SWEAT² study : effectiveness of trunk training on muscle activity after stroke: a randomized controlled trial

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SWEAT² study:
Effectiveness of trunk training on muscle activity after stroke - A Randomized Controlled Trial

Running title: Effectiveness of trunk training on muscle activity after stroke

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Abstract

Background: Trunk training after stroke is an effective method for improving trunk control, standing balance and mobility. The SWEAT² study attempts to discover the underlying mechanisms leading to the observed mobility carry-over effects after trunk training.

Aim: A secondary analysis investigating the effect of trunk training on muscle activation patterns, muscle synergies and motor unit recruitment of trunk and lower limbs muscles, aimed to provide new insights in gait recovery after stroke.

Design: Randomized controlled trial

Setting: Monocentric study performed in the rehabilitation hospital RevArte (Antwerp, Belgium)

Population: Forty-five adults diagnosed with first stroke within five months, of which 39 completed treatment and were included in the analysis.

Methods: Participants received 16 hours of additional trunk training (n=19) or cognitive training (n=20) over the course of four weeks (1 hour, 4 times a week). They were assessed by an instrumented gait analysis with electromyography of trunk and lower limb muscles. Outcome measures were linear integrated normalised envelopes of the electromyography signal, the amount and composition of muscle synergies calculated by nonnegative matrix factorization and motor unit recruitment calculated, by mean centre wavelet frequencies. Multivariate analysis with post-hoc analysis and statistical parametric mapping of the continuous curves were performed

Results No significant differences were found in muscle activation patterns and the amount of muscle synergies. In 42% of the subjects, trunk training resulted in an additional muscle synergy activating trunk muscles in isolation, as compared to 5% in the control group. Motor unit recruitment of the of trunk musculature showed decreased fast-twitch motor recruitment in the erector spinae muscle after trunk training: for the hemiplegic ($t(37)=2.44, p=0.021$) and non-hemiplegic erector spinae muscle ($t(37)=2.36, p=0.024$).

Conclusions: Trunk training improves selective control and endurance of trunk musculature after sub-acute stroke.

Clinical Trial Registration: Clinical Trial Registration-URL: http://www.clinicaltrials.gov. Unique identifier: NCT02708888

Clinical rehabilitation impact:

- Trunk training does not alter muscle activation patterns or the amount of muscle synergies over time.
- A decrease in fast-twitch motor recruitment in the erector spinae muscle was found during walking after trunk training
- Trunk training seems to increase the fatigue-resistance of the back muscles and enables more isolated activation.

Keywords: *Stroke, Trunk, Gait, Biomechanical Phenomena,, Core stability, Rehabilitation, Electromyography*

Introduction

Trunk training after stroke is not only an effective method for improving clinically assessed trunk control, standing balance and mobility (1), it also results in relevant kinematic changes in trunk motion during ambulation (2). The Stroke Recovery and Rehabilitation Roundtable of 2017 and 2019 recommends that biomechanical analysis is the best tool to measure motor recovery (3, 4), stating that trials should include both clinical and kinematic measures to assess the effectiveness of interventions. The SWEAT² trial (Stroke Walking Explained After Trunk Training) is the first study considering a more biomechanical approach by investigating the effectiveness of trunk training on lower limb and trunk kinematics (5). Results of this randomized controlled trial concluded that participants receiving trunk training walked with less thoracic flexion and anteroposterior displacements; increased rotational amplitudes and dissociation while also improving pelvic control in the frontal plane. In addition, no significant differences in lower limb kinematics were observed as compared to a control group. However, to date it still unknown which underlying mechanisms are responsible for balance and mobility recovery after trunk rehabilitation. Generating a better understanding concerning the current knowledge on recovery mechanisms and the driving forces behind these carry-over effects after trunk exercises aids in the optimization of current treatment plans for stroke survivors. To assess motor recovery after stroke, kinematic analysis is in inadequate to distinguish true recovery from compensation. When talking about true motor recovery, it is believed that other brain regions take over the control of muscles to produce the same motor patterns (6, 7). In contrast, motor compensations will result in new motor patterns, executed by different muscles, to accomplish the same goal (6, 7). So, understanding if the observed improvements are due to true recovery or a result of compensation, muscular activation should be assessed.

