INFLUENCE OF FUNCTIONAL ELECTRICAL STIMULATION OF THE HAMSTRINGS ON KNEE KINEMATICS IN STROKE SURVIVORS WALKING WITH STIFF KNEE GAIT

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Objective: To explore whether functional electrical stimulation of the hamstrings results in improved knee kinematics in chronic stroke survivors walking with a stiff knee gait.

Design: Quasi-experimental.

Subjects: Sixteen adult chronic stroke survivors.

Methods: Survivors received functional electrical stimulation of the hamstrings, 3 times a week for 1 h during a period of 5 weeks. 3D kinematics was calculated before the training period and after 5 weeks of training. Knee kinematics of walking without stimulation before the training period was compared with walking with stimulation after 5 weeks of training. (intervention effect). In addition, knee kinematics of walking without stimulation before the training period was compared with walking without stimulation after the training period (therapeutic effect).

Results: The intervention effect showed a significant increase, of mean 8.7° (standard deviation (SD) 8.3, p = 0.001), in peak knee flexion. The therapeutic effect showed a significant increase in peak knee flexion, of mean 3.1° (SD 4.7, p = 0.021)

Conclusion: The results of this exploratory study shows an increase in knee kinematics in swing after functional electrical stimulation of the hamstrings in stroke survivors walking with a stiff knee gait. The largest improvement in peak knee flexion in swing was seen when participants walked with hamstring stimulation. Participants with low neurological impairment responded better to hamstring stimulation, and there are indications that the effect of hamstring stimulation can be predicted during a single session. The effect of functional electrical stimulation is comparable to that of more invasive treatment options, such as botulinum toxin or soft-tissue surgery. Functional electrical stimulation is therefore a feasible treatment option for daily clinical practice.

Key words: stroke; walking; kinematics; functional electrical stimulation; hamstrings; stiff knee gait.

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Stiff knee gait is an abnormal movement pattern commonly observed in stroke survivors. It is characterized by reduced peak knee flexion (PKF) during the swing phase. The limited knee flexion may cause toe dragging or energy-inefficient compensatory movements (1), compromising the stability of the gait and increasing the risk of falling (2). The pathophysiology of stiff knee gait is only partly understood, and several hypotheses are postulated in the literature. The role of overactivity of the rectus femoris during the swing phase is often cited (3–5). Other possible causes of stiff knee gait are increased forces generated by the vasti (6), decreased hip flexion moments (7) and decreased ankle plantar flexion moments (8). However, the exact mechanisms remain unclear and seem to be multifactorial.

Different treatment options for stiff knee gait are available that are aimed at influencing the overactivity of the rectus femoris. These options include chemodenervation of the rectus femoris (9) and rectus femoris transfer (10, 11). The indication for chemodenervation or RF transfer treatment is related to overactivity of the rectus femoris in pre-swing or swing. This means that only those patients who exhibit this overactivity are eligible for this type of treatment. Electrical stimula-
tion of the calf and/or hamstring muscles (12, 13) is a treatment option that might be suitable for all patients, irrespective of the cause of stiff knee gait, as it might directly assist in achieving sufficient knee flexion. Studies on the effect of electrical stimulation of the calf or hamstrings on the hemiplegic gait pattern are, however, scarce and most of the studies stimulated 2 or more muscle groups in order to influence gait kinematics.

One practical problem of stimulating 2 or more muscles is the timing of the stimulation, as the proper timing of muscle contraction may differ between muscles. Providing adequate timing is easier when stimulating only one muscle, which makes it more feasible in clinical practice. From a clinical point of view, it is therefore interesting to investigate whether knee flexion during swing can be improved by stimulating only one muscle group.

The primary aim of the present study was to explore whether 5 weeks of functional electrical stimulation of the hamstrings results in improved knee kinematics during the swing phase in chronic stroke subjects with a stiff knee gait. The study compared: (i) walking without electrical stimulation pre-intervention with walking with electrical stimulation post-intervention (intervention effect). The secondary aims were to compare: (ii) walking without electrical stimulation pre-intervention with walking without electrical stimulation post-intervention (therapeutic effect); and (iii) walking without stimulation pre-intervention with walking with stimulation pre-intervention (immediate effect). Furthermore, based on clinically experience, the study explored: (iv) the relationship between the immediate effect and the intervention effect. Finally, based on the findings of Hanlon & Anderson (14) who found a positive relationship between walking speed and knee kinematics, the study aimed to explore: (v) the influence of walking speed on the intervention effect of stimulation.

