EFFECTS OF INTENSIVE PHYSICAL REHABILITATION ON NEUROMUSCULAR ADAPTATIONS IN ADULTS WITH POSTSTROKE HEMIPARESIS

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ABSTRACT

Andersen, LL, Zeeman, P, Jørgensen, JR, Bech-Pedersen, DT, Sørensen, J, Kjaer, M, and Andersen, JL. Effects of intensive physical rehabilitation on neuromuscular adaptations in adults with poststroke hemiparesis. J Strength Cond Res 25(X):000–000, 2011–Hemiparesis—disability and muscle weakness of 1 side of the body—is a common consequence of stroke. High-intensity strength training may be beneficial to regain function, but strength coaches in the field of rehabilitation need evidence-based guidelines. The purpose of this study was to evaluate the effect of intensive physical rehabilitation on neuromuscular and functional adaptations in outpatients suffering from hemiparesis after stroke. A within-subject repeated-measures design with the paretic leg as the experimental leg and the nonparetic leg as the control leg was used. Eleven outpatients with hemiparesis after stroke participated in 12 weeks of intensive physical rehabilitation comprising unilateral high-intensity strength training with near-maximal loads (4–12 repetition maximum) and body weight supported treadmill training. At baseline and 12-week follow-up, the patients went through testing consisting of isokinetic muscle strength, neuromuscular activation measured with electromyography (EMG), electrically evoked muscle twitch contractile properties, and gait performance (10-m Walk Test and 6-min Walk Test). After the 12-week conditioning program, knee extensor and flexor strength increased during all contraction modes and velocities in the paretic leg. Significant increases were observed for agonist EMG amplitude at slow concentric and slow eccentric contraction. Twitch torque increased, whereas twitch time-to-peak tension remained unchanged. By contrast, no significant changes were observed in the nonparetic leg. Gait performance increased 52–68%. In conclusion, intensive physical rehabilitation after stroke leads to clinically relevant neuromuscular improvements, leading to increased voluntary strength during a wide range of contraction modes and velocities, and improved gait velocity. Strength training coaches working in the field of rehabilitation can use this knowledge to safely and efficiently add high-intensity strength training to existing rehabilitation paradigms.

KEY WORDS electromyography, stroke, physical therapy, isokinetic, twitch, resistance training

INTRODUCTION

Stroke is the most frequent type of acquired brain injury and remains a leading cause of death and disability worldwide (40). In the United States alone, 780,000 people experience a new or recurrent stroke annually (47). The majority of adults suffering from stroke now survive, leaving a challenge for the medical system to provide efficient rehabilitation (37,63). Neurological and functional recovery occurs gradually for up to 20 weeks after the lesion and thereafter plateaus (34). A half year after the lesion has occurred, half of all adults surviving from stroke still display disabilities in essential activities of daily living (33). In the long term, more than a third of all the survivors of stroke are left dependent on other people for performing the activities of daily living (61).

Hemiparesis is common after stroke, affecting half of the survivors chronically (47). Poststroke weakness can be marked with losses of muscle strength of >50% (3,12,51). Contrastingly, a certain minimal threshold of muscle strength is required to perform activities of daily living (15,52) and to prevent falls in the frail elderly (16). Importantly, voluntary muscle strength of the knee extensors has been shown to be closely related to gait ability in patients with stroke (13,58). Thus, loss of muscle strength after stroke is considered a major determinant of disability (11,17,41). Consequently, a cornerstone in rehabilitation should be to regain muscle control. Gait performance increased 52–68%. In conclusion, intensive physical rehabilitation after stroke leads to clinically relevant neuromuscular improvements, leading to increased voluntary strength during a wide range of contraction modes and velocities, and improved gait velocity. Strength training coaches working in the field of rehabilitation can use this knowledge to safely and efficiently add high-intensity strength training to existing rehabilitation paradigms.
strength (46). Although some studies found no convincing effect of strength training on functional outcome (27,36,39), the majority of studies have documented positive effects of 4–12 weeks of strength training weeks on poststroke weakness (9,14,21,24,45,50,55,58,59). However, there is limited knowledge of the underlying neural and muscular adaptation mechanisms of strength gains in response to strength training in adults suffering from stroke (46).

