The Praxis24 Sensor System for Use in the Closed-Loop Control of Standing.

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Our aim is to develop a safe and reliable closed-loop sensing system for the implanted FES system (‘Praxis24’, Neopraxis Pty. Ltd., Sydney, Australia), which will be light weight and easy to don/doff. Open-loop FES standing has typically been achieved for 10-20 minutes. This system will be used by paraplegic individuals for prolonged standing (20 minutes +), sit-stand-sit transfers and stepping.

Our present closed-loop control of standing is achieved by monitoring the bilateral knee angles using electro-goniometers (Biometrics Ltd.), resulting in stance for over 60 minutes by subject CS (T10-paraplegic male; ASIA: A) and the stimulation time being reduced to less than 10%. Stance stability is achieved by the Andrews’ Anterior Ankle-Foot Orthosis (AFRO). Closed-Loop control of stand-sit transfer is achieved by monitoring the bilateral knee angles and angular velocity using electro-goniometers (Biometrics Ltd., UK), trunk inclination and vertical acceleration using accelerometers (ADXL05, Analog Devices), resulting in diminished slamming onto the seat.

Our next generation sensing system is based on sensor packs (Neopraxis Pty. Ltd., Sydney, Australia) located bilaterally on the thigh and shank. An additional pack is located on the trunk. Each pack is capable of measuring 3-D acceleration (2x ADXL202 2-D accelerometers, Analog Devices), and 1-D angular velocity (ENC-05D rate gyroscope, Murata). Each pack converts the sensor signal into digital values and performs further computation on these values. Preliminary results indicate that the knee angle can be computed from signals generated by the thigh and shank sensor packs. This paper describes the possibility of a simple knee buckle detection strategy using the angular velocity and accelerometer output of the sensor packs. Initial results indicate that the rate gyroscope is more sensitive to motion than the accelerometers, which makes the rate gyroscope give a significant signal the earliest in a knee buckle (200 msec earlier that the goniometer or the accelerometers).

**KEYWORDS:** Functional Electrical Stimulation, FES, Closed Loop Control, Micro Electro-Mechanical Sensor, MEMS, Accelerometer, Rate Gyroscope.

INTRODUCTION

We have demonstrated the possibility of long term implantation of a Functional Electrical Stimulation (FES) system /1,2/. With appropriate bracing and sensors for closed-loop control, this system allows paraplegic subjects to stand unassisted and uninterrupted for over 60 minutes, with the use of one hand to do tasks in a laboratory setup /1,2/. With the advance of micro-machined sensors (MEMS), it has been shown that small accelerometers and rate gyroscopes can be used in the control of FES /3/.

To achieve our primary goal of providing a rehabilitation system for use at home and the workplace /2/, our object is to design a sensing system for closed-loop control that is small, low-power, reliable, easy to use and independent of the laboratory.
METHODS

The sensor packs
As part of the Praxis24 FES system (Neopraxis Pty. Ltd., Sydney, Australia), sensor packs are being developed. Each sensor pack consists of two 2-D accelerometers (ADXL202, Analog Devices), a rate gyroscope (ENC-05D, Murata) and a microcontroller (Atmega 103L, Atmel). The signal from each sensor is digitized and transmitted to the external controller (Navigator), which in turn uses the data for closed loop control. The full system is composed of 5 sensor packs. Two sensor packs are attached to each lower extremity: one on the shank (or orthosis) and one on the thigh. Their function is to determine the position of each leg segment during closed-loop control of sit-to-stand, prolonged standing, stand-to-sit and stepping. An alternative function is to detect/predict a knee buckle during standing. The fifth sensor pack is attached to the trunk. Its function is to determine if the subject wants to initiate sit-to-stand, stand-to-sit or has safely reached the desired upright C-posture.

Pendulum Test
A pendulum was constructed with the sensor pack mounted on the swinging arm and a goniometer (Biometrics Ltd., UK) mounted across the pendulum axis of rotation. The damped swinging (approx. 1 Hz) is natural and gives a fluent movement.

Able Body Knee Buckling
An able-bodied subject was equipped with a goniometer (Biometrics Ltd., UK) across the knee and two Praxis24 sensor packs on the same lower extremity, one on the thigh and one on the shank. The subject starts from a C-posture and sways his/her center of gravity slowly backward. When the subject senses that the center of mass has shifted back, he/she allows the knees to buckle. This motion is similar to the one expected of paraplegic subjects when the center of mass shifts back of the knee joint and creates a flexion moment at the knee. The subject is allowed to train to generate reproducible buckles.

RESULTS

Comparison of dynamic behavior of both sensors
When testing with the pendulum, the rate gyroscope is more sensitive to motion than the accelerometers. This is illustrated in Figure 1. Although in this case the acceleration was the sum of gravity and a relative acceleration, the rate gyroscope gives a larger output. The accelerometer amplification can not be increased significantly, since the sensor packs are to be able to work in the full range of motion of the limbs (sitting, standing and stepping motions).

Test results with buckling
Figure 2 shows a typical knee buckle of an able-bodied subject as described above, with five signal represented: a] the knee angle measured with the goniometer, b] the Z-acceleration of both sensor packs which is the direction perpendicular with gravity, but most sensitive for knee movement, and c] the two angular velocities measured with the rate gyroscopes. As can be seen in the figure, the rate gyroscopes give a significant signal the earliest in a knee buckle: 200 msec earlier that the goniometer or the accelerometers. There is some variation in the accelerometer and goniometer outputs, but only in the later phase of the buckle is there a significant output.

T=2.40-2.80 sec: the subject is in stable stance with minimal sway (static situation).
T=2.85 sec: the rate gyro on the thigh shows a small decrease of angular velocity. Usually the angular velocity is between –10 and +10 deg/sec during standing.
T=3.05 sec: the accelerometer outputs are starting to provide indication of movement.
The buckle is almost at maximum velocity; the shank rate gyro gives an output of ~40 deg/sec and the thigh rate gyro has a value of ~-25 deg/sec.

T=3.15 sec: the accelerometers reach their maximum values (~0.4 g).

T=3.20 sec: at this moment the subject voluntarily stops the knee from buckling further.

DISCUSSION

The added value of the rate gyroscope in the Praxis24 system

The Praxis24 system is based on both accelerometers and rate gyroscopes. The inclusion of the rate gyroscope in the system has the following advantages:

- The rate gyroscope is more sensitive to movement than the accelerometers in the full range of motion of the limbs. Movement detection will be more accurate with the rate gyroscopes in the system.
- Measurements indicate that the rate gyroscope signal can detect the actual knee buckle earlier than the goniometers or accelerometers. This also indicates that the rate gyroscope signal can be used for prediction of knee buckling.

Future direction

The possibility of using the rate gyroscope as the primary signal for buckle detection will be tested using a standardized knee buckle. And in a later phase a strategy will be validated for use by paraplegic subjects. The capability of the Praxis24 sensor pack to process the sensor data will also be explored (i.e., sensor pack angle).

REFERENCES


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Figure 1: Difference in dynamical behavior of the accelerometers and rate gyro signal (pendulum test).

Figure 2: The signals accompanying a buckle