QUALITY AND SAFETY OF GAIT IN STROKE PATIENTS USING A DROPPED FOOT STIMULATOR.

J.Van Vaerenbergh[1,2,3], A. De Kegel[1], S. De Ruijter[1], S. Vandenberghe[1], Y. D'Hont[1], L.Briers[2]

[1] Department of Physiotherapy, Arteveldehogeschool, Gent, Belgium.
[2] Centre for Movement Analysis and Therapy, Brussels, Belgium.
[3]Faculty of physical education and physiotherapy, Katholieke Universiteit Leuven, Belgium

Abstract

In this study a reduced spring like model of walking was used to demonstrate the effect of FES on the quality and safety of gait. The acceleration profile of the COF was considered as a good quality estimator of the spring system. FES optimized the spring properties in most of the participating patients but especially in those reporting a reduced fear of falling

Introduction

To understand and describe the functional benefit of FES, the use of a reduced model is advisable. The simplification helps to derive better applications to customize them to fit a particular stroke patient. If we reduce walking to wheel like propulsion, generated by a counterbalancing mechanism symbolically represented by a system of springs, the latter might be replaced by the muscle model of Hill [1] [2]. Hence force is generated by nonlinear components that depend on neural activation (Q), length (L) and its derivative (dL/dt). (Fig. 1)

$$f_3(L_{CE}) + f_1\left(L_{CE}, \frac{dL_{CE}}{dt}, Q\right) = f_2(L_M - L_{CE})$$

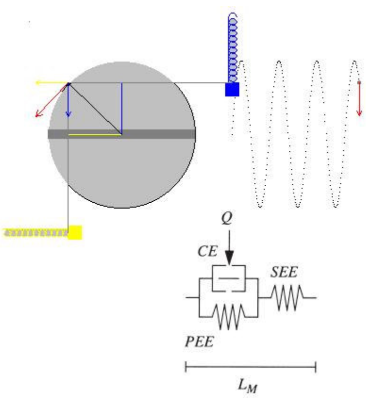

Fig. 1: walking represented as a reduced non linear model. CE (contractile element), SEE (series elastic element) and PEE (parallel elastic element)

The reduction model simulates a uniformly circular movement with a constant speed and responds to Newton's law. However in-shoe plantar pressure measurements recording ground reaction forces during walking at constant speed don't show a perfect sinusoidal behaviour as represented in fig.1. This is because the potential and kinetic energy curves generated during heel strike, foot flat and push off are generally out of phase and responsible for submovements. These submovements are demonstrable in the centre of force trajectory (COF). The frequency spectrum of them can be revealed by harmonic or Fourier analysis, converting the signal from the time to frequency domain.[3] The most dominant frequency shows up as a large wave at a position along the horizontal axis corresponding to its frequency. Any other frequencies (called harmonics) show up as smaller peaks at different positions according to their frequency. Fig.2 shows the existence of higher harmonics, responsible for the acceleration variations of the COF during the foot support phase.

Hemiparesis has far reaching consequences for the proposed model. In fact the Hill model is highly sensible for changes in muscle excitability and structural shortening. If FES is successful it will show a strong influence on the harmonics by improving the spring characteristics.

The following research will demonstrate that FES is perceived as comfortable and safe when this kind of optimisation takes place.

Material and Methods

The COF acceleration profile of the affected and non affected foot was investigated during walking in new FES users having a first stroke for at least six months and presenting with an obvious dropped foot. The Odstock one channel dropped foot stimulator was used to correct abnormal gait in 22 patients (mean age was 69 years).

The Fscan system (Tekscan Inc.) was used to record the COF trajectories. Ultra-thin flexible insole sensors were placed in the shoes of the subjects. Measurements were done during walking at a self-generated, comfortable speed and data with and without FES were compared. The acceleration of the COF trajectories in X and Y direction was obtained by a double derivative. These data were smoothed by a running average using 10 samples and low pass filtered with a 14 Hz 8 order Butterworth filter. Finally a Fourier analysis was performed to calculate the power density spectrum. The 2.34, 4.69, 7.03 and 9.38 Hz frequency ranges were further studied. The respectively power in each frequency bandwidth was compared with and without the use of FES. A Student t-test for paired samples was used to compare means. Significance level was set at $p \le 0.05$

At the same time the 'go up and downstairs', 'walk around neighbourhood', 'housecleaning', and simple shopping items from the Falls Efficiency Scale were recorded one week before the gait study and after six weeks of FES use.[4] The Wilcoxon matched-pairs signed ranks test was used to compare these results.

Results

In all investigated stroke patients the unrolling of the affected and unaffected foot was clearly disturbed. This coincided with superimposed irregularities or submovements to the normal acceleration curve, a high power at the sound side and a very low power at the affected side in most frequencies.

