The effect of repetitive arm cycling on post stroke spasticity and motor control

Repetitive arm cycling and spasticity

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Abstract

This study’s aims were (1) to test whether training on an arm ergometer improves motor performance, and (2) to develop a technique to quantify individual muscle spasticity. Nine patients with a stabilized hemisyndrome (in average 22 months after ischemic stroke in the territory of middle cerebral artery) underwent a 3-week training on an arm ergometer, 5 days/week. The patients were tested one week before training, at training onset, at the end of training and 2 weeks after training. Spasticity was quantified by (1) the Ashworth Scale of the elbow flexors and extensors, (2) the maximum active extension of the biceps, and (3) the minimum torque on the lesioned side during arm cycling. The data were standardized, pooled and a 2-way ANOVA revealed a decrease of the spasticity by the training (p=0.076). Similarly muscle force was evaluated by the Rivermead Motorik Assessment, the Motricity Index and the cycling force, and the range of active movement as the sum of the angles at a maximum shoulder flexion, shoulder abduction, elbow flexion and elbow extension. The training increased the force (p<0.01) and also the range of motion (p<0.05) significantly. The patients confirmed the clinical relevance of the results. The spasticity index – the relation between the muscle activity modulation on the normal and lesioned side – was shown to be a useful tool in quantifying individual muscle spasticity. It was concluded that cycling on an arm ergometer is a useful tool for rehabilitation.

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1. Introduction

Patients recovering from a stroke usually receive physiotherapy with the aim to improve the outcome of functional rehabilitation. Often conventional physiotherapeutic exercise programs are applied for which neurophysiological background is not well understood due to missing basic research in this field. In some programs, the difference between the functional outcomes cannot be detected [1–3]. Recently, an approach based on simple repetitive movements – which form the basis of motor learning – has been shown to accelerate the recovery of hand function after a stroke [4]. An observer-blinded randomized study [5] and a placebo-controlled study [6] showed benefit of intensive constrained-induced therapy in chronic stroke patients, confirming the use to train repetitively the paralytic arm even in chronic patients.

However, the training of complex movements did not further enhance recovery compared to functionally based physiotherapy [7]. The present investigation was based on the approach of Bütefisch et al. [4] and was realized by arm cycling.

The main purpose of rehabilitation is to improve motor function and the use of the affected limb in daily life.
Recovery itself can be attributed to several factors. One important aspect is to reduce spasticity, which often occurs in anti-gravity muscles some months after a stroke. The antispastic effect of exercises on a motorized ergometer, which moves the legs similarly as during cycling, was documented by the F-wave, reflecting changes of motor neuron excitability [8]. Clinical follow-up by the Ashworth Scale assessment confirmed these results [9]. The assessment of spasticity is, however, controversial [10]. Even if spasticity is tested using its definition, i.e. a velocity-dependent response to passive stretching, results, have been ambiguous with significant differences obtained in a supine and sitting position [10]. In the present context, the main purpose was to evaluate whether a rehabilitation program can lessen the degree of spasticity. We therefore studied whether training significantly changes the values of parameters which are related to spasticity. Correspondingly, we accounted for several factors, the Ashworth scale, the range of active movements, the breaking force of the biceps during cycling and a relational value based on the surface EMG. All these factors are somehow related to spasticity.

The aims of our investigation were (1) to quantify spasticity, muscle force and the range of active movements of stroke patients trained on an arm ergometer, (2) to test whether such training decreases spasticity and increases force and the range of movement significantly, and, furthermore, (3) to develop a technique to quantify the spasticity of individual muscles. A preliminary account of some of the results has already been presented [11].

2. Methods

2.1. Patients

One female and 8 male patients with a mean age of 66.3 years (range from 52 to 84) participated in this study, each having given written informed consent. All patients had a stable hemiparesis due, as revealed by computerized tomography, to a first and unique ischemic lesion that occurred in the 22 months before inclusion (range from 16 to 49). Inclusion criteria were (1) to be able to participate for at least 30 min of exercise using a hand ergometer and to be able even with the paretic arm to reach the arm-pedal without pain (2) to have no problems of comprehension, and (3) to be able to give their informed consent. Patients with aphasia, shoulder pain or serious neuropsychological deficits were excluded. The research received prior approval from the appropriate institutional ethics commission and review body.

