Patient-Adaptive Prosthetic and Orthotic Leg Systems

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Abstract: Two computer-controlled devices for leg rehabilitation are presented: 1) an external knee prosthesis for trans-femoral amputees; and 2) a force-controllable ankle-foot orthosis to assist individuals suffering from drop-foot, a gait pathology resulting from muscle weakness in ankle dorsiflexors. Here muscle-like actuators and biologically-inspired control schemes are employed to enhance patient stability, speed and dynamic cosmesis. Patient-adaptive control schemes are discussed in which the joint impedance of each device is automatically modulated to match patient-specific gait requirements. By measuring the total time that the prosthetic foot remains in contact with the ground during each gait cycle, the prosthetic knee controller estimates forward speed and modulates swing phase flexion and extension damping profiles to achieve biological lower-limb dynamics. For the ankle-foot orthosis, joint stiffness is automatically adapted to permit a smooth and biological heel strike to forefoot walking transition in drop-foot patients. Using only local sensing and computation, the adaptation schemes presented here automatically modulate joint impedance throughout the stance and swing phase of walking, enabling patients to walk in a safe, comfortable and smooth manner.

Keywords: Prosthesis, Orthosis, Control, Rehabilitation.

Introduction

A long standing goal in engineering is to exploit the unique designs of biological systems to guide the development of autonomous biomimetic machines that exhibit agility, strength and speed in a variety of natural environments. Most critical to this effort is the development of actuator technologies that behave like muscle and control methodologies that exploit principles of biological movement. In this paper, two biomimetic devices for leg rehabilitation are discussed. First, an external knee prosthesis used by trans-femoral (above-knee) amputees is presented in which biological data are used as desired targets in a patient-adaptive control scheme (1,2,3). Using only local mechanical sensing, the prosthesis automatically adjusts knee damping levels for each phase of walking without any parameter tuning required by a prosthetist. Computer controlled prosthetic knees currently on the market are not patient-adaptive and therefore require a prosthetist to define knee damping levels (4,5). In a second leg rehabilitation device, a force-controllable actuator is attached posteriorly to an ankle-foot orthoses and a controller modulates joint spring stiffness during the controlled plantarflexion phase of walking (6). The device is used to treat drop-foot gaits where ankle dorsiflexors are impaired from disease or traumatic injury. A biological model of normal ankle function (7) motivates a linear ankle spring control where the stiffness of the orthosis is adjusted from step-to-step to optimize the heel to forefoot transition during the early stance period of walking. For both the orthotic and prosthetic devices presented here, mechanism design, control and device functionality are addressed.

Materials and Methods

Patient-Adaptive Knee Prosthesis:

Using state-of-the-art prosthetic knee technology, a prosthetist must pre-program knee damping levels until a knee is comfortable, moves naturally, and is safe (4,5). However, these adjustments are not guided by biological gait data, and therefore, knee damping may not be set to ideal values, resulting in the possibility of undesirable gait movements. Still further, in such a system knee damping levels may not adapt properly in response to environmental disturbances. In this study, an external knee prosthesis is presented that automatically adapts knee damping values to match the amputee's needs, accounting for variations in both forward speed and body size (1,2,3). With this technology, knee damping is modulated about a single rotary axis using magnetorheological fluid in the shear mode, and only local mechanical sensing of axial force, sagittal plane torque, and knee position are employed as control inputs. With every step, the controller, using axial force information, automatically adjusts early stance damping. When an amputee lifts a suitcase or carries a backpack, damping levels are increased to compensate for the added load on the prosthesis. With measurements of foot contact time, the controller also estimates forward speed and modulates swing phase flexion and extension damping profiles to achieve biologically realistic lower-limb dynamics. For a normal walking cycle, the maximal flexion angle of the knee during the swing phase falls within a narrow angular range, approximately 60 to 80 degrees for moderate to fast walking speeds (3). The knee controller automatically adjusts the knee damping levels until the swinging leg falls within the biological angle range for each foot contact time or forward walking speed.

