Control of Triceps Surae Stimulation based on shank orientation using a uniaxial gyroscope

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Abstract

Until now, heelswitches have been the predominant method for triggering stimulation, during real-time FES applications. Heelswitches are readily available and give an easy signal for users to identify when stimulation should occur. This paper presents simple method that can easily replace heelswitches for control of FES of the triceps surae for improved push-off in subjects with a stroke. The method presented in this abstract uses the angular velocity of the shank in combination with its integrated signal (change of shank angle) since heel strike, to trigger stimulation reliably at every step.

1 Introduction

A gyroscope measures angular velocity (rad/s or deg/s). When this signal is integrated a change in angle results.

FES for gait improvement is a widespread technique; the most common application is minimisation or complete removal of drop foot occurrence as a result of stroke or incomplete spinal cord injury. The most common method for triggering this stimulation is using a force sensitive resistor (FSR) in the shoe (usually under the heel). The FSR is simple to use, it gives (or should give) an on or off signal, indicating that the foot is either on or off the ground. When the heel has left the ground (in the transition from stance to swing), the resistance becomes high and the stimulation should be triggered during the whole swing phase until heel strike. Pappas [1] highlighted that the heelswitch is not always reliable due to incorrect positioning in the shoe, and Dai [2] mentioned that a drawback for daily use is that the subject must wear shoes. Nevertheless, in practice, the heel switch still is the most commonly used method to control stimulation of drop foot correction.

Pappas [1] gave an overview of all methods that have been researched for controlling FES, including accelerometer clusters [3], inclinometers [2], heel switches and manual control. In this review, most drawbacks of current methods of control have been highlighted. Pappas' method utilises the use of a gyroscope built into an insole, along with three force resistive sensors. This method has the drawback mentioned by Dai that the user must wear a shoe for stimulation. In addition, heelswitches wear out relatively quickly due to continuous loading/unloading cycles.

The above review has been dedicated to the removal of drop-foot during the swing phase of gait. That is from heel off until heel strike. With a heelswitch, despite the disadvantages mentioned above, this is still relatively feasible, as swing lasts for 40% of the gait cycle.

For the purpose of triggering the FES of the triceps surae for push-off and provide knee flexion at initial swing, the heelswitch has proven to be insufficient. Push-off entails a mere 20% of the gait cycle, therefore the window for accurate stimulation timing is significantly less than for drop foot correction timing. For push-off optimisation, the heelswitch needs to operate on the basis of time delays. The heelswitch detects foot/floor contact, then an estimation of the optimal delay should be input to the controller for stimulation to occur. However, this is very dependent on the gait speed. In addition, due to the effect of triceps surae stimulation, the stroke subject does not always land on the ground with the heel first, therefore stimulation may come too late. The heel switch has caused other problems in its use with FES of triceps surae: when a good stimulation level has been achieved, the foot rapidly leaves the ground and with some stroke subjects, with poorest control, the heel re-strikes the ground, causing a re-activation of the heelswitch. This induces a phenomenon known as "limit cycling". The subject would cyclically re-stimulate the calf muscle until the stimulator had to be switched off. With the proposed mechanism described below, this problem did not occur.

The solution proposed in this paper is to remove the idea of triggering from foot activity, and to focus on the shank movement. For FES of triceps surae the centre of mass should have already passed over the ankle, such that the calf muscles are stretched, as with "normal" push-off. This adequate stimulation time can be estimated most accurately when using the shank angle. This leads to the main limitation of this method, which is that the stimulation is triggered using the change in angle ($\Delta\varphi$) after heel strike as opposed to the absolute angle (φ) of the shank. Regardless of this drawback, this method has proven to be more reliable than the heelswitch control.

2 Methods

2.1 Introduction

Figure 1a, helps to illustrate that during the swing phase of gait, the angular velocity of the shank around the knee is very high with respect to the shank angular velocity around the ankle during stance. At heel strike, the angular velocity decreases to a value below zero. The algorithm uses both the large threshold during swing and the fact that the shank angular velocity changes direction and then passes through zero as its basis. A small peak is usually visible at impact. Figure 1b shows the integrated angular velocity plot. In this plot, it is clear to see that some drift appears over time, as the signal is integrated.

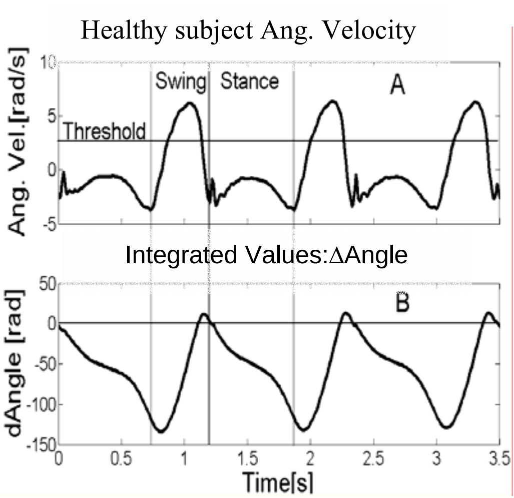

Figure 1A: *shows shank angular velocity. 1B shows integrated signal (shank angle) of healthy subject data. Note the angle drift in 1B, this is avoided in our proposed detection algorithm.*

