi-lateral Orthoses Condition. Technical and Anatomical Markers Were the Same for the Feet.*

At the hip, very similar hip flexion/extension profiles are shown for the no orthosis condition and the bi-lateral orthoses condition. Significant deviations characterize instead the uni-lateral orthosis condition. During early stance, the hip profile for the uni-lateral condition is marked by a faster extension pattern than for the no orthosis and bilateral conditions. The derivative of the hip extension then decreases to almost reach zero for the unil-lateral condition, while it continues to decrease at an almost constant rate for the no orthosis and bilateral condition until late stance. Peak hip extension is about the same across conditions. In contrast, the peak hip flexion in terminal swing is slightly decreased for the uni-lateral condition compared to the no orthsis and bi-lateral conditions.

The adaptations observed in the kinematics of hip, knee, and ankle motion in the three experimental conditions (i.e. no orthosis, one orthosis (uni-lateral), and two orthoses (bi-lateral)) indicate that the control of the lower extremity movement pattern is most difficult when an asymmetric load is attached to the lower limbs, as in the case of the uni-lateral condition. The main adaptation pattern that characterizes the uni-lateral condition appears to be the lack of knee flexion during early to mid-stance. The stiff-leg pattern guarantees relative symmetry at the knee, but causes deviations of the hip and ankle kinematics. At the hip, the lack of knee flexion observed in the uni-lateral condition leads to an exaggerated hip flexion pattern in early to mid-stance. At the ankle, the stiff-leg pattern results in an exaggerated plantarflexion in early to mid-stance. Also, the mass associated with the brace appears to affect control of tibia progression during mid to terminal-stance thus leading to an exaggerated ankle dorsiflexion. Finally, the foot attachment at the ankle and heel appears to constrain ankle plantarflexion pattern around toe-off. All these adaptations appear to be significantly larger in the patterns associated with the uni-lateral condition compared to the bi-lateral condition. It follows that the use of two orthoses allows one to minimize the perturbation of the gait patterns caused by the use of the knee orthosis to an extent that appear to be acceptable for gait retraining purposes at slow walking speeds.

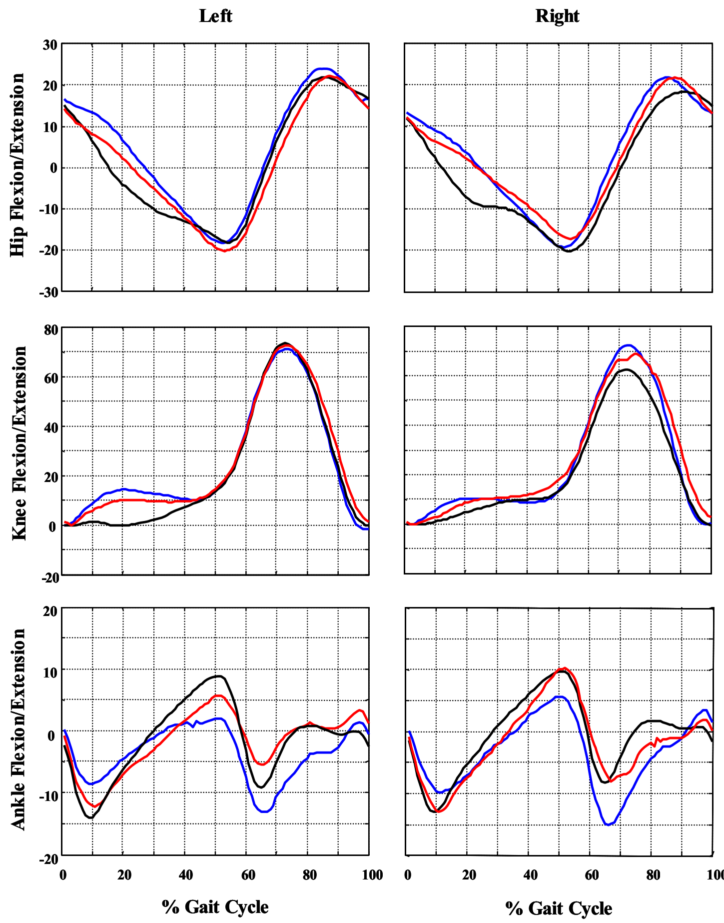


Figure 10: *Mean Sagittal Motion Kinematics of the Left and Right Hip, Knee and Ankle for the 3 Conditions: No Orthosis (Blue Line), Uni-lateral Orthosis on the Right Side (Black line), and (3) Bi-lateral Orthosis (Red line) – for Level Walking at ~0.9 m.s^{-1}.*