In people with stroke, decreased muscle strength, reduced activity levels, delayed onset times and diminished synchronization of trunk musculature have been reported (8-10). Recovery of truncal performance after trunk rehabilitation could therefore be the result of muscular improvements. Previous research has shown that trunk training is effective in restoring muscle symmetry and increasing the cross-sectional muscle area (11). However, muscular performance can be assessed in various manners which provides different information.

Therefore, to fully understand the recovery process behind trunk rehabilitation it was imperative to perform a secondary analysis on the same dataset (SWEAT² study) with regard to various muscle activity variables (5). This allows us to better comprehend the link between improved kinematic behaviour and muscular activity after trunk exercises. We chose to include three important outcome measures of muscle activity assessed by electromyography (EMG); temporal patterning, motor unit (MU) recruitment and muscle coordination.

First, muscle activation patterns (MAPs) of several individual muscles of the back and lower limb were chosen to assess temporal pattering by observing bursts of activity. These MAPs informs us about the timing and amplitude of each individual muscle, i.e. when and how much activity. Muscle activity after stroke is characterized by atypical on/off times and exhibits a great deal of inter-individual variability (12). Some common deviations are early activity of plantar flexors during terminal swing, prolonged activity of hamstrings and quadriceps during stance and absent dorsal flexor activity during swing (13-15). Normalisation of on/off times after trunk exercises might explain the possible improvements in mobility. However, MAPs are no measure for force production. As hemiplegia more than often results in muscle weakness and fatigue, it is beneficial to also assess the effect of trunk exercises on dynamic muscle force. Second, there are two ways to control muscle force; altering the number (spatial recruitment) or firing frequency (temporal recruitment) of active MU (16). Inaccurate activation of muscle fibres in a certain MU can result in changes in force generation (17), therefore, the second outcome measure was MU recruitment. The size principle of motor recruitment states that slow MUs are activated during low-force contractions and can sustain prolonged contractions, in contrast to fast MUs which are activated during high-force contractions for only a limited amount of time (18). High and low frequency bands of the EMG signal can distinguish between fast and slow MU recruitment (18), as slow MUs have low excitation thresholds they recruited before faster MUs. Third, the above mentioned outcomes assess muscle activity on individual level while movement is generated by a set of muscles which are activated simultaneously. Therefore, the last outcome measure consisted of muscle coordination, which is defined as a muscle synergy. Muscle synergies are a group of muscles contracting together as part of a functional unit (19). This group of muscles contribute to a particular movement suggesting that an individual muscle can be part of various muscle synergies and one synergy can be related to multiple muscles. Stoke survivors tend to have less synergies than healthy adults, as a result of merging of synergies (20). A change in coordination between muscles could be the cause of inefficient motor behaviour and might explain improvements after trunk training.

Aims and hypotheses

The aim of this secondary analysis of the original SWEAT² trial is to better comprehend if and how muscular activity is responsible for improved kinematic behaviour after trunk exercises in people with stroke. Examining various subtypes of muscular activations, on both individual and group level while also investigating force production (i.e. MAPs, MU recruitment and muscle synergies), might deepen our understanding in motor recovery after trunk training. We hypothesized that foremost muscular changes will be present in trunk muscles as these muscles are primarily targeted after trunk training. As improved trunk rotation and extension was observed in the original SWEAT² study, we hypothesize that the ability to use these trunk muscles in isolation will improve and help the subject to dissociate their trunk or maintain a more upright position. At last, the biomechanical improvements from the original SWEAT² study suggest a transition to a more efficient pattern, therefore we hypothesize to find a change from high to low MU activations implying that muscle work demands decrease.

Materials and Methods

Study design

The present study performs a secondary analysis on the outcomes of the original SWEAT² trial, a four week, assessor-blinded randomised controlled design. The original trial was registered (ID: NCT02708888), obtained approval from the local ethics committee and performed following the CONSORT guidelines (21). In addition to the extended version of the protocol which is available online (22), further details of the protocol and results of the primary outcome measures can be found in the original SWEAT² study (2).

Participants

Forty-five adults diagnosed with a haemorrhagic or ischaemic stroke within five months, with a confirmed unilateral localization of the stroke verified by medical imaging and without a history of previous stroke were included. Participants were excluded when they met the following criteria: 1) a score of 20 or higher on the Trunk Impairment Scale (TIS); 2) a score lower than 2 on the Functional Ambulation Categories; 3) unable to sit independently with foot contact on a stable surface for 30 seconds; 4) a neurological or orthopedic disorder, except for stroke, which could affect motor performance or balance; 5) a communication disorder which limits the understanding of verbal instructions; and 6) participants over the age of 85 years; 7) contraindications to physical activity (eg, heart failure) were present or excessive physical activity was deemed unsafe by the physician. Subjects who agreed to participate were only randomly allocated via concealed envelopes after signing an informed consent form.

