FES CLOSED-LOOP CONTROL FOR PARAPLEGIC STAND-TO-SIT TRANSITIONS USING ACCELEROMETERS AND ELECTRO-GONIOMETERS

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Abstract - A closed-loop controller was designed for the Cochlear FES-22 stimulator in the stand-to-sit phase. The combination of electro-goniometers and accelerometers provides information regarding position and inclination of the body, yielding to potential input-devices for a closed-loop control system for stand-to-sit transition in FES standing. Accelerometers measure inertial and gravitational acceleration, providing both actual acceleration and inclination information. The accelerometers are placed on the back between the shoulder blades, at T6 level, while the goniometers are attached across the knees to monitor the knee flexion angle. Combining these two information sources, the relative trunk inclination can be calculated. The controller uses the trunk inclination as one of the conditions for the start and end routines. The actual transfer is controlled by comparing the knee angular velocity, derived from the goniometer signal, to a angular velocity curve, representing an ideal trajectory. Stimulation is adapted according to the result of this comparison. The use of the angular velocity, in relation to the knee angle, as the criteria, enables the system to respond to changes in arm force used by the subject.

Key words- Spinal Cord Injuries, Paraplegia, Implantable Functional Electrical Stimulation, Feedback Sensor, Orthosis, Stand-to-sit Transition.

I. INTRODUCTION

This paper discusses the design of a closed-loop control system for the FES-aided stand-to-sit transfer. However such a closed-loop control system has yet to be developed. Different control strategies are described in the literature for application in FES-standing (up) and or walking [1, 5]. Research on the stand-to-sit transfer has been limited to a biomechanical analysis [2] and one study analyzing the different control strategies based on a biomechanical analysis [8].

FES stimulation during the stand-to-sit transfer has primarily been controlled by open-loop control systems [7]. Such open-loop systems are based on preset down ramps. Because of the fixed character of the down ramps, the system depends on the time span of the sit-down cycle. Response to external factors, like the used arm force, is not possible. Another disadvantage is the lack of control on the end velocity, which may lead to medical problems for the patients, such as, repeatedly slamming the buttock area on the seat can lead to pressure soars. A final problem encountered with open-loop systems is also related to the time span of the sit-down cycle. Patients may end with their knees extended, while already sitting. This caused by the difference between the ramp down duration and the actual sit-down time span.

Kralj [2] divided the stand-to-sit cycle into different phases, standardized using event markers. Sensors detecting the different event-markers, serve as feedback to the controller. The use of standardized event-markers rather than elapsed time to define the phases, makes the system time-independent.

II. METHODS

A 26 year-old, T-10 paraplegic male (CS) was implanted in November 1991 [1] with a modified FES-22 Cochlear stimulator. A companion paper described the FES-22 closed-loop system [10]. CS has been successful in conditioning his muscles and standing with FES [9, 10].

A. Biomechanical analysis

The usage of the FRO has a drawback for the stand-to-sit transfer: ankle dorsiflexion is inhibited by the FRO. In several studies [3, 6] conducted on sit-to-stand, the maximum ankle dorsiflexion during the transfer was found to be 30° (shank relative to the vertical). In the case of CS, the FRO kept the ankles at less then 3° of dorsiflexion.

Measurements using the FRO on a 23 years old able subject, show a breakdown angle (α0) of approximately 20°. The breakdown angle is defined as the largest knee angle, measured against the vertical, at which the body can be hold stable, without the use of the arms. Without the FRO, i.e., with ankle dorsiflexion, no breakdown was registered. The body could be held stable at any given point. By inhibiting ankle dorsiflexion, the FRO appears to introduce instability. The FRO forms an obstruction for normal sit-down, even for able subjects.

Restricting ankle dorsiflexion increases the ankle torque. For knee angles greater than α0, the support of the arms becomes necessary for stability. The use of the FRO increases the need for arm support, an external factor. A simple way of minimizing the required arm force is by tilting the trunk forward (the stooping posture), thus providing counterweight.

B. The feedback sensors

Electro-goniometers (Penny and Giles) and ADXL05 accelerometers (Analog Devices) are used for the sensory feedback. The goniometers have an analog output range of 0-5V measuring from -180° to +180°. Attached across the knees, the goniometers deliver an accurate measurement of the knee angle. The ADXL05, a force balanced capacitive accelerometer, can measure accelerations with full-scale...
ranges from ± 5g to ± 1g or less with the capability to measure both ac accelerations (typical of vibrations) or dc accelerations, (such as inertial force or gravity) in one sensitive axis. To monitor the two-dimensional motion, (up/down, fore/backwards), during sitting down, two accelerometers are used: one accelerometer (VAccel) is placed with its orientation to the earth’s gravity while the second one (HAccel) is orientated perpendicular to the earth’s gravity. After acquisition, the data is run through a digital second-order Butterworth low-pass-filter, with a cutoff frequency at 5 Hz.

C. The Stand-to-Sit Controller

While standing in the “C” posture, the Subject can show his intention of sitting down by pressing the remote switch. The stimulation is then applied to the knee extensors. The change in posture is confirmed by the accelerometers when CS is tilting his trunk forward. This is the posture required to provide necessary balance for the stooping posture. At this point the controller decreases the stimulation to the knee extensors to a pre-set level and waits for a knee buckle, which indicates the actual sit-down. The stimulation is then controlled in the angle/angular velocity phase plot by comparing the trajectory to an “ideal” sit-down, which combined empirical open-loop data from CS and prior work on normal subject by Kralj [3]. For a given knee angle, if the actual angular velocity is higher than the ideal velocity then the stimulation is increased. Otherwise the controller decreases the stimulation after a constant time delay.

The end of the transition, i.e. sitting, is indicated by the vertical accelerometer detecting the buttock reaching the seat. As a backup, the horizontal accelerometers detects if the trunk has returned to a vertical position. Then the transition is terminated and the stimulation switched off.

III. RESULTS

Preliminary results indicates that the controller is able to control the delivery of the stimulation during the stand-to-sit transition and to detect the sitting position. The patient has been training in the different phases of the transition. CS was able to trigger the controller by being in the stooping posture and eliciting a knee buckle. CS was also able to stop the controller by sitting in his chair with the trunk vertical or leaning back. CS learned also that it was easier to sit down with his feet close together so the legs could fit in front of his wheelchair.

IV. CONCLUSION

The preliminary results indicate that the system is able to control the stimulation in such a way as to provide a smooth stand-to-sit transition. The controller works without timing and appears to be able to react to external factors. Standardization of the different phases of the transfer proved to be very helpful. Fixed starting feet-positions and required stooping posture before sitting for example, simplified the system. The combination of goniometers and accelerometers provides all the necessary data, enabling the controller to monitor to the position and inclination of the body. With some adaptations, this controller can serve as a basis for the design of a closed-loop controller for the sit-to-stand transitions.

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REFERENCES