Cerebral Palsy (CP) often requires long-term physical therapy for neuromuscular re-education. This paper presents an electromyographic (EMG) feedback protocol that was developed during treatment of six patients, aged 6 to 35 years. Five were functional walkers, and one (age 6) used crutches. The goal was to improve the strength, relaxation, and coordinated control of the muscles of the trunk, pelvis, and lower extremities, to improve walking and performance of daily activities. The EMG methods for evaluation and biofeedback training are illustrated by selected examples from two individuals, together with the clinical gains that were achieved.

Introduction
Cerebral Palsy (CP) is a developmental disorder caused by damage to the developing brain that occurs perinatally in 3 per 100,000 births. Epidemiological studies (Maclennan, 1999) find that most cases of cerebral palsy result from events before the onset of labor or (especially in premature infants) events after delivery. A small minority of cases develop due to problems with labor and delivery. The most noticeable characteristics are neuromuscular deficits that vary according to the location of central nervous system (CNS) damage (Lundy-Eckman, 2002). These include disturbances of muscle tone (spasticity and flaccidity) and muscle control (muscle weakness, abnormal cocontraction of antagonists, and involuntary movements). CP can also include sensory and cognitive deficits, although many individuals with CP have normal or above normal intelligence. The CNS damage is not progressive; however, the impact of the damage becomes greater as the child gets older and fails to achieve normal developmental milestones. That is, problems with the ability to sit, crawl, or walk become more obvious as the normal age for these functional activities is reached and passed. Children with CP often require a long-term rehabilitation program of specialized pediatric physical therapy and medical management throughout the period of growth and development into young adulthood.

Biofeedback procedures using surface-recorded electromyography (SEMG) are reported to enhance neuromuscular re-education in CP in a number of well-controlled clinical studies as well as detailed clinical reports published in the applied psychophysiology literature (Bolek, Moeller-Mansour, & Sabet, 2001; Bolek, 2003; Cataldo, Bird, & Cunningham, 1978; Finley, Etherton, Dickman, Karimian, & Simpson, 1981; Finley, Niman, Standley, & Wansley, 1977), as well as in the rehabilitation literature (Coulborne, Wright, & Naumann, 1994; Dursun, Dursun, & Alican, 2004; Skrotzky, Gallenstein, & Osternig, 1978). At present, however, relatively little information is available on biofeedback-assisted clinical protocols for this important diagnostic group. With this in mind, we initiated a pilot program to develop a systematic protocol for integrating SEMG feedback with pediatric physical therapy for rehabilitation in CP. This paper presents SEMG procedures for evaluation and neuromuscular re-education that we developed and implemented over a period of 3 years at a tertiary care teaching hospital.

Method
Individuals who were receiving pediatric physical therapy on a regular basis, typically once or twice a week, were referred to the Clinical Biofeedback Program for concurrent treatment. Biofeedback treatment sessions were carried out by a physical therapist specializing in use of SEMG feedback techniques in close co-operation with the individual’s pediatric physical therapist who provided detailed information on the neuromuscular problems of the individual, identified specific and appropriate therapy goals, and actively participated as cotherapist in most of the biofeedback treatment sessions. The goal was (1) to develop protocols and methods for effectively integrating SEMG procedures with pediatric physical therapy for this important diagnostic group and (2) to develop an optimal treatment program for each individual participant.

The first 6 participants (3 male and 3 female) ranged in age from 6 to 35 years. All were living in the community and attending school (5) or working (1). Five were functional
walkers who did not require crutches but had significant gait problems. The sixth, aged 6, recently began walking with Lofstrand crutches. The SEMG feedback-assisted treatment program was primarily focussed on improving the quality of walking (gait) by improving the strength, relaxation, and coordinated control of the muscles of the trunk, pelvis, and lower extremities.