2.2. Material and methods

Training was conducted on a commercial motorized arm ergometer (Motomed viva Reck), which allows optimization of the training by biofeedback. A second scientific ergometer, developed by the Fachhochschule für Technik und Architektur, Freiburg, was used for quantitative measurements during cycling. This allowed measuring the torque on both sides independently (only the sum of the left and right torque can be measured with the motorized ergometer). Two angle encoders (12 bit resolution) fixed to the axes of both levers measured the angle of the pedals. The two pedals could be disconnected so that they turn independently and are equipped with a mechanical breaking system (friction), which increased the cranking resistance. With the pedals interconnected, the intact side could help the affected side during pedaling.

The electromyogram (EMG) of the biceps and triceps muscles of both arms was recorded using surface electrodes. Care was taken to place the electrodes in the same positions during the various sessions in order to obtain comparable results. The EMGs were low-pass filtered at 1 kHz to avoid aliasing and then, as the signals from the ergometer, fed into the ADC (3 kHz/channel) of a PC.

2.3. Experimental protocol

An A–B–A protocol with (1) a base line phase A of one week, (2) a training phase B of 3 weeks and (3) a follow-up phase A of 2 weeks was used.

The patients, who were positioned in front of the ergometer in their wheelchair or on an armless chair, performed the arm training at a constant, relatively low resistance for 30 min daily, 5 days a week. Each training session comprised 15 min of arm cycling in a forward direction and 15 min in a backward direction with a 5 min break in between. Patients were not assisted in any way during the exercise apart from being given verbal encouragement from the therapist.

Each patient was tested during 4 sessions: (1) at T0, the beginning of the base line phase A, (2) at T1, the beginning of phase B, (3) at T2, the end of phase B and (4) at T3, the end of the follow-up phase A. The tests included quantitative measurements on the scientific ergometer and a clinical assessment.

2.3.1. Recordings on the ergometer

All the subjects cycled in the same direction. The hand moving away from the body on the upper half-circle of the movement trajectory (extension phase), and toward the body on the lower half-circle (flexion phase). The pedal torque and the angular position were recorded independently on both sides, usually during 40 s of continuous pedaling. The surface EMG of the biceps and triceps muscles was recorded on both sides in some of the sessions.

2.3.2. Clinical assessment

The same physiotherapist performed the following tests on the patients.

Rivermead Motorik Assessment (RMA; [12,13]). Gross motor function, upper limb control, and lower limb and trunk control were evaluated as normally, but only data concerning the upper limb control are presented.
Ashworth Scale: Spasticity was clinically evaluated by the modified Ashworth Scale \[14\] of the flexors and extensors of elbow.

Motricity Index (MI, \[15,13\]). The force of the elbow and shoulder flexors and extensors was tested manually, with grading derived from the Medical Research Council grades ranging from 0 (no movement and no contraction can be palpated) to 5 (movements with normal power). The patients’ performance was evaluated by taking the sum of the quotation on the elbow flexors, elbow extensors, shoulder flexors and shoulder extensors.

Range of motion: The range of active movements of the elbow and shoulder of both sides was measured with a goniometer.

Maximum cycling force: The maximum force was evaluated at which the patient was able to cycle with the lesioned side during 10 s at a constant frequency.

2.4. Data analysis

Data acquisition, as well as processing, was performed using the LabView programming language (National Instruments), with data saved using the database Access (Microsoft), and statistical analysis performed using the statistical package SPSS (SPSS Inc.).

Cycling torque: The data obtained during a recording session was averaged across cycles. Since the cycle duration varied from cycle to cycle, the data was normalized by computing the torque as a function of the angle, obtained by eliminating time from the angle – time and torque – time relations. The minimum torque on the lesioned side was then measured for each trial on the averaged torque signal.

Cycling speed: This was computed by dividing the cycles performed during a trial by the duration of the trial.

EMG: The EMG activity was high-pass filtered (cut-off frequency 2 Hz), full-wave rectified and then low-pass filtered (cut-off frequency 5 Hz) in order to obtain the activation level. Similarly to the torque recordings, the cycles were normalized and the EMG activation level as a function of angle was averaged across the cycles. In order to obtain the EMG modulation, a time window during which the muscle was active and another window during which it was inactive were determined manually on a display of the EMG activation level. The curves were integrated between the windows and the relation between the two integrals was computed.