While neuromuscular activation can be estimated using surface electromyography (EMG) during maximal voluntary muscle contraction (1), intrinsic muscle contractile properties can be assessed by electrically evoked twitch contractions of the resting muscle (29). Weakness after stroke has been associated with decreased neuromuscular activation of agonist muscles of the paretic limb (20,26,28). In contrast, conflicting results exist with regard to muscular changes. Although muscular atrophy after long-term hemiparesis has been reported (35,49), a more recent study found no evidence for this (18). However, 1 study reported lower electrically stimulated twitch torque of the paretic leg compared with the contralateral leg (56), indicating decreased intrinsic contractile strength capacity. Thus, more research is warranted in this area.

Maximal voluntary muscle contraction strength is expressed by a combination of both neural and muscular factors and can be measured during various contraction modes and velocities using isokinetic dynamometry (60). In various clinical settings, isokinetic dynamometry combined with EMG has provided more useful functional information on muscle strength capacity compared with measurements of static muscle strength alone (7,19). In patients with stroke, isokinetic dynamometry has revealed deficits of muscle strength and neuromuscular activation that are more pronounced during fast concentric compared with static muscle contraction (19,38). Functionally, concentric and eccentric muscle strength is more important than static muscle strength, because most activities of daily living occur during situations of dynamic muscle work. Collectively, isokinetic dynamometry combined with EMG and percutaneous electrical muscle stimulation can be used to assess adaptations in neural, muscular, and functional parameters in response to physical training (6) and deconditioning (53).

The purpose of this study was to investigate the effect of intensive physical rehabilitation with strength training and body weight supported treadmill training (BWSTT) on neuromuscular adaptations in outpatients suffering from hemiparesis after stroke. We hypothesized that intensive physical rehabilitation would increase neuromuscular activation (EMG amplitude) and enhance muscle contractile properties (twitch torque) of the paretic limb compared with the nonparetic limb, leading to increased voluntary muscle strength during isokinetic and static contraction.

**METHODS**

**Experimental Approach to the Problem**

A within-subject repeated measures design with the paretic leg as the experimental leg and the nonparetic leg as the control leg was used. Outpatients with hemiparesis after stroke participated in 12 weeks of intensive physical rehabilitation comprising high-intensity strength training with near-maximal loads and BWSTT. Strength training was performed unilaterally with the paretic leg only (PAR). The contralateral nonparetic leg was used as a control leg that was tested but not resistance trained (CON). At baseline and 12-week follow-up, the patients went through testing consisting of isokinetic muscle strength, neuromuscular activation measured with EMG, electrically evoked muscle twitch contractile properties, and gait performance (10-m Walk Test and 6-min Walk Test).

**Subjects**

All the subjects had stroke in the chronic stage, that is, at least 6 months postinjury (Table 1). There was no upper limit for the postinjury duration. Three of the 11 subjects had a right hemisphere lesion. All brain lesions had been confirmed by means of computed tomography or magnetic resonance imaging. Inclusion criteria were chronicity (i.e., time since injury) of >6 months, a moderate to severe hemiparesis based on a clinical assessment by a physiotherapist on volitional function of the upper and lower limbs, an age of at least 16 years, moderate to severely impaired gait function defined as covering less than two-thirds to one-half of “normal” gait distance for healthy age-, weight-, height-, and sex-matched individuals (22) and that the subject was mentally prepared to participate in the intervention. The subjects were medically stable and generally independent with regard to most basic activities of daily living. Alcohol or substance abuse, psychiatric diseases, and any progressive diseases were the exclusion criteria.

Before the intervention, the amount of training per week with a physiotherapist varied considerably among subjects. However, 82% had received rehabilitation training between 2 and 7 h.wk⁻¹, and only 1 subject had not received rehabilitation at all. This study received approval from the local Ethics Committee (KF-01-240/04), and all the subjects provided written informed consent before participation.

**Procedures**

For clarity, this section is subdivided into a description of the 12-week training intervention and then the physiological measurements performed at baseline and follow-up.