Interventions

Both groups received daily multidisciplinary standard inpatient care (five times a week) which consisted of one hour physical therapy and one hour occupational therapy. In addition to standard care, subjects received either trunk training or cognitive training for one hour a day, four days a week continuing for four weeks (total of 16 hours). The control group performed seated cognitive exercises, while the experimental group focused on increasing trunk control. The control group performed cognitive exercises to ensure a useful task in which trunk activity could be excluded: The RevArte Visual Search Test and the Visuospatial Neglect Test Battery were performed (23, 24). The experimental group performed core-stability exercises to increase trunk control in a supine and seated position (eg, uni- and bilateral bridging, reaching, sit-ups, …), on both stable and unstable (e.g. table and physio ball) surfaces. A detailed overview of the intervention program can be found in the extended version of the protocol (22).

Data collection and EMG analysis

Subjects walked barefoot without aids or orthoses over a 12-m walkway at their self-selected. Data collection consisted of an instrumented gait analysis performed by 3D motion capture system (©Vicon Motion Systems Ltd., Oxford, UK) – by means of a Plug-in Gait full body model (22). In addition, a 16-channel telemetric wireless and synchronised Aurion Zerowire EMG system (©Cometa, Barregio, Italy) measured muscle activity. Disposable gel electrodes (KendallTM, 30 mm× 24 mm) were applied following the Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles (SENIAM) guidelines on the m. rectus femoris, m. vastus lateralis, m. semitendinosus (medial hamstrings), m. biceps femoris (lateral hamstrings), m. tibialis anterior, and m. gastrocnemius on the paretic side and m. erector spinae on both sides (25).

Data analysis (EMG)

Data was analysed in the VICON Nexus 1.8.5 software and custom made MATLAB® (R2015a for Windows) models to calculate the variables of interest. A minimum of 6 walking trials were recorded of which three trials were further analysed with each at least two fully visible left and right steps (entire trial consisted of 4 strides). This means the mean per trial, across three trials was further analysed for each outcome measure. Amplifier gain of the EMG signal was set at 1 Volt and sample frequency of the raw EMG signal was set at 1000 Hz. Afterwards, the myoelectric signals were band-pass filtered (2nd order zero-phase Butterworth filter: 10–300 Hz), rectified, smoothed using a 50 msec moving average window to generate a linear envelope, and normalized to 1000 points per stride. Graphs were plotted to visualize the EMG, a y-value of one represents the mean muscle activity calculated over the entire gait cycle. This method has also been reported by Schmitz et al (2009) (26). The parameter percentage of stance was used to distinguish stance and swing phase since great variations are present between the different participants. Normalisation to 100% of the stance and swing phase was performed by the Biomechanics Toolbar Version 1.02 (© Jos Vanrenterghem).

Wavelet analysis was performed on the filtered EMG signals to determine the frequency bands of the myoelectric signals. The mean wavelet centre frequency of each of the aforementioned muscles was used as outcome measure. The theoretical framework of wavelet analysis can be found in the works of Raez et al (2006) (27).

At last, muscle synergies and weighting coefficients were calculated by means of nonnegative matrix factorization (NNMF) which has been thoroughly described in previous studies (28). The NNMF algorithm was run five times, with an input of one to five synergies, extracting the best synergy with respect to the reconstruction error. The selection of the synergy was based on the total variance accounted for (VAF), a VAF over 90% determined the minimum of synergies for each individual.

Outcome measures

The secondary analysis of the original SWEAT² trial reports MAPs assessed with continuous curves of the linear integrated normalised envelopes of the EMG signal to examine temporal patterning (on/off times) of each muscle (29). In addition, MU recruitment was investigated by calculating the mean centre wavelet frequency across the gait cycle, which enables to distinguish slow, low-force MU contractions from fast, high-force contractions. At last, the amount of muscle synergies and their accompanying weighting coefficients per muscle synergy and the VAF for one synergy was calculated to assess muscle coordination.

