ANALYSIS AND CONTROL OF HUMAN LOCOMOTION USING NEWTONIAN MODELING AND NASA ROBOTICS

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Combining NASA technology, University insight and Industry know how NASA's Jet Propulsion Laboratory (JPL), the UCLA Brain Research Institute and Mechanical Dynamics Inc. (MDI) have developed an approach for enhancing strategies for rehabilitation of individuals with spinal cord injury (SCI). This approach utilizes robotics developed for manned space exploration, mathematical modeling used for commercial product testing and human research on spinal cord injuries. This collaboration resulted from conversations between JPL and UCLA on how the two could work together on the application of NASA technologies to neural repair and rehabilitation problems resulting from traumatic brain and spinal cord injury.

We know that a complete spinal cord injury severs the information flow between the brain and the neural networks below the level of injury. For example, paraplegics injured at a lower thoracic level of the spine lose control of their legs. Through research efforts there is now clear evidence that the efficacy of the remaining neural networks in the lumbosacral, or lower spinal cord, can be enhanced by specific locomotor training. These experiments demonstrate that the lumbar spinal cord, even without input from the brain, learns the specific motor tasks that are practiced. For example, the spinal cord can learn to step under full weight-bearing conditions over a range of speeds and to stand. Further, if the spinal cord is not allowed to continue to practice the motor task it will forget how to perform it. This learning phenomena can be associated with significant changes in the biochemistry of the spinal cord in the form of both excitatory and inhibitory neurotransmitters, as well as in the receptors that respond to these transmitters. In a sense, these findings suggest that a significant degree of functional neural regeneration might be directed intrinsically by the neural networks and their supportive cells.

Work on the rehabilitation of stepping skills performed at UCLA resulted in an approach called Body Weight Supported Training (BWST). This approach, although successful, was very labor intensive thus not available to most persons who could benefit from its ability to get them out of their wheelchairs. BWST requires that physical therapists move the lower extremities of the person while they are suspended over a moving treadmill. The therapists move the legs as required by the speed of the treadmill exerting pressure in all directions to maintain as normal a walking motion as physically possible. This method, although very successful, has two short comings; it is difficult to quantify the amount of exerted pressure and direction of that pressure being applied by the therapists, and it is equally difficult to measure the degree of improvement shown by the patient from treatment to treatment. To solve these two problems JPL proposed the use of a robotic exoskeleton to replace the therapists and a mathematical model to perform the motion analysis and control of the exoskeleton.

The exoskeleton technology originally developed to assist astronauts in the manipulation of devices in space was broken down into its basic technologies, enhanced for this application and retooled for prototype testing in the UCLA Neurorehabilitation Research Lab. The resultant technology consists of microdevices for measuring force and acceleration over six degrees of freedom. i.e. includes positive and negative rotations about all three possible directions. These devices placed at the major joints can detect even the most subtle abnormal movement in the patients stepping and coupled with recording capabilities provide the necessary data for complete analysis. Once prototyping has been completed the exoskeleton technology can be integrated into a body suit providing all necessary data required to analyze the motion of walking.

UCLA, MDI, and JPL have begun implementing the computer simulation needed to analyze and predict human motion. The model being used was originally designed by MDI and augmented by JPL. It currently implements all necessary joints (hip, knee, and ankle) of the lower limbs, incorporates classical Newtonian mechanics with six degrees of freedom and is completely dynamic. This modeling of lower limb stepping is currently providing new insights in efforts to develop effective rehabilitation strategies to improve mobility in spinal cord injured subjects as well as new counter measures to protect astronauts during long-term exposure to microgravity. The completed model will provide a research and therapeutic tool capable of:

a) calculating the force levels necessary at each joint to effect successful locomotion;

b) pinpointing which weak components of the step cycle need augmentation, and by how much;

c) simulating both normal and impaired locomotor strategies; and

d) devising and assessing alternative locomotor strategies that place fewer and/or less stressful demands on muscle force output.