VI. CONCLUSIONS

The design, closed loop control, first prototype and initial human testing of a novel active knee rehabilitation device called AKROD was presented in this paper. The key features of AKROD include: a compact, lightweight design with highly tunable torque capabilities through an electro-rheological fluid (ERF) variable damper component, portability and real-time capabilities for closed loop computer control for optimizing gait retraining in stroke patients. The initial results from human testing demonstrate that AKROD is able to accurately produce desired torque and velocity profiles while keeping an adequate level of comfort to the human.

REFERENCES

1. National Institute of Child Health & Human Development, "Research Plan for the National Center for Medical Rehabilitation Research," National Institutes of Health Publication No. 93-3509, March 1993.
2. M. Cook and S. M. Hussey, *Assistive Technologies: Principles and Practice*, 2nd ed: Mosby, 2002.
3. Blaya JA, Herr H, "Adaptive Control of a Variable-Impedance Ankle-Foot Orthosis to Assist Drop-Foot Gait", *IEEE Trans Neural Syst Rehabil Eng*, 12(1): 24-31, 2004.
4. Gordon KE, Sawicki GS, Ferris DP, "Mechanical Performance of Artificial Pneumatic Muscles to Power an Ankle-Foot-Orthosis", *J Biomech* (in press).
5. Weinberg B., Nikitczuk J., Fisch A., Mavroidis C. "Development of Electro-Rheological Fluidic Resistive Actuators for Haptic Vehicular Instrument Controls", *Smart Materials and Structures,* Vol. 14, pp. 1107-1119, 2005.
6. Vitrani M., Nikitczuk J., Morel G. and Mavroidis C., "Torque Control of Electro-Rheological Fluidic Resistive Actuators for Haptic Vehicular Instruments Control," *Journal of Dynamic Systems, Measurement and Control, Transactions of the ASME*, Vol. 128, No. 2, pp. 216-226, 2006.
7. Khanicheh A., Muto A., Triantafyllou C., Weinberg B., Astrakas L., Tzika A., and Mavroidis C., "MR Compatible ERF Driven Hand Rehabilitation Device", *Proceedings of the 9th IEEE International Conference on Rehabilitation Robotics (ICORR 2005)*, June 28 - July 1, 2005, Chicago, IL.
8. Winslow W. M., "Induced Fibrillation of Suspensions," *Journal of Applied Physics*, Vol. 20, 1949, pp. 1137.
9. Conrad H., "Properties and Design of Electrorheological Suspensions," *MRS Bulletin*, Vol. 23, No. 8, August 1998, pp. 35-42.
10. Weiss K. D., Carlson D. J. and Coulter J. P., "Material Aspects of Electrorheological Systems," in *Advances in Intelligent Material Systems and Structures-Volume 2: Advances Electrorheological Fluids,* Kohudic M. A. (Editor).
11. Kenaley G. L. and Cutkosky M. R., "Electrorheological Fluid-Based Robotic Fingers With Tactile Sensing," *Proceedings of the 1989 IEEE International Conference on Robotics and Automation,* Scottsdale AR, pp. 132-136.
12. Wood D., "Editorial: Tactile Displays: Present and Future," *Displays-Technology and Applications*, Vol. 18, No. 3, 1998, pp. 125-128.
13. Monkman G. J., "Electrorheological Tactile Display", *Presence*, MIT Press, Vol. 1, No. 2, 1992.
14. Taylor P. M., Hosseini-Sianaki A. and Varley C. J., "Surface Feedback for Virtual Environment Systems Using Electrorheological Fluids," *International Journal of Modern Physics B,* Vol. 10, No. 23 & 24, 1996, pp. 3011-3018.
15. Sakaguchi M. and Furusho J., " Force Display System Using Particle-Type Electrorheological Fluids," *Proceedings of the 1998 IEEE International Conference on Robotics and Automation,* Leuven, Belgium, May 1998, pp. 2586-2590.
