Sensitivity of the pendulum test for assessing spasticity in persons with cerebral palsy

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The sensitivity of the pendulum test to variation in spasticity in persons with spastic cerebral palsy (CP) was tested in 30 participants with CP and 10 participants without CP (controls) (mean age 13.8 years). The participants with CP were classified into three groups, with normal (mean age 15.9 years), mild/moderate (13.0 years), or severe (23.0 years) muscle tone, as assessed clinically using a modified Ashworth scale. Joint motion during the pendulum test was measured with an electrogoniometer. Muscle relaxation was confirmed using surface EMG. Outcome measures from the pendulum test were (1) number of oscillations, (2) duration of oscillations, (3) excursion of the first backward swing, and (4) relaxation index (first swing excursion/difference between the starting and resting angles). Data were assessed using one-way analysis of variance. Outcome measures 1 to 3 differed significantly between control participants and participants with CP ($p<0.05$). The first swing excursion was the best predictor of the degree of spasticity in persons with CP, being significantly different between all groups ($p<0.05$). The number of oscillations and their duration differentiated between control participants and all participants with CP ($p<0.05$) but not between participants with CP who had mild/moderate versus severe spasticity ($p>0.05$). The relaxation index was not a sensitive measure ($p>0.05$ between most study groups). We conclude that the pendulum test is a valid tool for assessing spasticity in persons with CP and that the first swing excursion is the most sensitive outcome measure.

Cerebral palsy (CP) is a disorder of muscle tone, posture, and movement (Wilson 1991), of which the spastic type is most common (Eicher and Batshaw 1993). The term 'spasticity' encompasses an array of neuromuscular symptoms; however, a widely accepted definition of 'spasticity' is 'a motor disorder characterized by a velocity-dependent increase in tonic stretch reflexes (muscle tone) with exaggerated tendon jerks, resulting from hyperexcitability of the stretch reflex, as one component of the upper motor neuron syndrome' (Lance 1980, p 485). Because the management of CP frequently includes interventions to reduce spasticity (e.g. surgery, physical therapy, drugs, electrical stimulation), the ability to quantify accurately the presence and/or severity of spasticity is important in making treatment decisions and evaluating the results. Spasticity is typically assessed by measuring resistance to passive joint motion. It should be remembered, however, that factors such as central reflexes and biomechanical restraint from muscle or connective tissue may contribute to the perceived resistance.

Clinically, spasticity is commonly assessed by numerically ranking the resistance to passive joint motion felt by the examiner, using the Ashworth scale (Ashworth 1964, Bohannon and Smith 1987, Peacock and Staudt 1991). Using this scale, researchers have been able to document substantial reductions in spasticity resulting from surgical and some pharmacological interventions (Ashworth 1964, Albright et al. 1991, Peacock and Staudt 1991, Campbell et al. 1995). It has not been found useful, however, in quantifying lesser changes (Brar et al. 1991), and it can be difficult to distinguish between mild spasticity and subtle voluntary interference during the test (McPhail and Kramer 1995).

The pendulum test is a biomechanical method of evaluating muscle tone by using gravity to provoke muscle stretch reflexes during passive swinging of the lower limb. Wartenberg (1951) developed it as an objective, diagnostic test of muscle tone at the knee. During the test, a person may lie supine or sit on a table with the legs hanging freely. The effects of position and of right versus left leg contribute very little to variability in healthy individuals (Brown et al. 1988a). To perform the test, the examiner lifts the relaxed lower limb to a horizontal position, extending the knee against gravity, and releases the limb, letting it fall and swing freely. In unaffected individuals, the observed pattern of the swinging limb, typically quantified using an electrogoniometer, has been described as smooth, regular, and like that of a damped pendulum. Irregularities in the characteristic motion of the swinging limb and a decrease in the number of oscillations have been observed in the presence of spasticity (Wartenberg 1951).

The advantages of using the pendulum test are that it (1) is non-invasive; (2) is easy and quick to use; (3) is specific to the quadriceps, an important muscle for functional activities; (4) is simple in nature and not intimidating to young children and individuals with cognitive impairment; and (5) has been validated in healthy adults (Brown et al. 1988a). Good reliability of the pendulum test can be achieved when rest intervals of 15 seconds are allowed between maneuvers (Bohannon 1987), but when the interval is less, decreased muscle tone has been observed (Bajd and Bowman 1982). The test's accuracy depends upon the participant being relaxed and inhibiting voluntary muscle contractions, which can interfere with the limb's freedom to swing (Wartenberg 1951; Brown et al.