**TABLE 1. Demographics (mean ± SE).**

<table>
<thead>
<tr>
<th>Age (y)</th>
<th>Height (m)</th>
<th>Weight (kg)</th>
<th>Time since injury (y)</th>
<th>Gender (men/women)</th>
<th>Side of lesion (right/left)</th>
</tr>
</thead>
<tbody>
<tr>
<td>51 ± 3.9</td>
<td>1.78 ± 0.02</td>
<td>85 ± 2.7</td>
<td>0.97 ± 0.17</td>
<td>9/2</td>
<td>3/8</td>
</tr>
</tbody>
</table>

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Intervention
The physical training intervention took place at the gait rehabilitation facility of the Center for Rehabilitation of Brain Injury in Copenhagen, Denmark. The facility had been especially equipped for the project that comprised 12 weeks of training, 5 times 1.5 h wk⁻¹. The intervention comprised 4 key elements: (a) high-intensity strength training; (b) BWSTT; (c) aerobic exercise; and (d) functional training. The chief objective was to improve walking speed, ambulatory safety, and maximum walking distance and to enhance the maximal muscle strength. High-intensity strength training was performed 3 d wk⁻¹, and aerobic exercise and functional training were performed 2 times a week. Each training session always began with BWSTT. All the training was performed at the highest possible level of voluntary intensity.

The strength training program consisted of the exercises: semiseated leg press, hamstring curl, knee extension, and seated leg press using Technogym® Isotonic Line with Power Control, offering visual feedback with regard to range of motion and power output for each repetition and set. General principles of strength training were applied (25). During the initial week, the relative exercise loading was 12 repetition maximum (RM), followed by 10RM loads during the second week and heavier loads of 8RM during weeks 3–6, and then increasing the number of repetitions again toward 12RM during week 8 and gradually increasing the load and decreasing the number of repetitions toward 4–8RM during the final weeks. The progression schedule is summarized in Table 2. All the subjects followed this progression schedule, but some individual adjustments were necessary; for the hamstring curl exercise, some of the subjects were not able to lift the minimum weight concentrically during the initial training sessions and thus had to start by isometric holds or eccentric lowering. Range of joint motion was gradually increased through the intervention as strength and flexibility improved. Three to 5 sets of each exercise were performed with rest periods of 90 seconds between sets. The subjects were instructed to exert full intentional acceleration of each repetition regardless of external load and actual movement velocity. Strength training was performed unilaterally to ensure the highest possible training intensity for the paretic leg.

Body weight supported treadmill training was performed for up to 25 minutes at the beginning of each training session, typically consisting of 3 gait periods of 6–8 minutes each, interspersed by a short rest period. A continuous high pace was used during the first period. To promote contralateral armswing and balance, this period was performed without holding on to the bar of the treadmill. Therapists offered discreet manual guiding when necessary. Interval training was used during second gait period, consisting of 1-minute intervals at the highest speed possible alternating with 1-minute intervals at slightly lower speed. This period was preferably performed without bar support and also offered discreet manual guiding if necessary. The third gait period was individually adapted to more specific requirements such as weight bearing, knee control, cadence, etc., the goal often being to challenge the cardiorespiratory system by increasing the treadmill gradient up to 10%. Body weight support varied from 10 to 25 kg and was determined by assessing the amount of support that would enhance optimal gait quality. Treadmill speed, intervals, gradient, and dosage were evaluated on a daily basis and increased whenever possible.

Aerobic activities besides BWSTT were performed twice a week and consisted of stationary bipedal and unipedal cycling (TechnoGym® Bikerace HC600), unipedal armcycling (TechnoGym® XT PRO Top600), and body weight supported stair climbing (TechnoGym® Steprace HC300). It was strived to gradually maximize the heart rate and increase the power output in each activity.

Functional training (weeks 4 and 10, Table 2) was individually adjusted, the goal being to ensure optimum carryover from functional improvements to activities of daily living. Functional training comprised training of specific details of the gait pattern, gait training in a nonclinical setting, stair climbing, etc.