Patient-Adaptive Ankle-Foot Orthosis:

A powered ankle-foot orthoses is presented for the treatment of drop-foot, a gait pathology most commonly caused by stroke, cerebral palsy, multiple sclerosis or trauma. Drop-foot results from a particular muscle impairment in the anterior compartment of the leg where a patient is unable to dorsiflex the ankle or lift the foot. The major complications of drop-foot are 1) slapping of the forefoot after heel strike and 2) dragging of the toes at the beginning of each swing phase. The ankle-foot orthoses, shown in Figure 1, employs a force-controllable actuator and control algorithms based on biomechanical models of normal ankle function (6). Attached posteriorly to the ankle-foot orthosis is an actuator comprising a spring placed in series with an electric motor like a tendon in series with a muscle (8). This series elasticity enables the system controller to modulate force instead of position. For this spring plus motor system, output force is proportional to the position difference across the series elasticity multiplied by the spring constant. By applying a position control on the spring, force or torque can be controlled across the orthotic joint.

The external sensors on the orthosis measure ankle joint position (potentiometer 3) and applied forefoot force (capacitive force sensors 4). These sensory data are then used to control 1) joint stiffness during the controlled plantarflexion phase of walking, and 2) ankle

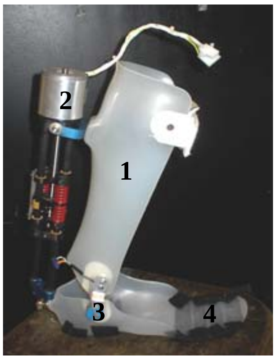

Fig. 1: An actuated ankle-foot orthoses is shown for the treatment of drop-foot, a gait pathology resulting from stroke, cerebral palsy (CP), multiple sclerosis (MS), or trauma. Using the actuator, the stiffness of the ankle joint is modulated from step to step to control the movement of the foot during controlled plantarflexion. The ankle-foot orthoses (1) comprises a series-elastic actuator (2), potentiometer angle sensor (3), and capacitive force sensors (4).

dorsiflexion angle at the start of the swing phase (to alleviate the toe dragging complication of drop-foot). The control law for controlled plantarflexion is a linear spring law where the actuator applies a torque proportional to joint position. As is shown in Figure 2, this linear control is consistent with the response of a normal human ankle during level ground walking (7). Although a normal ankle exhibits a spring-like response, the spring does not behave passively but seems to be actively controlled by the body's nervous system, changing stiffness from step-to-step even during steady walking. Hence, the stiffness of the applied virtual spring on the orthosis is not constant but is adjusted by the controller to optimize the heel strike to forefoot transition.

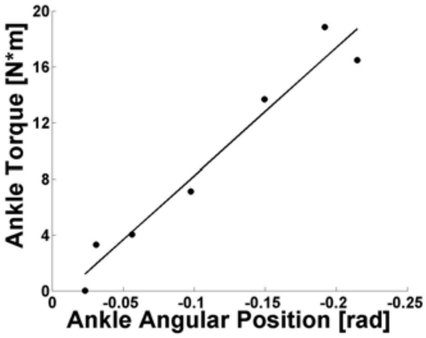

Fig. 2: Ankle torque versus position data are plotted for a normal subject walking on a horizontal surface. Only ankle data during the controlled plantarflexion phase of walking are shown. Although data for just one subject and one walking step are plotted, the human ankle behaves like a linear spring throughout early stance independent of walking speed, storing and releasing energy and allowing for a smooth heel to forefoot strike sequence (7).

Results

In Figure 3, the knee controller is shown to successfully adjust knee damping such that the swing phase peak flexion angle falls within an acceptable biological range of 60 to 80 degrees for moderate to fast walking speeds. Ovarall we find the adaptation scheme successfully controls early stance damping and swing phase extension damping, enabling amputees to flex and extend throughout early stance and diminishing swing leg accelerations when the knee prosthesis reaches full extension just prior to heel strike (3).