1988a, b). Electromyographic (EMG) assessment (Bajd and Bowman 1982, Bajd and Vodovnik 1984) and the phase plane diagrams of angle versus angular velocity data (Brown et al. 1988a, b) are useful for assessing relaxation in individuals without CP, by detecting voluntary input.

The pendulum test has been used to assess knee muscle spasticity in patients with neurological disorders including spinal cord injury (Boczko and Mumenthaler 1958, Bajd and Bowman 1982, Bajd and Vodovnik 1984, Robinson et al. 1988), cerebral vascular accidents (Brown et al. 1988b), intracranial lesions (Bohannon 1987), and multiple sclerosis (Brar et al. 1991). The number of oscillations, test duration, and the amplitude of the first backward swing were found to be quantifiable, comparable indicators of spasticity (Boczko and Mumenthaler 1958). In addition, a relaxation index, defined as the ratio between the magnitude of the first backward swing and the magnitude of the difference between the starting angle and resting angles of the knee, was developed to eliminate the effect of different resting angles in different patients, or in the same patients on different testing days (Bajd and Vodovnik 1984). This index has been reported to be a good indicator of spasticity (Bajd and Bowman 1982, Bajd and Vodovnik 1984, Brown et al. 1988b, Robinson et al. 1988, Jamshidi and Smith 1996). Using these indices of the pendulum test, a reduction in spasticity has been documented after drug treatment (Boczko and Mumenthaler 1958), surface electrical stimulation to the quadriceps muscle (Robinson et al. 1988), and ‘dermatome stimulation’ (Stefanovska et al. 1991) in patients with spinal cord injury. Using a modification of the pendulum test, Brar et al. (1991) found decreased spasticity in patients with multiple sclerosis treated with oral baclofen. Those authors measured joint angle by attaching the lower limb to the moving arm of an isokinetic testing device, using methods similar to those of Bohannon and Larkin (1985).

The use of the pendulum test to assess spasticity has been limited to adult-onset neurological disorders. CP, however, is a ‘developmental disorder affecting the total development of the child, either directly, relating to sensorimotor function, or indirectly through associated problems’ (Wilson 1991, p 30). Perinatal brain damage has different effects on reflexes (Mykelbust 1990, Leonard 1994) and on voluntary motor behavior (Leonard 1994) from those of adult-onset brain damage. We do not know of any studies that have used the standard pendulum test to assess spasticity in persons with CP. Although Lin et al. (1994) reported using the Wartenberg pendulum test to assess spasticity in children with CP, those authors elicited knee motion by the non-standard methodology of tapping the quadriceps tendon with a hammer. Our purpose in this study was to determine which parameters from the pendulum test – (1) excursion of the first backward swing, (2) relaxation index, (3) number of oscillations, and/or (4) duration of oscillations – are sensitive to variation in spasticity in patients with CP. We compared these outcome measures in participants with and without CP. Our findings can be used to develop a method of assessing the effect of treatment on spasticity in patients with CP.

Method

PARTICIPANTS

Individuals with CP were recruited from the Center for Cerebral Palsy clinics or local clinicians. Participants without CP were recruited from friends and family of staff members. The approval of the Human Subjects Protection Committee at the University of California Los Angeles was obtained before any participants were enrolled. Informed, written consent was obtained from all participants and from the parent(s) or guardian(s) of children who met the requirements for inclusion.

Quadriceps muscle tone was assessed using a modified version of the Ashworth scale (Ashworth 1964, Bohannon and Smith 1987, Peacock and Staudt 1991). Participants with CP were classified into three groups (Table I), according to the quadriceps spasticity: (1) normal tone (CP–N), (2) mild or moderate spasticity (CP–M), and (3) severe spasticity (CP–S). Ten individuals without CP served as controls. All participants met the following criteria: (1) had good general health, (2) were at least 7 years old, (3) could understand and follow simple verbal instructions, and (4) had not had any surgical procedures on the lower extremities in the previous 6 months. Participants with CP were not being treated medically (e.g. with baclofen or botulinum toxin) and had not previously been surgically treated specifically for spasticity (e.g. by selective posterior rhizotomy).