**METHODS**

**Study design**

The study was designed as an exploratory prospective quasi-experimental study (Fig. 1). It was approved by the local Medical Ethics Committee (MEC Twente).

**Study population**

A convenience sample of adult chronic stroke survivors (>6 months after stroke) were recruited for participation at Roes-singh Centre for Rehabilitation (RCR), Enschede, the Netherlands. Inclusion was based on: visible diminished knee flexion during the swing phase, ability to walk without physical support, ability to complete a 3.5-h assessment, and ability to understand and follow verbal instructions. Exclusion criteria were: a pacemaker, metal implants in the paretic leg, or orthopaedic problems or progressive diseases influencing the walking pattern. Participants were allowed to continue their regular treatment during the study and received oral and written information about the study before they decided to participate.

**Intervention**

Patients were treated with electrical stimulation for 1 h, 3 times a week, for a period of 5 weeks (15 h in total). Therapy was provided by a senior physical therapist with longstanding experience (over 20 years) in the use of electrical stimulation in the stroke population. Each session consisted of walking with electrical stimulation of the hamstrings of the paretic leg. Participants walked at a comfortable speed indoors at the physical therapy department and were allowed to stop or rest when necessary. The Odstock 2-channel footswitch controlled stimulator system (Odstock Medical Limited, Salisbury, UK) was used for stimulation. Self-adhesive skin surface electrodes, with a size of 50 × 100 mm (CefarCompex Medical, Lund, Sweden) were placed on the mediolateral aspect of the hamstrings (15). A footswitch was used to trigger the stimulation between heel off and toe off. The indifferent electrode was placed approximately 5 cm above the knee crease and the active electrode was placed approximately 10 cm above the indifferent electrode. During an initial, pre-intervention session the location of the foot switch, the locations for electrode placement and stimulation settings (amplitude, pulse duration) were determined for maximum optimization of the walking pattern. These locations remained the same during the 15 sessions. The pulse duration varied between 0.125 and 0.475 s. The stimulation frequency was 40 Hz.

**Experimental protocol**

All participants were tested pre- and post-intervention, both during walking without and with stimulation. During the pre-intervention session, anthropometric data were collected.

Participants were instructed to walk at their natural, comfortable speed. During both evaluations and training period, participants used the same walking aids, orthoses and shoes.

**Participant characteristics**

The Rivermead Mobility Index (16), Functional Ambulation Category (17), Motricity index (18) and the Duncan Ely test (19) were administered only at the pre-intervention assessment to determine participants’ characteristics. Furthermore, the use of an ankle foot orthosis (AFO) and walking aids were recorded. In addition, adverse events during the experiment, such as blisters, skin problems or intolerance of the stimulation, were recorded.

<table>
<thead>
<tr>
<th>Pre-intervention</th>
<th>Training period, 5 weeks</th>
<th>Post-intervention</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without ES</td>
<td>C</td>
<td>Without ES</td>
</tr>
<tr>
<td>With ES</td>
<td>A</td>
<td>With ES</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 1.** Study design. A: intervention effect (post-intervention with electrical stimulation (ES) minus pre-intervention without ES). B: immediate effect (pre-intervention with ES minus pre-intervention without ES). C: therapeutic effect (post-intervention without ES minus pre-intervention without ES).
To determine knee kinematics and preferred walking speed, an infrared opto-electronic 3D-motion analysis system (VICON MX + 6 MX13 cameras, frame rate 100 Hz; Vicon Motion Systems, Oxford, UK) was used. Participants walked a 10-m walkway. A standard marker-placement (Plug in Gait model) was used and one person made all the marker placements. To normalize data to the gait cycle, initial contact and toe-off events were detected. A minimum of 10 strides were analysed and averaged for each participant to determine PKF during swing, knee range of motion (minimum stance phase vs maximum swing phase) and walking speed.