FES reduced power (X en Y direction) in the non affected limb and increased the power in the affected limb. However the difference was only significant for the accelerations in X direction. (Fig. 3-4)

The average score on the Falls Efficiency Scale rose with 5.35 points ($p \le 0.001$) after six weeks of FES use.

Recalculating the power density spectrum statistics for those patients having an increase in the Falls Efficiency Scale higher than the average showed a strong influence on the acceleration characteristics especially in the Y direction. (Fig. 5)

Discussion

Stroke patients very often complain about an unsafe, low quality gait and fatigue during walking.[5] In many cases this is a consequence of an inefficient gait. In this study walking was simulated as wheel like propulsion, steered by counterbalancing mechanisms symbolically represented by springs driven by the Hill model.

The movement of the COF was the fingerprint of this spring system and Fourier analysis showed a superposition of several harmonics dealing with the specific spring capacities during heel strike, foot flat and push off. (fig 2)

According to the Hill model it is important to distinguish in stroke stiffness due to spasticity from that due to rheologic adaptations.

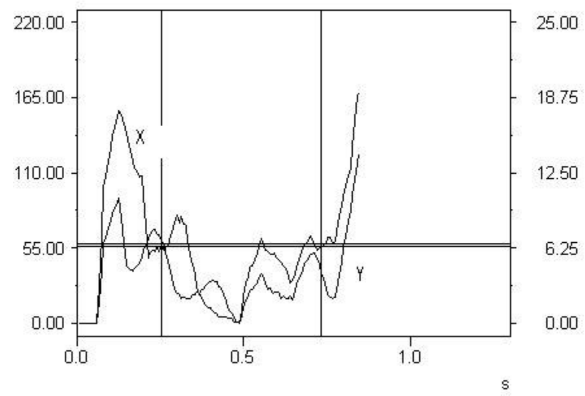

Fig. 2: COF X –Y acceleration profile of a stroke patient

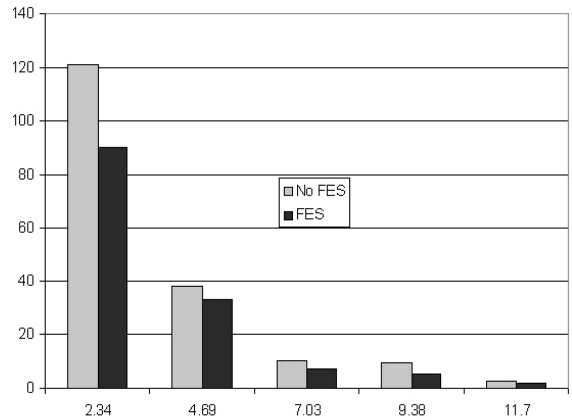

Fig. 3: Sound leg power spectrum for the X-COF accelerations. p=0.039 for 2.34 Hz and p=0.045 for 9.38 Hz

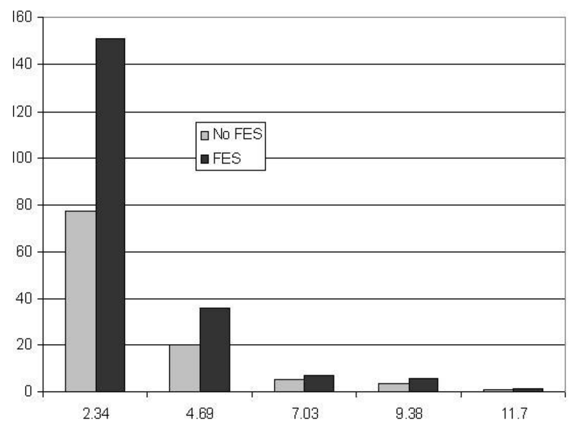

Fig. 4: Affected leg power spectrum for X-COF accelerations. p=0.049 for 2.34 Hz and p=0.02 for 4.69 Hz

The first is caused by disorganised reflexes, the latter by intrinsic changes in connective tissue arising from disuse secondary to hemiparesis.[6] This may be compounded by increased actin-myosin cross-bridge linkages, which are thought to be associated with reduced rates of cross-bridge detachment.[7]

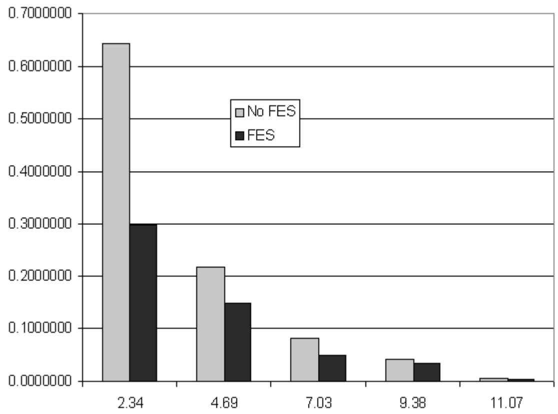

Fig. 5: Sound leg power spectrum for Y-COF accelerations. p=0.0001 for 2.34 Hz and p=0.05 for the higher frequencies.