Dynamometry
A KinCom dynamometer was used for the testing of isokinetic and static maximal voluntary muscle strength of the knee extensors (quadriceps) and knee flexors (hamstrings) (Kinetics Communicator, Chattecx Corp., Chattanooga, TN, USA). Unilateral measurements of PAR and CON were performed separately. Verbal encouragement and visual feedback on a computer screen were provided during all the contractions. After warm-up and preconditioning, 4 maximal attempts interspersed by rest periods of 60 seconds were performed during slow and fast concentric contraction
(30 and 240°·s⁻¹, respectively), slow eccentric contraction (30°·s⁻¹) for the quadriceps and hamstrings separately (5). Initial testing showed that for the hamstrings, the fast concentric contraction at 240°·s⁻¹ was unfeasible and was therefore disregarded for the remaining subjects. Further, 4 maximal voluntary static muscle contractions were performed at a knee joint angle of 70° for the quadriceps and hamstring separately. All torque and position signals were sampled synchronously at 1,000 Hz using a 16-bit A/D-converter (dt-9804, Data translation, Marlboro, MA, USA) and stored on a stationary computer for further analysis. During off-line analysis, the dynamometer force and lever arm position signal was digitally lowpass filtered at 15- and 8-Hz cut-off frequencies, respectively. Subsequently, the torque signal was corrected for the effect of gravity on the lower leg and foot (2). The average torque exerted in the 60–80° range of knee joint motion for each type of contraction was used for the further statistical analyses. The rationale for choosing this knee joint angle interval was that the highest torque occurred in this particular range of motion.

Noorizadeh et al. have previously shown that isokinetic strength measures are highly reliable in patients with stroke (intraclass correlation coefficient = 0.85–0.98) (42).

**Electromyography**

Neuromuscular activation was assessed by simultaneous recording of EMG from the quadriceps and hamstring muscles during the dynamometer test described above. After shaving and cleaning the skin with ethanol, bipolar surface EMG electrodes (Medicotest M-00-S, Medicotest, Ølstykke, Denmark) were placed on the medial portion of the 3 superficial heads of the quadriceps femoris (i.e., vastus lateralis, vastus medialis, rectus femoris) and hamstring muscles (i.e., biceps femoris and semitendinosus). If impedance was >10 kΩ, the procedure was repeated. Care was taken to place EMG electrodes at identical positions on both legs, and the exact electrode positions were registered and used during the subsequent posttraining test. The EMG electrodes were connected directly to small preamplifiers located 10 cm from the recording site. The signals were led through shielded wires to custom-built differential instrumentation amplifiers, with a bandwidth of 10–10,000 Hz and a common mode rejection ratio >100 dB and sampled at 1,000 Hz (5). During the process of off-line analysis, all raw EMG signals were digitally high-pass filtered at a cut-off frequency of 10 Hz using a fourth-order zero phase lag Butterworth filter (60). The EMG signal was then passed through a symmetric moving root mean square filter with a time constant of 20 milliseconds and averaged in the 60–80° knee joint angle interval for the isokinetic contractions and averaged over the peak 500 milliseconds of the static contractions at 70°. Quadriceps EMG amplitude was determined as the average of vastus lateralis, vastus medialis, and rectus femoris. Correspondingly, hamstring EMG amplitude was determined as the average of biceps femoris and semitendinosus. All the analyses of torque and EMG were performed using custommade macros developed in Matlab 7.5 (MathWorks, Natick, MA, USA) and Visual Basic for Applications (Microsoft Corp., Microsoft Danmark ApS, Hellerup, Denmark).

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**Figure 1.** Normalized knee extensor torque and quadriceps electromyography (EMG) amplitude at pretraining and posttraining. *, **p < 0.05 and 0.01, respectively, pretraining to posttraining.

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Electrically Evoked Muscle Twitch Contractile Properties

Electrically evoked muscle contractile properties of the resting quadriceps of PAR and CON were determined according to a procedure previously described in healthy subjects (6). Briefly, surface stimulation electrodes (Bioflex, model PE3590) were placed over the distal and proximal muscle belly of the largest head of the quadriceps femoris, that is, vastus lateralis. Care was taken to place the stimulation electrodes at identical positions on both legs, and the exact positions were registered and used during the subsequent posttraining test. Twitch contractions were evoked on the resting muscle using electrical stimulation consisting of single square wave pulses of a 0.1-millisecond duration delivered by a direct current stimulator (Digitimer Electronics, model DS7) while at the same time measuring knee extensor torque. Stepwise increments in current were delivered, separated by rest periods of 30 seconds, until no further increase in torque was seen (30), and subsequently 3 maximal twitch contractions were obtained. Twitch peak torque and time to peak tension of the maximal twitches were used for further statistical analyses.