16. Böse H., Berkemeier J. and Trendler A., "Haptic System Based on Electrorheological Fluid," *Proceedings of the ACTUATOR 2000 Conference,* 19-21 June 2000, Bremen GERMANY.
17. Sakaguchi M., Furusho J., Genda E., "Basic Study on Rehabilitation Training System Using ER Actuators," *Proc. of the IEEE International Conference on Systems, Man and Cybernetics*, Vol. 1, 1999, pp. I-135 - I-140.
18. Koyanagi K., Furusho J., Ryu U. Inoue A., "Development of Rehabilitation System for the Upper Limbs in a NEDO Project," *Proceedings - IEEE International Conference on Robotics and Automation*, Vol. 3, 2003, pp. 4016-4022.
19. Kikuchi T., Furusho J., Oda K., "Development of Isokinetic Exercise Machine Using ER Brake," *Proceedings - IEEE International Conference on Robotics and Automation*, Vol. 1, 2003, pp. 214-219.
20. Li W.H., Du H., Guo N.Q., Kosasih P.B., "Magnetorheological Fluids Based Haptic Device," *Sensor Review*, Vol. 24, No. 1, 2004, pp. 68-73.
21. Liu Y., Davidson R.I., Taylor, P.M., Ngu, J.D., Zarraga J.M.C., "Single Cell Magnetorheological Fluid Based Tactile Display," *Displays*, Vol. 26, No. 1, January, 2005, pp. 29-35.
22. Rov A. M., Neelakantan V. A., Washington G., "Design and Development of Passive and Active Force Feedback Systems Using Magnetorheological Fluids, *American Society of Mechanical Engineers, Aerospace Division (Publication) AD*, Vol. 68, 2003, pp. 333-339.
23. Scilingo E. P., Sgambelluri N., De Rossi D., Bicchi, A., "Towards a Haptic Black Box for Free-Hand Softness and Shape Exploration," *Proc. - IEEE International Conference on Robotics and Automation*, Vol. 2, 2003, pp. 2412-2417.
24. Carlson J.D., Matthis W., Toscano J.R., "Smart Prosthetics Based on Magnetorheological Fluids," *Proceedings of SPIE - The International Society for Optical Engineering*, Vol. 4332, 2001, pp. 308-316.
25. Furusho J., Takesue N., Nakagaki S., Tsuda T., Nakagawa A., Morimoto S., "Development of Intelligent Prosthetic Ankle Joint (1st report, development of linear-type MR-fluid brake)," *Nippon Kikai Gakkai Ronbunshu, C Hen/Transactions of the Japan Society of Mechanical Engineers, Part C*, Vol. 70, No. 7, July, 2004, pp. 2163-2170.
26. Herr H., Wilkenfeld A., "User-Adaptive Control of a Magnetorheological Prosthetic Knee," *Industrial Robot*, Vol. 30, No. 1, 2003, pp. 42-55.
27. Dong S., Lu K., Sun J.Q., Rudolph K., "Rehabilitation Device with Variable Resistance and Intelligent Control, *Medical Engineering and Physics*, Vol. 27, No. 3, April, 2005, pp. 249-255.
28. Li W.H, Du H., "Development of an Ankle Physiotherapy Device Using an MR Damper," *International Journal of Advanced Manufacturing Technology*, Vol. 25, No. 3-4, February, 2005, pp. 205-213.
29. Neder, JA; Nery, LE; Shinzato, GT; Andrade, MS; Peres, C; Silva, AC, "Reference Values for Concentric Knee Isokinetic Strength and Power in Nonathletic Men and Women from 20 to 80 Years Old", *Journal of Orthopaedic & Sports Physical Therapy*, 29(2), 1999, pp. 116 – 126.
30. Nikitczuk J., Das A., Vyas H., Weinberg B., Mavroidis C., "Adaptive Torque Control of Electro-Rheological Fluid Brakes Used in Active Knee Rehabilitation Devices", *Proceedings of the 2006 IEEE International Conference on Robotics and Automation*, Orlando, FL, May 15 - 19, 2006.