

TOWARDS AUTOMATIC OPTIMIZATION OF GAIT SUPPORTED BY A TWO CHANNEL IMPLANTABLE DROP FOOT STIMULATOR

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SUMMARY

An automated system is developed to optimize the timing and magnitudes of stimulation for a two-channel drop foot stimulator on the basis of criteria for the quality of the movement of the foot during the swing phase of gait. These criteria encompass the timing of the start of dorsiflexion movement after heel-off, foot clearance during the swing phase, and balance between inversion and eversion and heel-first foot placement at the end of the swing phase. These criteria are evaluated using a six degrees of freedom inertial sensor system placed on the foot. On the basis of this evaluation, the timing and magnitude of the stimulation are adapted from cycle-to-cycle.

The observability of the formulated movement criteria from the inertial sensor measurements have been preliminary evaluated in a patient experiment with and without stimulation of the peroneal nerve. The approach is intended to result in an evaluation and tuning system for clinical use.

STATE OF THE ART

Stroke may have many physical and cognitive consequences. Physically, the motor control of one side of the body may be deteriorated. Often, such a deteriorated motor function improves during the recovery period and by training, although in many cases motor control problems remain. Among others, a frequent consequence is the inability to voluntarily lift the foot at the affected side (drop foot). Since Liberson /1/, FES systems have been developed to artificially activate the dorsiflexor muscles during the swing phase of gait. More recently, a two channel implantable drop foot stimulator has been developed /2/, allowing electronic balancing of inversion and eversion during foot lift. In the past year, this system has been implanted in four stroke patients in Twente and Salisbury.

For effective application of the electronic balancing feature of this two channel implant, criteria for optimal movement patterns need to be stated, a sensor system for measuring relevant movement parameters of gait and procedures for the adjustment of the stimulation parameters both in time and amplitude of both channels need to be developed.

MATERIAL AND METHODS

Criteria for optimal gait improvement by drop foot stimulation

The potential improvement of gait through the use of a drop foot stimulator is not limited to the foot movement. It may prevent the lifting or circumduction of the affected leg due to drop foot gait. Foot landing after swing is also of primary importance. Heel first landing without excessive inversion or eversion contributes to stable gait and optimal loading transition from swing to stance. Heel-first landing also avoids excessive stretch reflexes in the calf muscle which may result from fast dorsiflexion when the forefoot first hits the ground /3/. Also at the onset of stimulation, fast dorsiflexion may elicit stretch reflexes in the calf muscles.

On the basis of these considerations criteria were formulated, concerning three phases of the walking cycle: the transfer from stance to swing phase, the swing phase and the transfer from swing to stance phase:

1. transfer from stance to swing:
 - 1a. dorsiflexion starts after heel-off, allowing for push-off, if available
 - 1b. dorsiflexion with limited angular velocity, avoiding excessive calf muscle stretch reflexes.
2. mid-swing:
 - 2a. foot clearance during whole swing phase without excessive heel lift or circumduction
 - 2b. limited inversion/eversion of the foot.
3. transfer from swing to stance:
 - 3a. heel-first landing
 - 3b. limited inversion/eversion of the foot

Assessment of foot movement during the swing phase of gait

Each of these criteria can be conceived as the reference value for related movement parameters (e.g. time of start of dorsiflexion movement after heel-off, foot clearance during mid-swing, foot orientation at foot contact). These movement parameters can be assessed for each walking cycle using a six degrees of freedom inertial measurement unit (IMU) attached to the foot. The IMU consists of 2 dual-axis accelerometers (Analog Devices ADXL210) and 3 uni-axial angular rate sensors (Murata ENC-03J). Advantages of micro-machined inertial motion sensors are that they do not need external sensors or references to operate, their small size and low cost. When interpreted correctly an IMU will not only provide angular velocity and linear acceleration but also position and orientation with respect to an inertial frame of reference. Orientation is optimally estimated using sensor fusion and Kalman filtering techniques /4/. Here, however, straightforward integration and coordinate system transformation is used.

Adequate application of initial conditions during the stance phase of gait (zero linear and angular velocity of the foot) and adequate subtraction of the gravity acceleration component result in accurate calculation of the 3D orientation and position of the foot during the swing phase without integration drift. This has first been used in a step-to-step velocity meter for runners (RunnersWatch™ by Xsens). It should be noted that the orientation and position of the foot are calculated with respect to the inertial reference frame, not with respect to the shank, since for most movement criteria the orientation and movement of the foot with respect to the floor is of interest. If an additional inertial sensor system is integrated with the transmitter or implant of the stimulator on the shank, additional information about the movement of the foot relative to the shank is available.