Gait Performance

Gait speed was evaluated using a 10-m Walk Test. The subjects were instructed to walk the distance as fast as possible, starting from static. Gait endurance was evaluated with a 6-min Walk Test on a 50-m track. The subjects were instructed to walk as far as possible in 6 minutes, and subsequently the distance was measured. The subjects used their habitual assistive devices during the test. When possible, the subjects were requested to walk without support from an elbow crutch or cane. This test was performed on a separate day by the physiotherapists of this study.

Statistical Analyses

Friedman’s 2-way analysis of variance by ranks for related samples was performed in SAS version 9 to locate differences from pretraining to posttraining for torque and EMG of the quadriceps and hamstring muscles and to locate the differences across contraction modes and velocities. Spearman’s correlation coefficient was determined between the baseline variables and between the training-induced change in torque and EMG. In addition to absolute values, the torque and EMG amplitude of PAR was expressed as a percentage of CON to compare the relative deficit between muscles, contraction modes, and velocities. A value of $p < 0.05$ was chosen as statistically significant, and results are reported as mean $\pm$ SE unless otherwise stated.

RESULTS

After the 12-week intervention period, changes in muscle strength and EMG activity were observed solely in PAR. Normalized values of torque and EMG amplitude for PAR are given in Figures 1 and 2 (i.e., expressed as a percentage of CON), and absolute values for PAR and CON are provided in Table 3.

Baseline Observations

At baseline, torque and quadriceps EMG during knee extension and torque and hamstring EMG during knee flexion were significantly lower in PAR compared with those in CON during all contraction modes and velocities.

Figure 2. Normalized knee flexor torque and hamstrings electromyography (EMG) amplitude at pretraining and posttraining. *, ** $p < 0.05$ and 0.01, respectively, pretraining to posttraining.
Normalizing torque and EMG were significantly lower during knee extension during all contraction modes (compare Figures 1 and 2) \((p < 0.0001)\).

When comparing across velocities, normalized torque and quadriceps EMG were marked lower during fast concentric knee extension compared with slow eccentric, static, and slow concentric contraction \((p < 0.0001)\) (both at pretraining and posttraining, Figures 1A and B).

### Participation and Training Load

Thirty strength training sessions were planned during the 12-week intervention period. The actual number of strength training sessions was 29 ± 1.0. The training load was increased in a linear fashion and was more than doubled during the 12 weeks, which confirmed the high level of participation. From the initial to the final week of training, the unilateral load for PAR increased from 39 ± 4.4 to 86 ± 11 kg for seated leg press, from 17 ± 2.5 to 36 ± 4.4 kg for knee extension, from 47 ± 3.9 to 98 ± 7.1 kg for semisided leg press, and from 15 ± 1.9 to 28 ± 3.0 kg for hamstring curls. Although not measured, the actual muscle load was probably increased even more than the nominal training load because the range of joint motion was increased as strength and flexibility improved. The average progression in training load for 2 of the exercises is given in Figure 3.

### Intervention, Knee Extension (Quadriceps)

In PAR, normalized knee extensor torque increased significantly in response to the intervention during all the contraction modes and velocities (Figure 1A); slow eccentric from 72 ± 6.2 to 99 ± 9.2\% \((p < 0.05)\), static from 67 ± 8.3 to 84 ± 9.2\% \((p < 0.01)\), slow concentric from 62 ± 9.2 to 78 ± 7.8\% \((p < 0.01)\), and fast concentric from 19 ± 4.3 to 33 ± 7.1\% \((p < 0.05)\). Absolute knee extensor torque increased during slow eccentric, static, and slow concentric contraction \((p < 0.01–0.001)\) (Table 3).

Significant increases in normalized quadriceps EMG amplitude were seen during slow eccentric contraction (from 61 ± 7.0 to 83 ± 11\%, \(p < 0.05\)) and slow concentric contraction (from 59 ± 9.0 to 69 ± 8.8\%, \(p < 0.01\)) (Figure 1B). Increased quadriceps EMG amplitude was significantly correlated to increased knee extensor torque during slow eccentric \((r = 0.75, p < 0.01)\) and slow concentric contraction \((r = 0.84, p < 0.01)\). Absolute quadriceps EMG amplitude increased during slow eccentric and slow concentric contraction \((p < 0.05–0.001)\) (Table 3).