Statistical analysis

Normal distribution was analysed by the Kolmogorov Smirnoff Test and differences between participant's characteristics were calculated by the independent samples t-test/chi-squared test using SPSS® 24 (©IBM Corporations, New York, USA). Sample size was based on the power reported in the original SWEAT² trial as we intended to explain kinematic improvements, power was set at 0.80 for the primary outcome measure (Tinetti POMA). Post power calculations for the current study showed a lack of power (0.75) in EMG outcomes, a sample size of 28 participants per group was necessary to report sufficient power.

First, to investigate the effectiveness of trunk rehabilitation on all muscles, multivariate statistical techniques were used. This technique has been suggested to deal with multiple dependent variables in biomechanical analysis as a statistical correction (30). Within-group differences were examined using a univariate ANOVA with "group" as fixed factor. Dependent, discrete variables which were significantly different according to the univariate ANOVA were further explored in a multivariate general linear model test. If the overall differences between groups were deemed significant ($p<0.05$), post hoc comparisons, paired and independent samples t-test were performed. The size of the difference between groups was reported based on eta squared calculations to investigate linear association between variables, as described by Knudson et al. (30). In addition, to investigate the effectiveness on the continuous joint angular time profiles a paired samples t-test by means one-dimensional Statistical Parametric Mapping was performed (31). Level of significance was set at 0.05.

Results

The flow chart of the subject inclusion can be seen in Figure 1. In total, 39 participants completed the full treatment. No significant differences were found at baseline (Table 1).

Insert Figure 1 - Table 1

Muscle activation patterns

Analysis of the MAPs did not reveal any significant differences within groups (Figures 2 and 3).

MU recruitment

Univariate analysis withheld the mean changes of the mean centre wavelet frequency of the hemiplegic and non-hemiplegic erector spinae muscle, as depicted in Table 2. The overall multivariate analysis for the selected dependent variables was significant (F(2,30)=8.43, p=0.001).

Post hoc comparisons within groups resulted in significant changes for the experimental group for the centre wavelet frequency of the hemiplegic erector spinae muscle (t(18)=5.27,p<0.001), non-hemiplegic erector spinae muscle (t(18)=4.78,p<0.001), medial hamstrings (t(18)=2.23,p=0.040) and tibialis anterior muscle (t(18)=2.12,p=0.049). For the control group significant changes were only found for the vastus lateralis muscle (t(19)=2.38,p=0.028).

Post hoc comparison between groups resulted in significant changes for the wavelet centre frequency of the hemiplegic (t(37)=2.44,p=0.021) and non-hemiplegic erector spinae muscle (t(37)=2.36,p=0.024) in favour of the experimental group.

Insert Table 2 - Figure 2 - Figure 3

Muscle synergies

The number of muscle synergies varied between two-three synergies before intervention and two-four synergies after. The latter was only achieved in the control group. However, no significant differences were found within and between groups for the amount of synergies and the VAF for one synergy. Six distinctive muscle synergies were found before treatment and seven after treatment in the entire population (Figure 4). Since the maximum of muscle synergies found was four, a varied combination of these synergies was seen in individuals. The following synergies were found pre and post intervention in the entire population: S1) co-activation of quadriceps and hamstrings; S2) quadriceps and plantar flexors; S3) dorsal flexors and back muscles; S4) hamstrings and dorsal flexors; S5) hamstrings and plantar flexors; and S6) dorsal flexors. Most subjects had a combination of synergies 1 and 3, the presence of an additional synergy varied mostly between synergies 2, 4 and 6. In nine participants, of which eight received trunk training, an additional synergy 7 was seen post-treatment which consisted of sole activation of the erector spinae muscles (Figure 5). Significant differences over time were found in S2: decreased activity of gastrocnemius; S5: increased activity medial hamstring and decreased activity of gastrocnemius; S6: increased activity of gastrocnemius.