Statistical analysis

All variables showed sufficient closeness to a normal distribution, as determined visually by a senior statistician.

To identify the effect of ES on knee kinematics and walking speed, data for the 3 walking conditions were compared: (i) the intervention effect (pre-intervention without ES vs post-intervention with ES); (ii) the therapeutic effect (pre-intervention without ES vs post-intervention without ES); and (iii) the immediate effect (pre-intervention without ES vs pre-intervention with ES). Data were analysed with paired samples *t*-test. (iv) To predict the intervention effect in one try-out session (immediate effect) the correlation between knee kinematics of the intervention effect and those of the immediate effect were calculated using Pearson’s correlation. (v) To explore the influence of walking speed on the effect of stimulation the correlation between knee kinematics of the intervention effect and the intervention effect for walking speed were calculated using Pearson’s correlation.

Table II. Knee kinematics and walking speed

<table>
<thead>
<tr>
<th>Outcome measure</th>
<th>Pre-intervention</th>
<th>Post-intervention</th>
<th>Difference effect</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Without ES Mean (SD)</td>
<td>With ES Mean (SD)</td>
<td>Without ES Mean (SD)</td>
</tr>
<tr>
<td></td>
<td>Mean (SD)</td>
<td>Mean (SD)</td>
<td>Mean (SD)</td>
</tr>
<tr>
<td>Peak knee flexion (°)</td>
<td>29.1 (9.0)</td>
<td>32.2 (11.6)</td>
<td>37.9 (13.4)</td>
</tr>
<tr>
<td></td>
<td><em>p = 0.001</em></td>
<td>(CI 4.3; 13.2)</td>
<td><em>p = 0.021</em></td>
</tr>
<tr>
<td>Knee range total cycle (°)</td>
<td>27.7 (8.0)</td>
<td>30.2 (9.6)</td>
<td>35.9 (10.7)</td>
</tr>
<tr>
<td></td>
<td><em>p = 0.001</em></td>
<td>(CI 4.0; 12.2)</td>
<td><em>p = 0.027</em></td>
</tr>
<tr>
<td>Walking speed (m/s)</td>
<td>0.86 (0.22)</td>
<td>0.91 (0.21)</td>
<td>0.97 (0.23)</td>
</tr>
<tr>
<td></td>
<td><em>p = 0.000</em></td>
<td>(CI 0.06; 0.17)</td>
<td><em>p = 0.005</em></td>
</tr>
</tbody>
</table>

*Denotes a statistically significant difference between the conditions. p ≤ 0.05. (Paired sample *t*-test).

RESULTS

Participants

A total of 16 chronic stroke survivors were included in the study (Table I). All participants attended all therapy sessions and there were no dropouts. Eight patients walked with an AFO, 5 patients walked with a cane, and 1 patient walked using a quad cane. No adverse events were reported.

Kinematics and walking speed

The kinematic parameters analysed for the different testing conditions are shown in Table II. The kinematic parameters and walking speed of the intervention effect, therapeutic effect and immediate effect are shown in Table II.

Correlations

The calculated correlations are shown in Table III.

DISCUSSION

The aim of the present study was to quantify the effect of hamstring stimulation during the swing phase of
gait in chronic stroke survivors with a stiff-knee gait. The results showed that walking with stimulation of the hamstrings after 5 weeks of training resulted in a statistically significant increase in PKF and knee range of motion in chronic stroke survivors with a stiff knee gait. In addition, a statistically significant therapeutic and immediate effect was found for PKF and knee range of motion. Self-selected walking speed increased statistically significantly with hamstring stimulation (intervention effect).

It is not known what the clinically meaningful difference in PKF is for treatment options for stiff knee gait. Therefore, it is debatable whether the statistically significant increase of 3° as a therapeutic effect is clinically meaningful for the patient. The intervention effect of hamstring stimulation is considerably larger (8.7°). Thus, hamstring stimulation might be regarded more as an assistive device than a therapeutic device, as the effect of functional continuous stimulation (comparison of pre with stimulation and post with stimulation) is much larger than when it is used only as a training device (comparison of pre without stimulation and post without stimulation).