Mirbagheri e.a [8] found a decreased reflex stiffness of 53% after FES assisted walking, and also intrinsic stiffness dropped by 45%. In contrast, both reflex and intrinsic stiffness increased in the non-FES control subjects. These findings suggest that FES-assisted walking has an important influence on the passive and active components of the muscle respectively represented by the SEE, PEE and CE elements in the Hill model. These findings are consistent with our study, which shows that FES for a dropped foot restores some feature of the spring mechanism. However our study only addressed temporary effects in chronic stroke.

Indeed the electrical induced contraction in the anterior Tibial Muscle of the affected limb is not only responsible for a better clearance during swing with an improved balance at the sound side, it also stretches the calf muscles during heel strike, which facilitates the storage of potential energy needed for the kinetic release during the powerful push off. This is visible in the normalisation of the 2nd harmonic in both affected and non affected limbs. At the same time, movement fragmentation is reduced which adheres the minimum jerk theory in control optimization.[9]

The fact that the acceleration scheme for the Y direction is only improved in patients who had the impression of an improved safety with the dropped foot stimulator makes us believe that in some cases FES is fighting against some remaining or altered spring properties. This is perceived by the patient as a less comfortable way of walking even when visual inspection of their gait gives the impression of an overall improvement. It is even not excluded that in those patients safety is on its turn compromised.

There is also the possibility that FES was not optimally tuned for each patient. If this is true, our approach will be an attractive method to guide this process. However the need for normative data is requested. In an unpublished study we found a positive relationship between power and speed in the 2.34 Hz frequency range.(fig.6) The increased walking speed seen in FES users can explain partly our observations, but seemingly it looks more complicated than that.

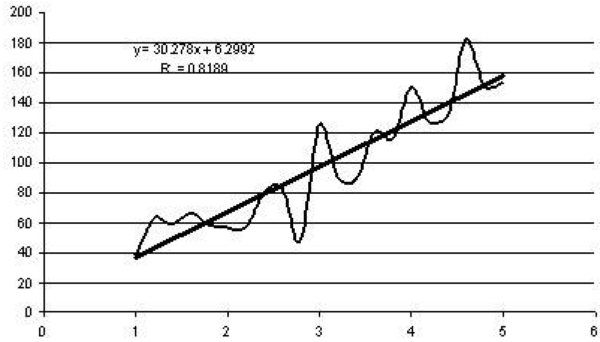

Fig. 6: Relationship between walking speed and power in 2.34 Hz frequency range

If we interpret the mean power values of our investigated stroke patients in accordance to the normal curve, we should expect a speed of 4 km/h for them, which is of course completely absurd. In the most case it was only between 1 and 2 km/h. With FES the speed increases but the power decreases in the sound limb. This might suggest an regained optimised relation between speed and energy input.

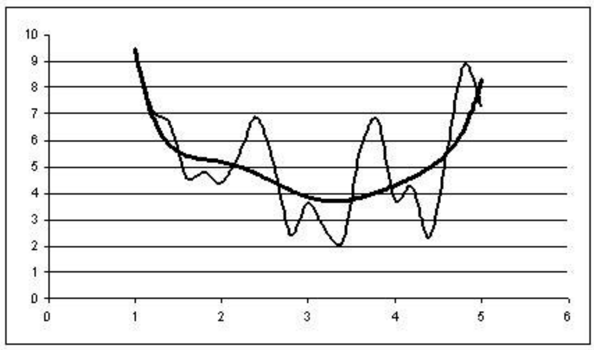

Fig. 7: Relationship between the power in the higher frequencies (>7.03Hz) and walking speed.

The higher frequencies, which are the indicators for the number of submovements don't show this linear relation between speed and power; but argue for the existence of a advantageous speed, with an optimal signal/noise ratio.(fig.7)

Under those circumstances FES can bring patients to a better signal/noise ratio by increasing speed. This optimization could be the prime factor for an improved feeling of safety.

However these interpretations should be treated very cautiously and further research is necessary. Also more clarifications explaining which factors are exactly influenced in the Hill equation by the dropped foot stimulator in stroke are needed.

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Author's Address

Drs. Jo Van Vaerenbergh
Center for movement analysis and therapy
R.Reniersstraat 11
B-1090 Brussels
E-mail: jo.vanvaerenbergh@cmat.be