Insert Figure 4

Insert Figure 5

Discussion

By investigating the effects of trunk training on MAPs, MU recruitment and muscle synergies, we aim to provide new insights in gait recovery after stroke. Therefore, examining muscle activity-related changes after trunk training might help us in shedding some light on the underlying mechanisms resulting in mobility carry-over effects observed in the original SWEAT² study. We hypothesized that foremost muscular changes were present in trunk muscles to maintain a more upright position or generate sufficient dissociation. The results of the current study showed no significant differences after trunk training for MAPs and amount of muscle synergies, while observing important changes in synergy loadings and MU recruitment for the erector spinae muscle. No significant differences were observed in lower limb muscles after trunk training. However, some limitations must be acknowledged. First, although improvements in abdominal musculature were also reported after trunk training (11), these muscles were not included which could be seen as a limitation of this study. Yet, it was decided to exclude abdominal muscle output since subcutaneous fat increases the distance between muscle fibre and electrode which lowers the EMG signal. Subcutaneous fat distribution is often localized at the abdomen, making measurement less reliable as our population had a mean body mass index of 25 which classifies them as overweight. Second, only superficial musculature was assessed by means of surface EMG as compared to deep trunk stabilizers. It might be that increased truncal control during ambulation is generated by these deep stabilizers rather than the superficial muscles which might shed a new light on our findings. At last, sample size was based on the original SWEAT² study has we aimed to explore kinematic mechanisms of clinical improvements. Therefore, power was based on the primary clinical outcome measure (Tinetti POMA). For interpretation purposes a power analysis was performed on EMG outcome measures (reported in the current paper), which showed a lack of power (0.74) and could explain why significant improvements in the ES in the experimental group were found before statistical correction, but not after. The sample size was therefore too small for current biomechanical outcome measures, to fully substantiate findings of the current paper a larger sample size is necessary. However, this study does add to the current knowledge concerning underlying biomechanical mechanisms to clinical improvements after trunk training post-stroke.

Muscle activation patterns

MAPs of the current study were comparable to those reported in literature (13-15). In addition, the results of this study suggest that the muscle activation patterns (on/off times) of the back and lower limb muscles did not alter after one month of rehabilitation in sub-acute stroke survivors. However ambulation did improve in the original SWEAT² study (2). These results support the hypothesis that stroke survivors with unaltered MAPs are still able to improve their gait (15, 32). This suggests that normalisation of muscle patterns are no prerequisite for the recovery of gait after stroke and generated compensatory muscle patterns might be important for regaining functionality and independence.

MU recruitment

After a stroke a shift towards a greater usage of fast-twitch motor fibres in hemiparetic muscles is observed, which is mostly due to muscle immobilization (33). This would result in a more fatiguing activation of these muscles than a similar activation in healthy muscles. Changes in muscle fibre phenotype have been found to be a strong predictor for gait deficits (33, 34). Although it is difficult to determine cut off scores for high –and low band frequencies due to the non-stationarity of surface EMG, frequency bands can be categorized as low <30 Hz, middle 40-120 Hz and high <135 Hz (35). Since the erector spinae is a postural muscle (36), the amount of slow-twitch fibres are larger as compared to lower limbs muscles which should be able to activate fast-twitch muscles when asked, e.g. during sprinting. The most power is generated in the gastrocnemius muscle during push off, it is consistent that this muscle has a higher frequency band. Most muscles fall into the mid-frequency band, which means that activation cannot clearly be subdivided as fast-twitch or slow-twitch muscle fibre activation. Within this mid-frequency band, muscles tended to use more fast-twitch than slow-twitch fibres. Previous literature suggests that aerobic exercise can induce changes in muscle fibre phenotypes, shifting from fast to slow twitch fibres (33). This shift was also observed in our study sample, with only between-group differences for the erector spinae muscle. As trunk training specifically targeted this muscle group during exercise, it is no surprise that the greatest changes were seen in this muscle group. The muscle fibre shift seen in the experimental group can be related to changes observed in gait and trunk performance from the original SWEAT² trial. High-twitch fibres are activated during high-force contractions which can only be executed for a limited amount of time. This would result in increased muscle fatigue, which relates to increased mediolateral and anteroposterior centrum of mass displacements, greater vertical acceleration variability of the centre of mass and a broader base of support (37, 38). Therefore, creating a larger proportion of slow-twitch fibres after trunk training tends to generate fatigue-resistance in these muscles.

Muscle synergies

The amount of muscle synergies in participants ranged between two and four, which is similar to previous findings (20, 39). Muscle synergies are task-dependent and can change as a result of the amount of muscles included (39, 40). Although the task was similar to reported muscles synergies, trunk muscles were not yet included in previous studies. As a result we found slightly different types of synergies. Due to the great amount of variability in muscle activity, six different synergies could be described in the entire study sample, although individual subjects only showed two to four synergies. Although no significant changes in the amount of muscle synergies after trunk training was seen, synergy loadings were altered. A seventh synergy was found solely describing the activation in the erector spinae muscles. This trunk synergy was found in nine subjects of which eight were allocated to the experimental group (42%) and could assume increased dependence on trunk musculature. The non-significant changes observed in the amount of synergies can be related to the unchanged temporal patterning of the muscles and has also been reported after treatment in children with cerebral palsy (41). However, they did find significant changes in VAF of one synergy. The weightings of the muscles in each synergy had a tendency towards normalisation over time. First, decreased co-activation of the gastrocnemius muscle and quadriceps muscles was seen in S2 which suggests a diminished extensor synergy of the lower limbs. Second, a lower weight coefficient of the gastrocnemius and a higher one of the medial hamstrings seen in S5 combined with the increasing weight of the gastrocnemius in S6 suggests normalisation in plantar flexor activity during body propulsion. Similar changes in synergy composition were also found after gait training and have been related to changes in step length and walking speed (39, 42), which did improve in this study population reported in the original SWEAT² study.