Spasticity and muscular force: Both forces were estimated applying the same technique. Spasticity was measured by (1) the Ashworth scale, (2) the maximum active extension of the biceps, and (3) the minimum torque on the lesioned side during arm cycling. The muscular force was measured by (1) the RMA, (2) the MI and (3) the cycling force. There were thus 3 data sets related to spasticity and another 3 related to muscular force. Within both groups of data, the Pearson correlation coefficients between the data sets were computed. In order to allow pooling of the 3 data sets, a z-transformation was performed. An analysis of variance (ANOVA) was then performed on the pooled data with the factors time of testing and patient.

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**Fig. 1.** Torque and position signals of a normal subject during 20 s of pedaling. From top to bottom: torque signal on the left side (calibration: 3 Nm), torque signal on the right side (calibration: 3 Nm) and position signal of the left pedal (calibration: 435°). The position signal is reset with the stretched left arm. The horizontal lines indicate level 0. Torque signals are nearly symmetrical in a normal subject.

**Fig. 2.** Torque, position and EMG recordings from a subject with a paretic right arm. A. From top to bottom: torque signal on the left side (calibration: 3 Nm), torque signal on the right side (calibration: 3 Nm) and position signal on the left side (calibration: 390°). The position signal is reset with the left stretched arm. The horizontal lines indicate level 0. B. From top to bottom: the EMG of the left biceps, the left triceps, the right biceps, the right triceps (calibration: 3.6 mV), and the position of the left pedal (calibration of EMGs: 3.6 mV and of position: 560°). The EMG signals on the right side are nearly not modulated during cycling.
Range of movement: In order to quantify the performance of a patient, the sum of the angles on the lesioned side was taken: (1) for shoulder flexion and abduction (up to 180°), (2) for elbow flexion (up to 140°) and (3) elbow extension (up to 0°). As above, an ANOVA was computed with the factors time of testing and patient.

3. Results

3.1. Spasticity

Although spasticity is defined as a velocity-dependent response to passive stretching, there was no significant relation between spasticity as evaluated in the present investigation and cycling speed (not documented), and which was therefore not considered in the further presentation of the results.

Besides the Ashworth scale and the maximum extension of the biceps, the minimum torque on the lesioned side during arm cycling was considered as a parameter related to spasticity. If a normal subject is cycling with relatively little force as the subject presented in Fig. 1A (and as per all the patients), the torque of either arm approximates zero when the arm is closest to the body and the signals on the right and left side are nearly identical except a phase shift of half a cycle. In a stroke patient, however, the torque signals are lower on the paralyzed than on the normal side (Fig. 2A). Since the patients are not able to relax the flexor muscles of the spastic arm during the extension phase, these contracted flexor muscles can even result in a negative torque on the spastic side. This is exemplified in Fig. 2 where the biceps of the subject was constantly active on the affected side and scarcely modulated during cycling. The minimum torque on the spastic side was thus assumed to be related to the degree of spasticity.

In order to quantify as accurately as possible the level of spasticity in the arm muscles, the following were considered as mentioned above: (1) the Ashworth scale, (2) the maximum active extension of the biceps, and (3) the minimum torque on the lesioned side during arm cycling. As expected, the 3 data sets correlated: The correlation between the Ashworth scale and the biceps extension was \( r = -0.634 \), between the Ashworth scale and the minimum torque \( r = -0.732 \), and between the biceps extension and the minimum torque \( r = 0.760 \). The data was

Fig. 3. Training effect of arm cycling. A: Average spasticity 3 weeks before (0) at the beginning (1) at the end (2) and 3 weeks after (3) the training with confidence limits (\( p = 0.05 \)). The differences are not significant. Due to the \( z \)-transformation, values are positive and negative and the grand mean is 0. B and C: Average arm force. The 4 bars with confidence limits in B represent the data at the testing dates as in A. The differences are highly significant (\( P < 0.001 \)). In C the same data as in B but broken down into the individual patients. Each block of columns represents the data of one patient obtained at the 4 testing dates as in B. Patients are ordered according to their force. All of them had an increased force after training. D: Training effect on the range of active movements. The maximum flexion and extension movements of elbow and shoulder were measured in degrees and the values were added, resulting in mean values around 300 (see text). The 4 bars with confidence limits represent the data at the testing dates as in A and B. The differences between the values before and after the training are significant (\( p < 0.001 \)).
transformed (z-transformation), pooled and an ANOVA was performed (Fig. 3A). Due to the data transformation, the average of all values was 0 and the ordinate dimensionless. Before the training (test times 0 and 1) spasticity was greater than after training (test times 2 and 3; \( p=0.076 \)).