SEMG recording was carried out with a 4-channel J & J I-330™ (J&J Engineering, Poulsbo, WA), using 20-1000 Hz bandwidth. An oscilloscope display of the raw SEMG signal was used concurrently for quality control. For most procedures, a 90-second screen duration was selected, using the Filter 2 setting to smooth the signal. For gait analysis, which requires differentiation of rapidly occurring muscle events, a 15-second screen time and Filter 1 setting were used, with 20-foot shielded cables to provide a 40-foot walking distance. A portable EMG (J & J M56A™, 100–200 Hz bandwidth, 250 msec time constant) was used for additional muscle assessment and for biofeedback training while walking and performing other activities such as stair climbing, outside of the Biofeedback Lab. For the younger participants, this could (and often did) include riding a tricycle or bike, pushing a scooter, or roller-skating in the hallway. Disposable silver/silver chloride electrodes, 1 cm diameter, were placed over the target muscle with the 2 active electrodes spaced 2.5 cm center-to-center parallel to the direction of the muscle fibers and the ground electrode placed equidistant and adjacent. For large muscles, such as hamstring muscles in teenagers or adults, a wider placement (6 cm) was used, and the ground electrode was placed between, and in line with, the 2 active electrodes.

**Results Part I: Development of an SEMG Biofeedback Protocol**

The following protocol was developed over the course of 3 years to incorporate 4 different aspects of SEMG feedback procedures that were identified as making clinically useful contributions to physical therapy treatment goals. The protocol for the SEMG feedback sessions consisted of the following 4 components, which were usually carried out in an overlapping sequence. That is, 2 to 4 muscle groups were evaluated and biofeedback training was initiated for 1 or more of those muscles as indicated; then, additional muscles were evaluated and biofeedback training initiated, etc.

**Component 1**

Major muscle groups in the legs, hips, and trunk were systematically evaluated bilaterally by recording SEMG during (1) manual muscle testing by the physical therapist, to aid assessment of motor-unit recruitment in muscles on the right versus left side; (2) instructions to contract, hold (10 seconds), and relax a target muscle, in sitting or lying, to evaluate quality of isolated voluntary muscle control and assess cocontraction of antagonist muscles; and (3) gait analysis, to evaluate functional use of the muscles for walking and stair climbing. The following major muscles or muscle groups were routinely assessed: anterior tibialis, triceps surae, hamstrings, quadriceps (vastus medialis for knee extension, proximal rectus femoris for hip flexion), hip adductors, glutaeus maximus and medius, lumbar paraspinals, and abdominal muscles. Additional muscles (e.g., scapular muscles) were evaluated as indicated. This component was clinically useful because it provided more accurate information than was otherwise available through clinical observation alone. For example, with SEMG feedback the therapist could readily determine whether a muscle that performed satisfactorily during manual muscle testing (which requires a relatively simple, brief contraction) was also performing as expected while walking (which requires complex and coordinated action).

**Component 2**

Problem muscles were monitored by SEMG to evaluate the effectiveness of the physical therapy exercise program. The physical therapist coached the patient through the exercises and therapeutic play activities that comprised their current, ongoing physical therapy program (including a home program). SEMG recording was used to determine whether the target muscles were, in fact, performing as expected during each exercise or activity and to determine which of several alternative exercises/activities were most effective in producing the desired muscle response (e.g., increased muscle recruitment or muscle synergists working together). The most effective exercises/activities were retained, and the less effective ones were discarded, to optimize the individual’s therapeutic program. This component was particularly clinically useful because individuals with CP often use a stronger muscle during an exercise/activity intended to strengthen a weaker muscle, and this muscle substitution can be difficult, if not impossible, to spot without SEMG monitoring.