Clinical implications

The SWEAT² trial is the first to report and explain significant and meaningful between-group differences in several spatiotemporal, kinematic and muscular parameters after trunk training as compared to a control group. Although patients were already able to walk at inclusion, mobility improvements after trunk exercise can still be achieved. It has to be stressed that the *ability to walk* is not at all equal to the *ability of walking properly and efficiently*. Lower limb recovery is crucial for regaining the ability to walk, yet optimisation of the walking pattern is not solely achieved by lower limb recovery, as observed in the SWEAT² study. The trunk plays a crucial role in the promotion of stability during walking. An increased upright position (sagittal plane kinematics) during walking was seen next to a decrease in the proportion of fast-twitch motor units of the trunk extensors (i.e. enhanced fatigue-resistance and endurance in trunk muscles). As the strongest relationship between spatial mobility improvements and sagittal trunk kinematics was found in the original SWEAT² study, it could be suggested that bilateral trunk activity is of greater importance than unilateral activity.

Conclusions

Although, trunk training was unable to normalise MAPs and the amount of muscle synergies, the compositions of these synergies were altered over time. In addition, MU recruitment of the erector spinae muscle improved after trunk training by observing a decrease in fast-twitch motor recruitment. These findings suggest that trunk training resulted in increased endurance of trunk muscles.

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Figure legends

Figure 1. Flow chart of subject inclusion

Figure 2. Muscle activation patterns before (dark grey) and after (light grey) trunk training

Figure 3. Muscle activation patterns before (dark grey) and after (light grey) cognitive training

Figure 4. Comparison of mean muscle weight coefficients pre –and post treatment per synergy for control (n=20, solid) and experimental group (n=19, dashed)

Figure 5. The 7th trunk muscle synergy (n=9)

Tables

Table 1. Participant characteristics

Table 2. Comparison of discrete parameters for experimental and control group

	Control (n=20)	Experimental (n=19)	Mean difference	p-value	95% CI of diff	
					Lower	Upper
Descriptive subject characteristics						
Sex (m/f)	7/13	8/11		0.91		
Age (years)	63.6 ± 14.4	61.4 ± 10.3	1.93	0.59	-5.42	9.27
Weight (kg)	68.82 ± 10.80	73.27 ± 14.60	4.45	0.25	-12.14	3.24
Length (mm)	1698.91 ± 74.78	1694 ± 73.78	4.59	0.84	-40.08	49.28
Leg length (mm)	876.96 ± 51.21	882.45 ± 43.26	5.49	0.70	-34.06	23.06
Paralysis side (left/right)	13/7	14/5		0.40		
Type (ischaemic/haemorrhagic)	13/7	16/3		0.18		
Lesion location (infra/supra)	4/16	2/17		0.41		
Time post-stroke (days)	59.9 ± 36.0	52.5 ±29.0	8.29	0.38	-10.63	27.14
Baseline subject comparability						
FAC (/5)	2.80 ± 1.05	2.58 ± 0.77	0.22	0.46	-0.38	0.82
TIS (/23)	14.20 ± 3.02	13.16 ± 3.11	0.99	0.59	-0.98	3.06
POMA Tinetti (/28)	16.85 ± 7.65	16.32 ± 6.00	0.53	0.81	-3.94	5.01
Barthel Index (/100)	67.50 ± 25.52	59.21 ± 26.42	8.29	0.71	-8.56	25.14
Walking speed (m/s)	0.52 ± 0.37	0.38 ± 0.24	0.14	0.18	-0.07	0.34