### Intervention, Knee Flexion (Hamstrings)

In PAR, normalized knee flexor torque increased significantly during all the contraction modes and velocities (Figure 2A); slow eccentric torque from 14 ± 5.9 to 50 ± 21\% \((p < 0.01)\), static from 31 ± 9.4 to 44 ± 13\% \((p < 0.01)\), and slow

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**Table 3.** Isokinetic and static muscle strength for the knee extensors (quadriceps) and knee flexors (hamstrings) and electrically evoked twitch peak torque and TPT at preintervention and postintervention for the PAR and CON.

<table>
<thead>
<tr>
<th></th>
<th>Maximal voluntary contraction</th>
<th>Twitch contraction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Quadriceps</td>
<td>Hamstrings</td>
</tr>
<tr>
<td>Velocity ((° \cdot \text{s}^{-1}))</td>
<td>Torque ((\text{N-m})) EMG ((\mu\text{V}))</td>
<td>Torque ((\text{N-m})) EMG ((\mu\text{V}))</td>
</tr>
<tr>
<td>PAR Pre (-30)</td>
<td>112 ± 12</td>
<td>100 ± 12</td>
</tr>
<tr>
<td>0</td>
<td>125 ± 17</td>
<td>112 ± 14</td>
</tr>
<tr>
<td>30</td>
<td>74 ± 11</td>
<td>81 ± 11</td>
</tr>
<tr>
<td>240</td>
<td>17 ± 5</td>
<td>71 ± 14</td>
</tr>
<tr>
<td>Post (-30)</td>
<td>147 ± 14†</td>
<td>137 ± 22‡</td>
</tr>
<tr>
<td>0</td>
<td>157 ± 20§</td>
<td>132 ± 22</td>
</tr>
<tr>
<td>30</td>
<td>108 ± 12§</td>
<td>134 ± 22‡</td>
</tr>
<tr>
<td>240</td>
<td>21 ± 5</td>
<td>85 ± 15</td>
</tr>
<tr>
<td>CON Pre (-30)</td>
<td>164 ± 16</td>
<td>173 ± 24</td>
</tr>
<tr>
<td>0</td>
<td>191 ± 21</td>
<td>203 ± 29</td>
</tr>
<tr>
<td>30</td>
<td>131 ± 16</td>
<td>175 ± 35</td>
</tr>
<tr>
<td>240</td>
<td>82 ± 12</td>
<td>281 ± 41</td>
</tr>
<tr>
<td>Post (-30)</td>
<td>159 ± 18</td>
<td>193 ± 31</td>
</tr>
<tr>
<td>0</td>
<td>193 ± 24</td>
<td>220 ± 28</td>
</tr>
<tr>
<td>30</td>
<td>144 ± 16</td>
<td>211 ± 34</td>
</tr>
<tr>
<td>240</td>
<td>67 ± 13</td>
<td>270 ± 57</td>
</tr>
</tbody>
</table>

*TPT = time to peak tension; PAR = paretic; CON = nonparetic control leg; EMG = electromyography.

†\(p < 0.05\) pretraining to posttraining.
‡\(p < 0.01\) pretraining to posttraining.
§\(p < 0.001\), pretraining to posttraining.
concentric from 6.3 ± 3.4 to 34 ± 15% (p < 0.05). Absolute knee flexor torque increased during slow eccentric, static, and slow concentric contraction (p < 0.05–0.01) (Table 3).

Significant increases in normalized hamstring EMG amplitude were seen only during the slow dynamic contractions (Figure 2B); slow eccentric from 16 ± 7.0 to 43 ± 13% (p < 0.05), and slow concentric from 11 ± 5.5 to 32 ± 8.5% (p < 0.01). Absolute hamstring EMG amplitude increased during slow eccentric and slow concentric contractions (p < 0.01) (Table 3).

**Electically Evoked Muscle Contractile Properties**

At baseline, twitch peak torque of the resting quadriceps was significantly lower in PAR compared with that in CON (p < 0.05) and increased significantly with training from 92 ± 4.9 to 115 ± 6.4% (p < 0.001). The posttraining value of 115 ± 6.4% was significantly higher in PAR compared with that in CON (p < 0.05). Twitch time to peak tension was not significantly different between PAR and CON and remained unchanged from pretraining to postraining (101 ± 3.6 vs. 103 ± 2.0%). Absolute values are provided in Table 3.