**Component 3**

SEMG biofeedback-assisted muscle training was carried out for selected problem muscles using auditory and visual biofeedback combined with verbal coaching and manual assistance by the therapist as needed. SEMG biofeedback was used for 3 types of muscle training: (1) SEMG feedback was used to teach, and practice, basic muscle control skills, typically recruiting the target muscle without excessive
cocontraction or associated reactions by other muscles, holding a consistent contraction for 10–20 seconds, and relaxing the muscle quickly; (2) SEMG biofeedback was used to teach correct use of problem muscles while performing the exercises and therapeutic activities selected in Component 2 above; and (3) SEMG biofeedback (portable) was used to teach the patient to use target muscles correctly for functional activities, including standing, walking, and stair climbing (generalization of skills). This component was clinically useful for problem muscles that were not improving with the existing physical therapy program. SEMG biofeedback was unique in its ability to provide muscle training during dynamic activities such as walking, stair climbing, and therapeutic play activities such as riding a scooter or roller skating.

**Component 4**

SEMG recording was used to monitor progress and document gains in the individual patient, as a result of his/her physical therapy program (whether this program included biofeedback-assisted muscle training as in Component 3 or not). It was especially useful for objective, quantitative assessment of improved use of problem muscles during active, functional activities. SEMG recording was also useful for providing information to the physician to assist decisions on medical interventions, such as botulinum toxin injections or baclofen pump, for hypertonic muscles that seriously interfered with functional gait.

**Results Part II: SEMG Feedback to Optimize Treatment for Individual Patients**

The 6 participants varied considerably in the number and content of biofeedback sessions received. The youngest, a 6-year-old girl, received 7 sessions over a 2-month period, primarily for evaluation of muscles (Component 1) and selection of optimal exercises and therapeutic play activities to be carried out, without SEMG biofeedback, in her regular pediatric physical therapy sessions and at home (Component 2). The other 5 participants received 16 to 38 sessions over 6 to 26 months that included all 4 biofeedback protocol components. These 5 patients worked well with SEMG biofeedback for direct muscle retraining (Component 3) including a 7-year-old girl with Attention Deficit Hyperactivity Disorder (ADHD) as well as CP. Figures 1–3 provide brief examples of SEMG biofeedback training methods, and the improvements achieved, for 2 participants.

**Case Example 1**

A 17-year-old participant (male) had quadriceps muscle weakness, greater on the right, that limited knee control and led to knee hyperextension (back knee) while standing and walking. Attempts to strengthen the quadriceps using knee extension exercises had not been successful in his regular physical therapy sessions because voluntary knee extension,
Either in a sitting position or during straight leg raising while lying supine, produced painful muscle cramps in the upper thigh.

During initial evaluation (Figure 1), SEMG was recorded (without biofeedback) from 2 components of the quadriceps muscle (ms): the vastus medialis at the knee and the rectus femoris at the upper thigh. Both muscles participate in knee extension, but painful cramps were reported only in the upper thigh. In a sitting position, starting with the knee flexed and hanging freely, he attempted to extend the knee. In his initial 2 attempts (Figure 1A), he began to extend the knee, gradually increasing muscle recruitment, but experienced a painful cramp that occurred at very low levels of muscle contraction, approximately 20 microvolts (µV), with minimal knee extension. The onset of the painful cramp was reported verbally and corresponded to the sudden, large increase in SEMG amplitude (80 µV to > 100 µV) in the cramping muscle, the rectus femoris.

In the same session, he began SEMG biofeedback-assisted muscle training using visual SEMG feedback as a guide (as shown in Figure 1B) using a ramping protocol. In the same sitting position as in Figure 1A, he followed instructions to extend the knee until the rectus femoris muscle reaches 10 µV (well below the 20 µV cramp threshold), hold the contraction for 10 seconds, relax the muscle for 15 seconds, and repeat this sequence throughout the 90-second trial. He produced 4 contractions, each without cramping. On each successive 90-second trial he was instructed to increase the muscle contraction by 10 µV (3 to 4 contractions at 20 µV, then 3 to 4 contractions at 30 µV, etc.). By the end of the first training session, he was able to perform 60 µV muscle contractions without cramping. The session ended when, at the 70 µV threshold, the muscle started to cramp. He was asked to practice this same ramping sequence daily at home, without biofeedback, starting with a series of minimal contractions, gradually increasing contraction strength, and stopping when the muscle felt fatigued or about to cramp. He reported no difficulty doing this. Two sessions later (Figure 1C) he easily achieved 70 µV to 100+ µV contractions and complete knee extension without muscle cramping. In the following session (not shown), he successfully added a 3-lb ankle weight during biofeedback training, without cramping, and ankle weights were added to his home program. He then tolerated systematic, progressive weight training without cramping, and SEMG feedback was discontinued for this task.