2.2 Equipment

The algorithm operates real-time on an imbedded controller in a-purpose built and programmed symmetrical bi-phasic stimulator. The gyroscope used is a component of the MT9 inertial sensor from Xsens Motion Technology B.V. Each MT9 contains 3x (accelerometers, gyroscopes, and magnetometers) as well as one temperature sensor. The inertial sensor signals are read into the busmaster (also from Xsens) at 100Hz sample frequency here signals are converted to binary data. The stimulator is connected to the busmaster via a cable. The stimulator selects the channel required for stimulation control, which is the angular velocity perpendicular to the sagittal plane. The signal-to-angular velocity calibration is carried out in the stimulator.

2.3 Algorithm

The algorithm is based on the above information. The gyroscope signal is an arbitrary signal in volts. The voltage is proportional to angular velocity. This signal must be calibrated, by removing the offset and the sensor sensitivity. The algorithm is programmed in the stimulator to do the following:

1) Wait for angular velocity to pass a threshold during swing (T_{sw}).
2) When this has been passed, the algorithm waits for the signal to pass through zero.
3) At zero, the algorithm starts integration of the signal – thereby the new signal is angle.
4) At a pre-defined change in angle, the stimulator will give a burst. Then again, wait for T_{sw} to be exceeded.

Due to the nature of the algorithm, it is clear to see that the problem of gyroscope drift that is evident in figure 1 is avoided, as the beginning of integration is reset each time the signal fulfils the pair of conditions.

2.4 Experimental Procedure

The subject should walk in the gait lab; usually this involves the subject walking backwards and forwards numerous times. The person should stand still at the beginning of each trial to enable the offset of the gyroscope to be determined. During the gait trials, MT9 data is recorded using purpose-built software to enable quick analysis of the correct gyroscope and the integrated signal to give an indication of the timing (change in angle) required for optimal timing of stimulation of the calf muscles of stroke subjects during gait.

3 Results

Figure 2A shows angular velocity results that have been recorded from the worst walker of the stroke subjects involved in the "FES of triceps surae" experiments. The horizontal line at approximately 100 indicates an example of the value that can be chosen for T_{sw}, the algorithm waits for the signal to pass through this value. The vertical lines represent where the algorithm detects the zero crossing and from this point, the algorithm begins to integrate. Figure 2B shows the integrated values. The values are not on the same time scale as the angular velocity signal, however both A and B of figure 2 clearly shows the working of the algorithm on this subject. It is clear to see that this subject does not display the exact characteristics that are displayed in figure 1. But it is also clear to see that the relative large amplitude of angular velocity during the swing phase, followed by the signal passing through zero allows the algorithm to be meaningfully implemented.

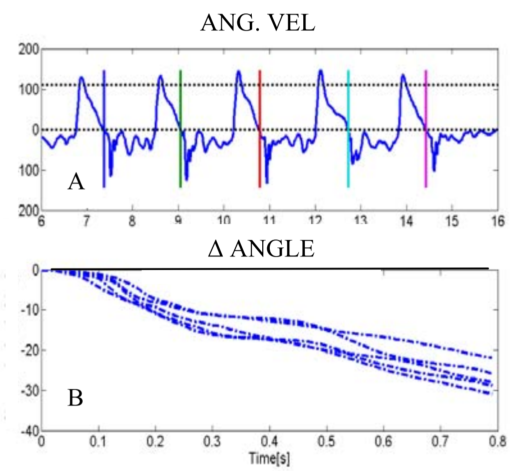

Figure 2: *Stroke subject Gyroscope signal. Subject is very poor walker. 2A: Angular velocity, [deg/s] versus time [s]. Horizontal line: T_{sw}. Vertical lines: zero-crossings as detected by the algorithm. 2B: Each line represents an integrated pattern (change in angle in [deg] versus time [s]) after the signal has passed through T_{sw} then passed through zero.*

The above results have been tested successfully on five stroke subjects. The same five stroke subjects were present during a previous study, during which time the stimulation reliability from the triggering using a heelswitch was less. The precise number of applied stimulation per attempt have not been recorded but the use of the gyroscope has proven to be more reliable, even in the worst walkers, for which FES was practically impossible to control using heel switches.

4 Discussion and Conclusions

The above results demonstrate quite clearly that real-time triggering of stimulation is possible and useful from the gyroscope signal.

The heelswitch posed a number of problem sources:

1) Unwanted stimulation due to change in pressure in the heelswitch during stance. Using this algorithm, this situation is avoided, as the subject should first have a forward angular velocity before triggering of the stimulation.

2) Limit cycling occurred during gait and stance. When a good stimulation level was obtained, some subjects re-initiated the stimulation in a cyclical manner. This situation did not occur while using the gyroscope for stimulation control.

3) FES of the triceps surae caused the foot to land on the ground in non-optimal/non-normal ways (e.g., toe strike instead of heelstrike). This meant that the heel switches were not activated properly. However, with the gyroscope on the shank, changes in angular velocity were always detected and stimulation could be applied regularly.

References

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