Although this study found a positive result for hamstring stimulation at the group level, there was a strong heterogeneity in effect at the individual level (see Fig. 2 for the exemplary data for 3 individuals). In other words, there were participants in whom a large intervention effect was seen and there were participants in whom no or only a small intervention effect was seen. The 4 participants with the largest response showed an improvement of more than 16° in PKF during swing. From a clinical point of view, insight into the participant characteristics that distinguish this subpopulation from the overall study population is of interest. All 4 large responders walked without an AFO or walking aid, had a high score on the Motricity Index (>69) of the lower extremity, and had a low spasticity score of the rectus femoris measured with the Duncan Ely Test (score = 1). Therefore, responders with the largest improvement appeared to have low neurological impairment and were able to adapt their walking pattern to the electrical stimulation. Following this line of thought, patients with severe neurological impairments may have limited ability to adapt their walking pattern to incorporate the hamstring stimulation.

A strong statistically significant correlation was found between the knee kinematics of the immediate effect and the knee kinematics of the intervention effect. Participants with a large immediate response also showed a large response after 5 weeks of training and for participants in whom the immediate response was low, the response after 5 weeks of training was also low. Clinically this might be a crucial issue. It means that the effect of functional electrical stimulation of the hamstrings at the individual level can be predicted with a high probability during a single session.

A statistically significant increase in walking speed was found, which may have contributed to an increase in knee kinematics (14), reducing the true effect of hamstring stimulation. However, a non-significant correlation between the change in walking speed and the knee kinematics (PKF and knee range of motion) was found. Furthermore, van Hedel et al. (20) showed that, in healthy subjects, an increase in walking speed of 0.9–1.0 m/s, which is the magnitude of the differences that we found, led to an increase in PKF of 1–2°. Based on this, it can be concluded that positive influence of the increased walking speed on knee kinematics is negligible in our study, and that the described differences are the result of the electrical stimulation.

In addition, it is debatable whether the significant improvement in walking speed, of 0.11 m/s from mean 0.86 (SD 0.22) to 0.97 (SD 0.23) m/s (intervention effect), was clinically meaningful for the patients, as there is no consensus on the magnitude of the minimal

![Fig. 2. Heterogeneity in intervention effect.](www.medicaljournals.se/jrm)
Influence of FES on stiff knee gait

The effect of functional electrical stimulation is comparable to that of more invasive treatment options, such as botulinum toxin (BTX) or soft-tissue surgery. Functional electrical stimulation is therefore a feasible treatment option for daily clinical practice.

**Study limitations and future research**

A limitation of the present study was the lack of a control group. Furthermore, both participants and assessors were not blinded in the present study.

Despite the general increase in PKF and knee range of motion, not all participants in the present study responded equally to hamstring stimulation. The multiple reasons mentioned for stiff knee gait, such as overactivity of the rectus femoris in the swing phase (3–5) or a lack of push off from the gastrocnemius moments (8, 27), may have influenced the effect of hamstring stimulation. In addition, generalization of the present study results to the broader stroke population is difficult, because of the relatively small study population.

Future research with more participants (control group, randomization, blinding) should deepen our understanding about the aetiology of stiff knee gait and evaluate how interventions can influence the causative factors of stiff knee gait.

**Conclusion**

This exploratory study shows an increase in knee kinematics in the swing phase after functional electrical stimulation of the hamstrings in stroke survivors walking with a stiff knee gait.

The largest improvement in peak knee flexion in the swing phase is seen when participants walked with the hamstring stimulation. Participants with low neurological impairment responded better to hamstring stimulation and there are indications that the effect of hamstring stimulation can be predicted during a single session.

The effect of functional electrical stimulation is comparable to that of more invasive treatment options, such as botulinum toxin (BTX) or soft-tissue surgery. Functional electrical stimulation is therefore a feasible treatment option for daily clinical practice.

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The authors have no conflicts of interest to declare.

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