The same 17-year-old participant also had poor voluntary control of his calf muscles. As a result, he walked with a flat-footed gait, with little toe pick-up (ankle dorsiflexion) and poor push-off on the ball of the foot (plantar flexion). Figure 2 illustrates his poor muscle control prior to biofeedback training (Figure 2A) and improvement with biofeedback training (Figure 2B). SEMG was recorded from the anterior tibialis muscle, the primary ankle dorsiflexor, and the triceps surae muscle (posterior calf plantar flexors). Figure 2A shows his first 3 attempts to dorsiflex the foot (bend the ankle upwards), in sitting, without biofeedback. He was not able to initiate and hold a consistent contraction of the anterior tibialis muscle. All 3 attempts showed very poor muscle recruitment, below 12 µV, and as he tried harder (third contraction), the triceps surae muscle cocontracted to interfere with ankle motion. In 5 sessions of SEMG biofeedback training of both muscles, he learned to contract, hold for 10 seconds, and quickly relax the anterior tibialis

### Figure 2.
EMG (mean microvolts) in the same 17-year-old boy with Cerebral Palsy in sitting. (A) EMG evaluation indicates poor recruitment (< 13 µV) of the anterior tibialis muscle and cocontraction of the antagonist, triceps surae muscle, during 3 attempts to dorsiflex the ankle. (B) Session 5 of EMG biofeedback training: Recruitment of the anterior tibialis muscle is excellent (> 50µV) with little cocontraction of the triceps surae muscle during 3 ankle dorsiflexions.
without cocontraction of the triceps surae. His Session 5 performance is shown in Figure 2B: he was able to recruit and maintain a strong contraction of the anterior tibialis muscle (70–80 µV), while keeping cocontraction of the triceps surae to a minimum (< 5 µV). In these 5 sessions, he also learned to contract the triceps surae muscle without cocontraction of the anterior tibialis muscle and to smoothly alternate contraction and relaxation of the 2 muscles in a coordinated manner. In addition, SEMG was used to select strengthening exercises that combined plantar flexion with knee extension (but not hyperextension) for his home program—squats performed with his back supported against the wall accomplished this nicely. The focus of biofeedback training then shifted to SEMG biofeedback training while walking, using a portable EMG unit with auditory feedback. He was able to increase toe pick-up, develop a more forceful toe push-off, and improve knee control while walking.

Case Example 2
A 35-year-old participant (male) had abdominal muscle weakness with marked lumbar lordosis (anterior pelvic tilt) while standing and walking. As a result, the lumbar paraspinal muscles were over-worked, and he had recurring episodes of lower back pain. This posture, and poor control of the pelvis, also led to reduced use of hip flexor and ankle dorsiflexor muscles while walking. SEMG was initially recorded from the lumbar paraspinal muscles and abdominal muscles (external oblique muscle and rectus abdominis muscle) bilaterally. He was first instructed on basic abdominal exercises, in standard supine position. SEMG monitoring was used to verify that he was doing these exercises correctly, and his abdominal muscles were contracting relatively strongly. SEMG biofeedback was then used to teach him to actively engage these abdominal muscles while standing, walking, and performing daily activities.