**Gait Performance**

From pretraining to postraining, gait speed (10 meter walk test) increased 52% from 0.89 ± 0.14 to 1.35 ± 0.12 m·s⁻¹, and gait endurance (6 minute walk test) increased 68% from 250 ± 30 to 420 ± 43 m (corresponding to an average gait speed of 0.69 ± 0.08 to 1.17 ± 0.12 m·s⁻¹) (p < 0.001). Relative to “normal” gait distance covered during a 6-MWT in healthy age-, weight-, height-, and sex-matched individuals (22), this corresponded to 42 ± 4.0% at pretraining and 70 ± 4.5% at postraining.

**DISCUSSION**

The main findings of this study are that intensive physical rehabilitation with unilateral strength training of the paretic limb combined with BWSTT improves the neuromuscular activation of agonist muscles and enhances twitch torque, leading to increased strength during maximal voluntary eccentric, concentric and static contraction. Together, these findings show that persons with hemiparesis after stroke can get clinically relevant improvements of neural and muscular function in response to intensive physical rehabilitation.

Several interesting observations were made at baseline before the intervention. The baseline correlations of this study validate that the reduced neuromuscular activation is primarily responsible for muscle weakness (20,26,28). However, with the technique of percutaneous electrical stimulation of the resting quadriceps, we further showed that muscle twitch torque is impaired in the paretic leg compared with that in the nonparetic control leg. The twitch torque deficit of 8% during electrical stimulation was relatively small compared with the neural deficit of 40% during maximal voluntary static contraction. Nevertheless, this result shows that the intrinsic contractile strength of the muscle is negatively affected after long-term hemiparesis, which is in agreement with the findings of a previous study (56). These findings are in line with the observations that long-term hemiparesis can lead to muscular atrophy of the paretic limb (35,49).

Another interesting finding at baseline was the severe weakening of the hamstrings. For instance, muscle strength during slow concentric knee flexion of the paretic leg was only 6% of the nonparetic control leg. This may partly explain the common observation of awkward gait pattern in persons with hemiparesis, that is, the knee is barely flexed and the leg is swung in a circumduction fashion from the hip with the pelvis tilted upward and the hip abducted. Thus, special attention should be paid to increased hamstring activation during rehabilitation. Although not specifically investigated in this
study, it should also be noted that hip and planter flexor strength are considered important for normal gait as well (62).

In line with previous observations (19,38), muscle strength and EMG were more heavily impaired during rapid compared with slow muscle contraction, which may explain the inert movement pattern of this patient group. Although fast concentric knee extensor strength (quadriceps) was only 19% of the nonparetic control leg, fast concentric knee flexor strength (hamstrings) was minimal (−0%). At baseline, the highest level of neuromuscular activation of the hamstrings was achieved during static contraction, which can be a starting point for the practical strength training, that is, static holds and then slowly lowering the weight eccentrically. This method was implemented during the initial training sessions in those subjects who could not lift the minimal weight concentrically during the knee flexion exercise. Clark et al. showed a higher preservation of eccentric compared with concentric knee extensor torque after stroke and suggested the implementation of eccentric contractions during rehabilitation (19). This study extends these findings by showing a severe weakening of eccentric knee flexor torque (i.e., hamstrings), despite preserved eccentric knee extensor torque (i.e., quadriceps). Thus, although concentric and eccentric contractions may be feasible during rehabilitation of the quadriceps, static contractions followed by eccentric contraction may be more appropriate during rehabilitation of severely weakened hamstrings.

This study highlights that persons with hemiparesis are able to complete an intensive physical training intervention and make progression in training loads comparable with that previously observed in healthy individuals (6,8). Thus, training load increased in a linear fashion throughout the intervention and did not plateau within 12 weeks, indicating further potential for improvement.