Table 1. Participant characteristics

Independent sample t-test, Chi-Square test: * $p \leq 0.05$

m: male, f: female, kg: kilograms, mm: millimetre, infra: infratentorial, supra: supratentorial, FAC: Functional Ambulation Categories, TIS: Trunk Impairment Scale, m: metre, s: seconds, diff: difference

Outcome measure	**Control:** ***mean [95% CI];*** **(n=20)**			**Experimental:** ***mean [95% CI];*** **(n=19)**			**Between-group differences** [a] *p-value* *[95% CI of the difference]*	**Effect size Between-group differences** *Eta squared*
	Pre-test	**Post-test**	**Within-group differences** [b]	**Pre-test**	**Post-test**	**Within-group differences** [b]		
Mean centre wavelet frequency (Hz)								
M. Erector Spinae (hemiplegic side)	92.10 [84.44,99.77]	87.70 [78.82,96.57]	-4.41 [-14.19,5.38]	95.91 [88.24,103.57]	77.35 [68.48,86.23]	-18.56 [-26.02,-11.09]***	**0.021*** [2.32,25.98]	0.157
M. Erector Spinae (non-hemiplegic side)	94.23 [84.62,103.85]	92.28 [83.33,101.22]	-1.96 [-12.05,8.14]	96.27 [86.39,106.15]	80.41 [71.22,89.59]	-15.86 [-22.87,-8..86]***	**0.024*** [1.93,25.89]	0.137
M. Vastus Lateralis	112.53 [97.11,127.95]	97.70 [80.38,115.02]	-14.83 [-27.90,-1.75]*	110.08 [94.11,127.95]	101.70 [80.38,115.02]	-8.38 [-21.35,4.59]	0.467 [-24.22,11.34]	0.015
M. Rectus Femoris	115.38 [98.47,132.29]	103.94 [89.00,118,88]	-11.44 [-31.04,8.16]	109.65 [92.30,127.00]	99.19 [83.86,114.52]	-10.46 [-26.69,5.78]	0.936 [-25.72,23.76]	0.000
Medial Hamstring	116.22 [102.24,130.20]	92.98 [75.36,110.59]	-23.24 [-48.90,2.42]	110.88 [96.53,125.24]	98.88 [80.78,116.98]	-12.01 [-23.37,-0.64]*	0.414 [-38.86,16.39]	0.019
Lateral Hamstring	117.77 [97.53,138.02]	102.86 [87.11,118.61]	-14.91 [-37.26,7.43]	111.67 [90.33,133.01]	99.75 [83.15,116.36]	11.92 [-25.57,1.73]	0.817 [-29.00,23.02]	0.002
M. Tibialis Anterior	117.12 [107.00,127.25]	107.97 [96.42,119.53]	-9.15 [-20.25,1.95]	114.66 [104.54,124.79]	106.95 [95.39,118.50]	-7.72 [-15.41,-0.03]*	0.824 [-14.44,11.57]	0.001
M. Gastrocnemius	134.20 [116.56,151.85]	126.07 [107.12,145.02]	-8.13 [-22.61,6.34]	137.54 [119.89,115.18]	125.90 [106.95,144.86]	-11.63 [-26.79,3.53]	0.728 [-16.73,23.73]	0.003
Muscle synergies								
N muscle synergies	2.50 [2.28, 2.73]	2.70 [2.43,2.97]	0.20 [-0.09,0.49]	2.32 [2.09,2.55]	2.42 [2.15,2.70]	0.11 [-0.21,0.70]	0.945 [-0.32,0.51]	0.006
VAF for 1 synergy	55.11 [44.51,65.72]	55.64 [44.82,66.47]	-0.53 [-12.41,13.47]	58.14 [47.53,68.74]	52.69 [41.86,63.52]	-5.44 [-14.30,3.41]	0.275 [-9.12,21.08]	0.019
2 synergies (n)	10	8	-2	13	11	-2		
3 synergies (n)	10	10	0	6	8	2		
4 synergies (n)	0	2	2	0	0	0		

Table 2. Comparison of discrete parameters for experimental and control group

Parameters that differ significantly between groups after multivariate analysis are in bold

a: post hoc analysis independent samples t-test: differences between mean changes (pre/post) of experimental and control group, after Holm's correction no significant p-values remained (p=0.168)

b: post hoc analysis paired samples t-test: differences between pre/post/follow-up within groups – *<0.05, **<0.01 ***<0.001, after Holm's correction only ES significance in experimental group remained (p<0.000)

n: amount of subjects, SD: standard deviation, Hz: Hertz, CI: confidence interval