3.2. Muscular force

Muscular force was estimated by the Rivermead Motorik Assessment (RMA), the Motricity Index (MI) and the cycling force. The correlation RMA–MI was \( r=0.939 \), the correlation RMA–cycling force \( r=0.945 \) and the correlation MI–cycling force \( r=0.91 \). All of them were significant (\( p<0.01 \)). As for the spasticity, the data was normalized, pooled and an ANOVA was performed. The differences between the patients and the recording times were highly significant (\( P<0.001 \)). The force of the patients remained constant during the base line and during the following-up period, but increased significantly over the period of training (Fig. 3B). The confidence limits are not overlapping, illustrating a significant training effect. The patients are sorted according to decreasing force in Fig. 3C providing details of the performance of the individual patients. All the patients gained force during the training and this increase in force persisted during the following 3 weeks.

3.3. Range of movement

The range of movement was evaluated as the sum of the angles at a maximum shoulder flexion, shoulder abduction, elbow flexion and elbow extension. All patients had approximately normal values on the non-lesioned side (not presented here). On the lesioned side, the variability between the patients was very large (\( p<0.001 \)) ranging from 20° to 500° with a mean range of 288°. However, there was a significant increase of 18° of the average range due to the training on the ergometer (\( p<0.005 \), Fig. 2D).

3.4. Quantification of muscle spasticity

The procedure is exemplified with the EMGs of the biceps and triceps muscle (Fig. 2B), which were recorded from a patient with the Ashworth scale 2, a maximum active extension of the biceps of −20° (0° corresponding to full extension) and a mean minimum torque during cycling of −.04 Nm. A time window during the active and inactive period were determined manually on a display of the average EMG curves of the biceps and triceps of the intact side (the two upper curves of Fig. 4). The relation of the mean EMG activity during the two windows was 6.1 for the biceps and 3.4 for the triceps, i.e. the biceps was 6.1 times more active during the flexion than during the extension phase, and the triceps was 3.4 times more active during the extension than during the flexion phase. On the contralateral side, the relation was 1.8 for the biceps and 0.70 for the triceps muscle (the two upper curves of Fig. 4). The spasticity index of a muscle was defined as the relation between the modulation of activity on the intact side divided by the modulation on the lesioned side. In the present example it was 4.2 for the biceps and 4.9 for the triceps. Further results confirmed that the spasticity index correlated well with qualitative estimators of spasticity.

4. Discussion

4.1. Patient performance

4.1.1. Spasticity

Many clinical tests to assess spasticity correlate unsatisfactorily, suggesting that they evaluate different aspects of spasticity [16]. One of the principal questions was in the present investigation how to quantify spasticity. The best solution seemed to use several parameters which were assumed to be related to spasticity. Their relation to spasticity was tested by their correlation. The following 3 parameters were used: the Ashworth scale, the range of active elbow extension, and the minimum torque during cycling. Their correlation indeed indicated that all of them are related to spasticity. In order to test whether training reduced spasticity, they were pooled. The results clearly show that the training was beneficial for the patients. These first quantitative results regarding the effect of repetitive training by an arm ergometer on spasticity were corroborated by Durner [9] who evaluated spasticity by the Ashworth Scale immediately after training on an arm-trainer. Furthermore, Rösche et al. [7] reported on the basis of F-wave recordings a significant decrease of spasticity after leg training with a motorized exercise-bicycle.

4.1.2. Force

Similar to spasticity, force can be evaluated in different ways. Different results can be expected since different tests might require co-activation of different muscles which the
motor system might be able to activate at different levels. Since all aspects of muscle force increase might be beneficial for an adequate motor control in daily life, 3 different parameters to evaluate force were considered. Two of these, the RMA and MI are qualitative and assessed by a physiotherapist and the third, the maximum cycling force is quantitative. After the training, all patients were able to cycle against a higher resistance and performed better in the clinical tests related to force.

More the arm is paretic less the functional Rivermead improved. Spasticity, however, improved independently of the degree of paresis.

Increased force due to training could be expected on the control side since the patients had not experienced any arm cycling before participating in the investigation. It was, however, not known whether training can result in increased force on the lesioned side. The observed increase could thus be due to training mechanisms as on the control side or/and other special mechanisms, such as plasticity. Independent of the mechanisms, it is clear that an increase in force is favorable not only for arm cycling but also for activities of daily life, which is finally the principal aim of rehabilitation. Our results implicate that not only cycling force but also the shoulder, elbow and hand function with and without manipulation of objects (reflected by the RMA) and elbow and shoulder function as quantified by the MI improved. The results are corroborated by Kamps [17] who showed that cyclic movement training of the lower limbs in stroke rehabilitation improved maximum walking distance and gait speed as well as balance.