For the orthotic device, we find that when the applied ankle stiffness is too low, excessive forefoot collision occur, causing the drop-foot condition. To alleviate this complication, the orthotic controller increases stiffness at each walking speed and for each terrain until forefoot collisions are minimized. Given this biomimetic control, we find the system provides a more biological and stable ankle response for drop-foot patients (6).

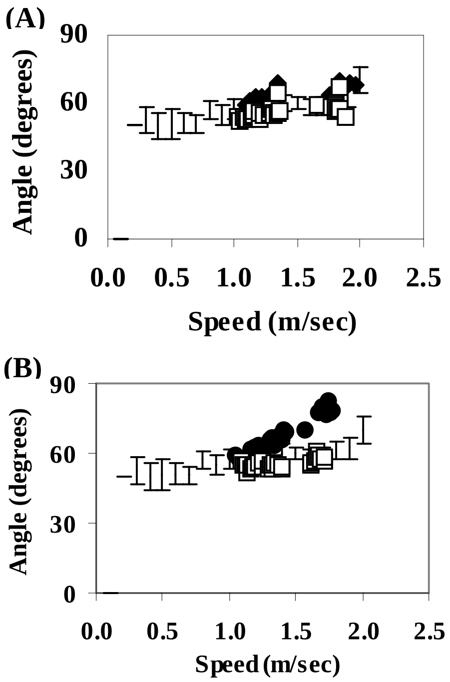

Fig. 3: Peak flexion angle during the swing phase versus walking speed is shown for one subject using the adaptive knee (plot A, filled triangles) and a non-adaptive, mechanical knee (plot B, filled circles). In (A) and (B), the subject's sound side leg is shown (open squares), along with reference data from unimpaired walkers of comparable height and body size (error bars). In (A), peak flexion angle is consistent with biological data, but in (B) the peak angle increases with increasing speed.

Discussion

In order for individuals suffering from leg dysfunction to walk in a variety of circumstances, leg rehabilitation devices must provide stance control to limit buckling when weight is applied to the device. In addition, leg devices must provide swing phase control so that biologically realistic dynamics emerge during swing. Unlike a biological leg, an autonomous leg prosthesis or orthosis, using only local mechanical sensing, must accomplish both stance and swing control without direct knowledge of its user's intent or of the environment. Rather, such a device must infer whether its user desires stance or swing behavior and predict when future stance/swing transitions should occur. Such a device must also determine when dramatic changes occur in the environment, as for example, when an amputee decides to lift a suitcase or walk down a slope.

An autonomous leg device must not only be safe to use, but should also help the patient walk in a smooth and non-pathological manner. Conventional prosthetic knees often force the amputee to walk with an awkward gait. As an example, many prosthetic knees lock up throughout early stance, not allowing the amputee to go through normal knee flexion and extension motions typically observed in normal gait (9). The amputee is therefore forced to roll over a perfectly straight leg, resulting in large vertical fluctuations in the amputee's center of mass and diminished shock absorption.

In this paper, we discribe autonomous leg devices that employ local mechanical sensors and computation to improve the locomotory capability of individuals suffering from gait pathology. Although some improvements in gait were observed, a great deal of work still remains. An important area of future research will be to combine local mechanical sensing about the artificial joint with peripherial and/or central neural signals measured by internal sensors distributed throughout a patient's body. The fact that only local mechanical sensors were imployed in the devices of this study leads to dramatic limitations in the systems ability to assess user intent. The prosthesis and orthosis presented here cannot determine whether a patient wishes to turn to the right or to the left, or that an obstacle falls directly in a patient's intended pathway. In the development of human-machine systems, we feel a distributed sensory system, combining both external and internal body sensors, is an important area for future investigation.

Conclusions

We report in this paper on the design and functionality of two biomimetic rehabilitation devices: an external knee prosthesis and an ankle-foot orthosis. Perhaps the simplest summary of our findings is that muscle-like actuators and biomimetic, patient-adaptive control schemes can improve some measures of patient stability and dynamic cosmesis. It is our hope that this work will lead to further studies in orthotic and prosthetic design to the benefit of an even wider range of locomotory functions.

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