This effort incorporates state-of-the-art simulation software tools to automatically formulate and solve the equations for both the physiological and neural control model allowing higher order sophistication as well as the development of a much more robust controller. With this current approach, higher-order elements such as surface-contact joints (knees), soft tissue wrapping around hard tissues, sophisticated muscle force algorithms, fully articulating foot, distributed plantar surface contact forces and detailed spine will be included to make the model more closely emulate the kinematics and kinetics of a particular patient. In addition, the model will be "personalized" including features such as parametric hard tissue geometry and joint axis orientation, soft tissue geometry and configuration as well as a controller which may be configured to the state of the subject.

Current prototype exoskeleton components located in hand held interfaces at the knee and foot to quantify the level of assistance given by the trainer clearly depicts changes in needed assistance both during and across training sessions. These types of data are a valuable tool for assessing the subject's progress while training to achieve the appropriate kinematics and kinetics for locomotion for both spinal cord injured patients desiring normal walking capabilities here on earth and astronauts operating in space.

We are using a neural oscillator constucted as a linear state space matrix and augmented with non-linear state functions through "Simulink" software that functions as a central pattern generator with a sensory feedback system combined with closely simulated limb mass, kinetics and moment arm data of individual muscles of the hip, knee and ankle. Currently the modeling is focused on the locomotion of a subject walking with a range of relative loads, i.e. from full weight bearing to stepping with no load (air stepping). Variables that are being studied include percent of body weight loading, speed of stepping, frequency of stepping, changes in muscle output, e.g., as would occur with muscle hypertrophy or atrophy, and changes in the number of motor units recruited during selected phases of the step cycle. The model currently permits the evaluation of the alterations in kinematic, kinetic and ground reaction force dissipation signatures for the lower extremity during walking gait simulations at varying gravity loads. As anticipated, all three signatures from the model predict decreased reliance on the shock dissipation mechanism of the lower extremity under decreasing gravity loads. The model is sufficiently detailed to permit analysis of the passive (heel strike) and active (mid- and forefoot impact) peaks in the ground-reaction dissipation signature to predict effective shock at each joint. In the coming months, addition of modular neural control elements will enable the testing of a variety of locomotor regulating systems. Based on these studies predictions of the pattern of force, and thus the level of motor unit recruitment necessary for successful locomotion, will be made.

One of the reasons that the exoskeleton can be as important to patients as it will be to astronauts is because the spinal cord as well as the brain learns the motor task that it is being taught. It appears that if the spinal cord remains idle in bed or in space, then it begins to forget how to walk. Similarly, if you teach the spinal cord to walk improperly, then it learns to walk improperly. If a robotic exoskeleton is used to move the legs in the proper manner, the spinal cord will learn or maintain the appropriate sensory information that must be present for normal walking to persist.

This robotic stepper will permit optimal sensory inputs to be "seen" by the spinal motor pools alone in the case of patients with complete SCI, and by the spinal and higher networks in the case of incomplete SCI and stroke patients. From a scientific point of view, the study of complete thoracic spinal injured subjects with this device and its measures will allow us to study in greater detail the adaptability of the cord. This feedback should also allow patients to gradually increase the use of their residual motor control and, with consistent training, gradually reduce the assistance provided by the motorized exoskeleton.

More than a half million Americans are hospitalized each year with stroke, 10,000 with spinal cord injury, and 100,000 with a traumatic brain injury. These diseases and injuries result in anything from partial to total paralysis. Approximately 30 percent of those with stroke and 75 percent with a spinal cord injury suffer lifelong physical impairment in ambulation, balance, strength, and endurance. Many of these patients could be retrained to walk. Physiological principles that have evolved from studies of gravitational loading and locomotion in rats, cats, monkeys and humans show that retraining is possible. It is the intention of this collaboration to use the model controlled exoskeleton approach to show that automated BWST retraining is possible and to then commercialize it for global application.

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