4.2. Spasticity of individual muscles

Usually spasticity is measured by the Ashworth Scale which is based on the resistance to joint movements. Since several flexors and extensors act on most joints and thereby contribute to joint torque, the Ashworth Scale can not give detailed information about the spasticity of individual muscles. Furthermore it is a qualitative parameter. The values can depend on the rater. When raters receive standardized training on the use of the Ashworth Scale and are tested on the same patients, there is a significant statistical agreement among them [18]. It can, however, not be expected that raters are identically trained in different clinics. Larger differences in the Ashworth Scale can then be expected. In contrast to the Ashworth Scale, the spasticity index is computed on the basis of the EMG on a particular muscle is thus rater-independent. Since it is a relational value it is also independent of the absolute size of the EMG recordings.

Since the main purpose of the training on the arm ergometer was to improve motor performance in daily life, the quantification of the degree of spasticity of individual muscles was not warranted. In future studies it is, however, envisaged to paralyze the most spastic muscles by botulinum toxin which changes the cortico-motor representation [19], prolongs the effect of the injection or even enables the injected muscles to assist the cycling after regeneration of the motor end-plates.

There are then muscles acting on a joint which have been and which have not been injected with botulinum toxin. Using the Ashworth Scale, it is impossible to distinguish the performance of the two types of muscles. Using the spasticity index, each muscle can, however, be characterized individually and its changes due to the training can be quantified. In view of investigations of this type, it is crucial to have a tool to quantify the spasticity of individual muscles as the spasticity index.

We have thus defined the spasticity index which is based on the surface EMG. On the unaffected side with normal cyclic muscle activation, two time windows were defined on the mean muscle activation curves, the first during which the muscle was active and the second when the muscle was relaxed (Fig. 4). The relation between the mean activities during these two windows was taken as value for the modulation of muscle activity. The same calculations were performed with the EMGs on the lesioned contralateral side, but with the windows shifted by 180° in relation to the unaffected side. The spasticity index of a muscle was defined as the relation between the values from the two sides. In the example presented in Results, we obtained 4.2 for the biceps 4.2 and 4.9 for the triceps. The corresponding values in a normal subject would be close to 1. The spasticity index has the advantage that (1) it is not affected by amplitude variations of EMG recordings due to different electrode positions and other factors, (2) it can be evaluated in each muscle of interest, (3) it requires standard techniques and can be easily computed, (4) it can be computed for complex repetitive movements as arm cycling, and (5) it is not affected by partial paralysis. In such a patient, the activation levels of the affected muscles are reduced by the same factor and the spasticity index would be similar to that of the unaffected side, i.e. close to 1.

4.3. Conclusions

An ergometer is a suitable device for training stroke patients with unilateral paralysis. The intact side can help the affected side during pedaling. The performance of the affected limb can be investigated quantitatively if the torques acting on the right and left side are measured separately. The situation is easier when cycling is performed with the legs rather than with the arms. Subjects push the pedals downward with their legs and usually there are no pulling forces during the upward movements. In this situation, forces from the right and left leg can be separated since at one time only one leg is developing torque. The arms, however, pull and push during circular movements and these torques have to be measured independently in order to quantify the contribution of each arm.

Although the stroke of the patients participating at this investigation occurred on average nearly 2 years before the study and their condition remained stable, the training on the arm ergometer decreased their spasticity, increased their force and range of active movement. This finding was corroborated by other studies in which recovery over the course of several years was observed [20–22] and several test results improved in parallel [23,24]. Repetitive movements seem to be particularly effective in rehabilitation and motor learning.
The major mechanisms are attributed to synaptic plasticity and synaptic efficacy in existing neural circuits [26]. Alternative descending pathways, secondary and ipsilateral motor areas and other brain areas implicated in motor control might also contribute to motor recovery [27–32].

An important advantage of ergometer training over conventional physiotherapy is that patients who are motivated to continue training, can do so themselves, which is an alternative to hand-to-hand therapy, often limited by budget constraints. A new field, robot-assisted motor rehabilitation, has emerged for other repetitive movements, such as walking, which are more complex to achieve [33].

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References