Automatic tuning of a two-channel drop foot stimulator

The timing and amplitude of the stimulation patterns generated by the two-channel implantable drop-foot stimulator can be adjusted automatically by a controller consisting of two levels:

1. finite state detection of gait phases, especially transitions from stance to swing and from swing to stance, including heel- and toe-off moments. Control of the timing of the stimulation (onset, ramp-up, ramp-down, offset time) is relative to the timing of the states assessed using this finite state control scheme.
2. A cycle-to-cycle control scheme /5/ adjusts the timing and amplitude parameters of the stimulation. This discrete-time control scheme determines the amplitude and timing parameters of stimulation for all cycles of gait on the basis of the evaluation of the movement parameters of all cycles in relation to the criteria. The timing parameters are relative to the phases determined by the finite state detection scheme.

RESULTS

Assessment of foot movement during the swing phase of gait

The feasibility of the assessment of the movement parameters is illustrated in figure 1. 3D foot orientation and position during the swing phase are shown for one step of a stroke patient walking with and without the application of an external drop foot stimulator. Without stimulation (figures 1a,b), this example patient walks with extreme eversion of the foot (positive x-rotation in fig. 1a), which, among others, results in non-optimal foot contact during the transfer from swing to stance phase. This is improved with surface stimulation (figure 1c,d).

