Design of a Novel Robotic Dynamometer: An Isokinetic Knee Joint Torque Measurement System for FES

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Introduction

Recumbent cycling exercise achieved by functional electrical stimulation (FES) of the paralysed leg muscles is effective for cardiopulmonary and musculoskeletal conditioning after spinal cord injury but its full potential has not yet been realised. Various studies highlighted current limitations of this technology. In order to overcome these limitations, different activation patterns should be studied systematically on upper leg muscle groups during isokinetic leg extension.

The aim of this work was to develop and test an ergonomic robotic dynamometer to simulate cyclical isokinetic knee-joint motion during actual cycling. Stimulation trains can be applied repetitively to the quadriceps during the knee extension phase across an angle range similar to recumbent FES-cycling.

Methods

The dynamometer consists of three major parts. The first part is an actuator system to simulate isokinetic knee joint motion. Position and torque sensors for making repeatable and reliable measurements form the second part. The third part is a control system/model with a graphical user interface. A well-padded leg extension/curl machine (Tuff Stuff, RLE-382) is used as a base to ensure comfort.

Optimal cadence in FES-cycling is known to be around 50 rpm, but our system can control to an arbitrary cadence value. On the dynamometer an actuator system is used to simulate this motion while the hip joint remains fixed. A brushless motor (Maxon EC45, 250W) is used with a planetary gearhead (Maxon, GP52C) with a ratio of 156:1. The motor can generate a maximum continuous torque of 0.348 Nm. When the gear ratio of the sprockets (40:24) is also taken into consideration, the total torque of 90 Nm can be generated for resistance or support.

The generated torque is transformed from the chain drive system to the torque sensor. The actuator and gearhead are placed on the other side of the torque sensor shaft which allows torque resistance and/or support when needed. A magnetostrictive torque sensor (NCTE series 2000) is used to bi-directionally measure the effective torque on the gauge bar in real time both at rest and in rotation. An analogue position sensor (Contelec Vert-X) is used for angle measurement.

For the specific needs of isokinetic torque measurements in biomechanics, a software program is specifically designed. The user interface is designed with a Matlab GUI and the Dynamometer is controlled by a Matlab/Simulink Model by using Real-time Windows target. Closed loop control strategies and filters are used to simulate the cyclical motion and to make accurate noise-free sensor readings. The software additionally enables the user to carry out acquisition of signals coming out of the torque sensors, perform analysis, and export data in different formats (raw signal, signal graph and parameters values).

Results

All controllers were tested and sensors calibrated by using an external actuator-torque sensor calibration system. A series of experiments with able-bodied subjects was carried out and the isokinetic mechanical power output was measured. Stimulation cost was calculated offline for different stimulation patterns (single mode, doublet and triplet trains) with different amplitude and pulse-width values for each test. Range of motion for the knee joint during recumbent cycling exercise (*ROM:* 72˚, *max:* 146˚ - *min:* 74˚) was also calculated with active marker based kinematic digital image processing measurement and transferred to the dynamometer. Outcomes for the controllers were compared in relation to nominal cadence during cycling and simulated motion in the dynamometer.

Conclusion

The aim of this work was to develop and test an ergonomic robotic dynamometer to simulate cyclical isokinetic knee-joint motion during actual cycling for FES investigations.

The isokinetic knee joint torque measurement system can be used to develop novel muscle activation strategies to optimise isolated muscle performance and will play a key role in fundamental research on activation patterns and development of appropriate stimulation patterns. This will make human powered mobile cycling a more realistic recreational option and opens the potential to increase the beneficial effects on cardiopulmonary and musculoskeletal health.