In response to the 12-week training intervention, both EMG amplitude and intrinsic contractile strength (i.e., twitch torque) of the paretic leg were enhanced, leading to increased voluntary muscle strength. Although general increases in torque and EMG were observed, the most consistent gains—in terms of both torque and EMG—were found during slow concentric and eccentric contraction. This was consistent for both knee extension and flexion. This resulted in an altered shape of the torque-velocity and EMG-velocity curves, that is, the most pronounced gains occurred during slow concentric and slow eccentric contractions. These findings reflect the velocity specificity of neural adaptations (10), that is, strength training was performed with heavy loads and consequently relatively slow external movement speeds of approximately 60–120° s⁻¹, which may have facilitated gains in the neural drive relatively more during slow contractions than during static and fast contraction. In line with the present findings, a previous study reported increased EMG amplitude of the quadriceps after isokinetic strength training (21). However, the generalizability of that study may be limited because of learning effects owing to the identical conditions of training and testing (48).

As in this study, training-induced changes in EMG amplitude are commonly used to estimate the changes in neuromuscular activation. However, it should be noted that the EMG signal may be affected by confounding factors, for example, changes in muscle architecture and subcutaneous fatty tissue with training, skin conductance, EMG electrode placement, etc. Despite the inherent variance associated with EMG measurements, the amplitude of the EMG signal is roughly related to muscle force (32), expressing a combination of recruitment, rate coding, and synchronization of motor units (23). In this study, correlation analyses confirmed a strong relation between training-induced changes in torque and EMG during slow concentric and slow eccentric contraction ($r = 0.75–0.84$). Similarly, in healthy young men and in women with chronic neck muscle pain, a moderate to strong association exists between increased EMG amplitude and gains in slow eccentric and slow concentric muscle strength in response to strength training (4,5). Together, these findings support that the changes in EMG amplitude represent a fair estimate of the changes in neuromuscular activation.

Although improvements of neuromuscular activation were significant only at the slow concentric and eccentric contractions in this study, strength gains were observed throughout the whole range of contraction modes and velocities, indicating that adaptations in intrinsic contractile strength positively influenced voluntary strength gains as well. As a novel finding, we showed that electrically evoked twitch torque of the paretic muscle relatively to the homologous nonparetic control muscle was enhanced 23% by strength training. After the intervention period, twitch peak torque of the paretic leg even exceeded that of the nonparetic control leg. This finding indicates gross muscular hypertrophy and adaptations at the muscle cellular level, as also seen in healthy subjects doing lower-body strength training of similar type, volume, intensity, and duration (6,8).

This finding may also reflect training-induced adaptations of sarcoplasmic reticulum Ca$^{2+}$ kinetics (44). Time to peak tension remained unchanged, indicating unaltered relative proportion of type I and II muscle fibers (31). Future studies should evaluate the impact of high-intensity strength training on muscle cellular adaptations in this population.

The intervention led to improved gait performance, as evidenced by a 52 and 68% increase in gait speed and gait endurance, respectively. Although some studies found no additional effect of strength training on gait performance (27,36,39), others have reported between 6 and 30% increase in gait speed (50,54,55) and 12–23% increase in gait endurance (43,54). In this study, both gait speed and gait endurance were positively affected by the rehabilitation program. A systematic review concluded that gait-oriented training is effective in improving gait performance after stroke (57). The marked improvement in gait performance in this study may be caused by a combination of gait-oriented functional training, BWSTT, other aerobic activities, and unilateral strength training.
In conclusion, this study demonstrated that intensive physical rehabilitation comprising unilateral strength training and BWSTT of persons with hemiparesis after stroke can lead to clinically relevant improvements of neuromuscular activation of agonist muscles and enhancement of intrinsic contractile strength, leading to increased voluntary strength during a wide range of contraction modes and velocities. The overall efficacy of the rehabilitation program was further reflected in improved gait speed and gait endurance. Together, these results show a promising potential toward achieving functional independence in activities of daily living in this population.

**Practical Applications**

Our study shows that high-intensity strength training can be implemented successfully in rehabilitation programs for patients with hemiparesis after stroke. Using heavy loads of 4–12RM 3 times a week in a periodized and progressive manner—quite similar to that used in healthy individuals—patients with stroke can partially regain muscle strength and gait function in 12 weeks. Particular attention should be paid to regaining hamstring strength because our study showed severe weakening of this muscle group at baseline. Strength training coaches working in the field of rehabilitation can use this knowledge to safely and efficiently add high-intensity strength training to existing rehabilitation paradigms.

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**References**

Rehabilitation of Stroke