SEMG biofeedback from the abdominal and lumbar paraspinal muscle was first used to teach him to correct the lumbar lordosis in standing. As he used his abdominal muscles to position his pelvis in a correct, neutral position, his lumbar muscles decreased from his typical 20–30 µV (marked elevation) to normal standing baseline levels (< 4 µV). The next step was to train coordinated use of these muscles during a more demanding, dynamic task, as shown in Figure 3. With SEMG biofeedback, he was instructed to actively contract the abdominal muscle to hold the pelvis in a correct neutral position while standing up from a deep squat position (lightly touching a chair seat on either side for balance). During his first 2 attempts, each indicated in Figure 3A by an asterisk, abdominal muscle control was poor. The left lumbar muscle were overused, while the right lumbar muscle contracted in a disorganized manner. By the end of this training session (Figure 3B), he achieved good muscle control with well-coordinated and balanced use of all 4 muscles. This exercise was assigned as homework, without biofeedback. When rechecked in the next weekly session, without biofeedback, he was performing this exercise consistently. A portable EMG unit, with auditory feedback, was used for muscle training while walking. This included training to reduce and equalize (right vs. left) lumbar paraspinal muscle use. This required active use of abdominal muscle while walking and equal

Figure 3. EMG (mean microvolts) in a 35-year-old man with Cerebral Palsy with poor pelvic muscle control resulting in lumbar lordosis and back pain during an EMG biofeedback training session. (A) Abdominal muscle recruitment is poor, and the lumbar paraspinal muscle are asymmetrical, during the first 2 attempts (*) to hold the pelvis in a correct neutral position while standing up from a deep knee squat position. (B) By session end, the abdominal muscle contract well, and the lumbar muscle are symmetrical.
weight shift from right to left with each step. SEMG feedback training was also used to increase use of the anterior tibialis muscle for ankle dorsiflexion and the rectus femoris muscle for hip flexion while walking and stair climbing. As a result of his treatment program as a whole, his posture and gait improved, and his lower back pain decreased substantially.

Conclusions

Overall, this 4-component SEMG Feedback Protocol was well received by each participant and his/her physical therapist. This protocol required close collaboration between the biofeedback specialist and the individual participant’s physical therapist, who identified clinical problems, specified treatment priorities, and typically participated as cotherapist during biofeedback sessions. Based on our experience with the initial 6 individuals who participated in the development of our clinical protocol, we found that SEMG feedback procedures contribute to rehabilitation of individuals with CP in several distinct, clinically useful ways.

(1) SEMG provides quantitative monitoring and documentation of patient progress during treatment. This is especially valuable when treatment is extensive and prolonged and progress is incremental, as is usually the case with CP rehabilitation.

(2) SEMG increases the efficiency and effectiveness of a nonbiofeedback therapeutic exercise program. All 6 of the CP individuals who participated in the development of this clinical protocol were on an exercise program at the time that SEMG was introduced. In each case, SEMG revealed that some exercises were not, in fact, producing appreciable contractions in the target muscle; instead, the exercise was being performed using substitute muscles. SEMG provides a simple, and valuable, method for optimizing each individual’s exercise program.

(3) SEMG provides a method for systematic evaluation of how the individual is using problem muscles, from basic motor control skills, to coordinated use of synergists and antagonists, to functional use during daily activities. There is simply not another clinical method available for directly observing muscles as they are being used. In each of the initial 6 CP individuals, this information led to relevant changes in his/her individual treatment program. For the younger children, for example, it substantially improved selection of therapeutic play activities to better focus on specific target muscles.

(4) SEMG provides a method for systematic training of muscles; not only training for basic muscle control but also for coordinated action with synergists and antagonists and especially for use during complex daily activities. SEMG biofeedback is unique in its ability to take muscles through this complete sequence of training—from basic skills to functional use—accurately and systematically. Five of the 6 participants worked well with the SEMG biofeedback-assisted muscle training portion of the protocol, which was carried out with children as young as age 7 without special adaptation, except for a lot of “cheering on” and, of course, brightly colored stickers at the end of each session.

References