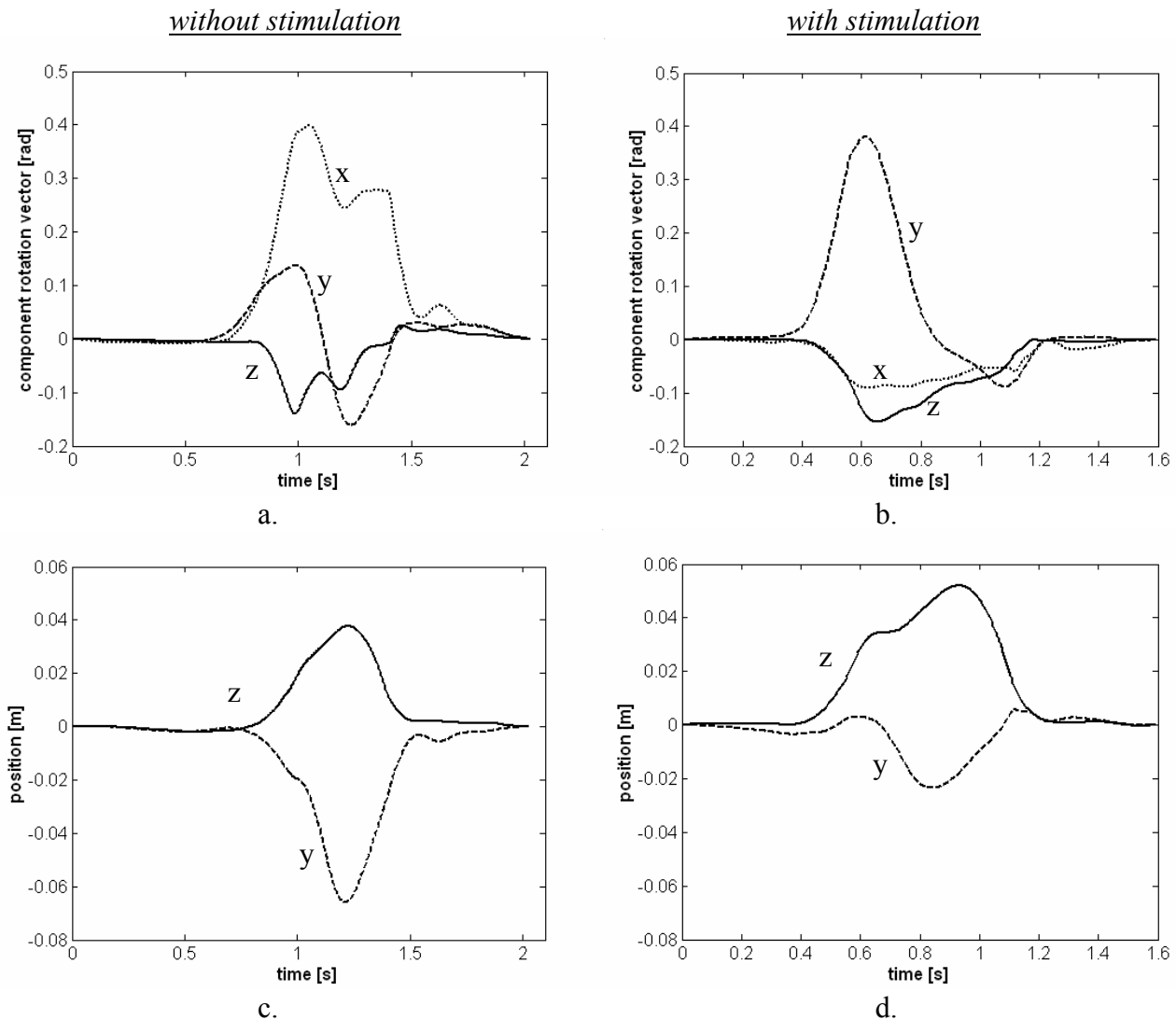


Figure 1: Example foot orientation (a,b) and position (c,d) with respect to the inertial reference frame during swing phase of gait for a stroke patient with (b,d) and without (a,c) surface stimulation of the peroneal nerve, as measured by a 3D inertial measurement unit on the foot. Dotted (x) is walking direction, dashed (y) is medial/lateral direction, solid (z) is vertical direction

Relevant movement parameters can be derived from these measurements. As an example, figure 2 shows one of the movement parameters, the inversion/eversion angle at the instance of foot contact, as a function of cycle number without and with stimulation.

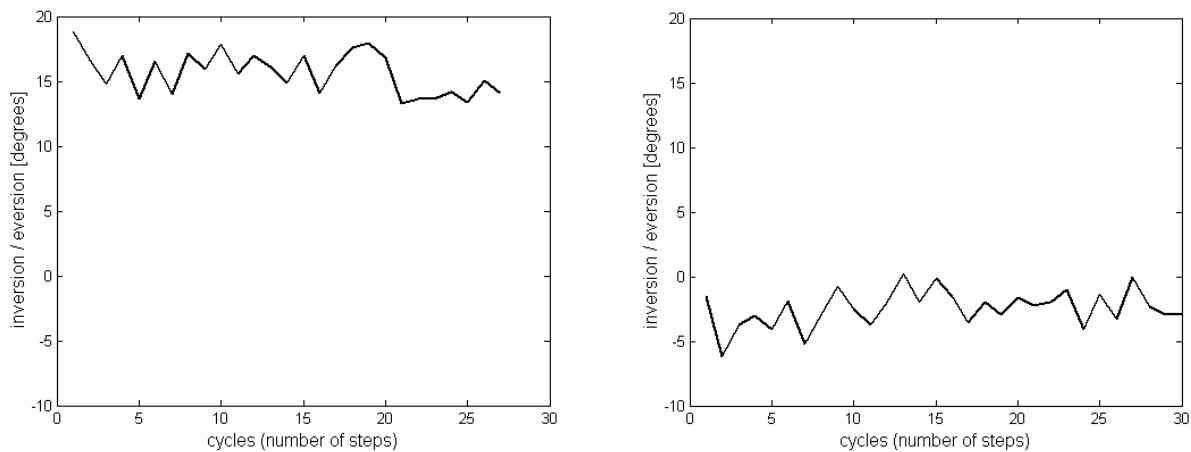


Figure 2. Example registration of one of the movement parameters, the inversion/eversion foot angle (orientation around x-axis) at the instance of foot contact, as a function of cycle number without (a) and with stimulation (b) (same stroke patient as in figure 1)

DISCUSSION

The preliminary results of movement measurement and cycle-to-cycle movement parameter extraction are the basis for the automatic adjustment of stimulation patterns for the two-channel implantable drop foot stimulator. In first instance, the automatic adjustment may only be performed during clinical sessions. In this case, the foot sensor module is only applied during these clinical sessions and not during daily use. An inertial sensor module integrated with the transmitter or implant stimulator on the shank is used for phase detection during daily use /6/. This avoids the daily use of sensors on the foot, which has been a major practical drawback of dropfoot stimulators using footswitches. If, eventually, the foot inertial sensor unit can be integrated in the sole of the shoe and telemetrically linked to the stimulator, the continuous use of the cycle-to-cycle controller during daily application of the stimulator is an option. This would enable continuous adjustment of stimulation patterns when muscles fatigue or when the walking surface, walking speed or other circumstances change.

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