INSTRUMENTATION/TESTING PROTOCOL

The data acquisition system consisted of an analogue-to-digital board and computer with customized software. The electrogoniometer consisted of a potentiometer attached to both a stationary and a moving arm. The moving arm slid within a

Table I: Characteristics of participants with cerebral palsy and control participants

Group	*Diagnosis*	*N*	*Mean age (y)*	*Range (y)*	*Modified Ashworth score*[a]	*Description*
Control	–	10	13.8	7.6–32.3	1	Normal: no resistance to passive joint motion
CP–N	Diplegia	7	15.9	7.5–39.4	1	Normal: participants with CP who had no resistance to passive joint motion
	Hemiplegia	3				
CP–M	Diplegia	10	13.0	8.5–23.0	2 or 3	Mild or moderate: resistance to movement through most of the range of motion
CP–S	Diplegia	6	23.0	7.3–50.1	>3	Severe: resistance to movement; passive movement is difficult
	Quadriplegia	4				

CP, participants with cerebral palsy; CP–N, normal quadriceps tone; CP–M, mild or moderate spasticity of quadriceps; CP–S, severe spasticity of quadriceps.

[a] See Peacock and Staudt 1991; scores are taken directly from this paper.

precision-milled encasement that allowed the center of the potentiometer to maintain alignment with the center of the knee joint.

The participant was seated in a semireclined position to obtain a hip joint angle between 50° and 70° of flexion to minimize the effects of possible hamstring tightness (Fig. 1). All participants wore shorts and were barefoot. The medial hamstring and vastus lateralis muscles were assessed by surface EMG during the pendulum test to ensure the participant was relaxed. Before the electrodes were applied, the skin was shaved if necessary and cleaned and lightly abraded with an alcohol wipe. Two disposable silver–silver-chloride electrodes were applied over each muscle. A reference electrode was placed over the patella. The electrodes were hardwired to a lightweight connector box and the signal was differentially amplified and sent to a personal computer via a fiber-optic cable (Konigsberg Instruments, Incorporated, Pasadena, California). The data were then sampled at 1 kHz and high pass filtered (40 Hz).

The arms of an electrogoniometer were taped to the lateral aspect of one lower limb – the right one unless the participant reported discomfort or recent injury of that limb. All participants with hemiplegia had right-side involvement. The axis of rotation was aligned with the center of the knee joint, and the stationary and moving arms were taped securely to the midline of the thigh and shank, respectively. The equipment was calibrated by recording voltages at various positions throughout each participant's knee range of motion in order to convert volts to degrees.

A pillow was placed behind the participant's head to promote comfort and relaxation. Padded straps were secured around the waist and the distal thigh to prevent movement during testing. The participant was asked to relax and sit quietly to assure success of the pendulum test. The investigator held the participant's heel and extended the knee from its resting position, at approximately 90°, to the point of maximum passive knee extension (or, for participants with spasticity, the onset of increased passive knee tension). The heel was released and the lower leg allowed to drop into flexion (see Fig. 1). The knee flexed after being dropped and then continued to oscillate at lesser excursions until it came to rest. The participant's relaxation was determined by: (a) an absence of visible movement or muscle contraction; (b) in the unaffected participants, an absence of EMG activity; and (c) in participants with CP, EMG bursts occurring only during muscle lengthening. A 15-s rest interval followed each pendulum test. The tests were repeated until at least four successful trials were obtained.

DATA ANALYSES

For all trials that appeared successful during data collection, the EMG data were carefully examined to determine (for all the participants) that there was no increase over baseline activity and (for the participants with CP) that the EMG signals observed occurred as a response to stretch, i.e. during knee flexion for the vastus lateralis and knee extension for the medial hamstring. Trials in which EMG signals were observed during muscle shortening, indicating voluntary activity, were excluded from further analysis.

For the unaffected participants, we created phase plane diagrams of angle (degrees) versus angular velocity data (degrees/second) (Fig. 2). A uniform 'whirlpool' pattern is associated with healthy individuals, and voluntary input is detected as aberrations in the concentric pattern (Brown et al. 1988a, b). Trials showing evidence of voluntary interference were eliminated from further analysis. This method is not helpful to determine relaxation in participants with CP, as the involuntary effects of spasticity upon the limb can also cause aberrations in the phase plane diagram.

The following outcome measures were obtained from the

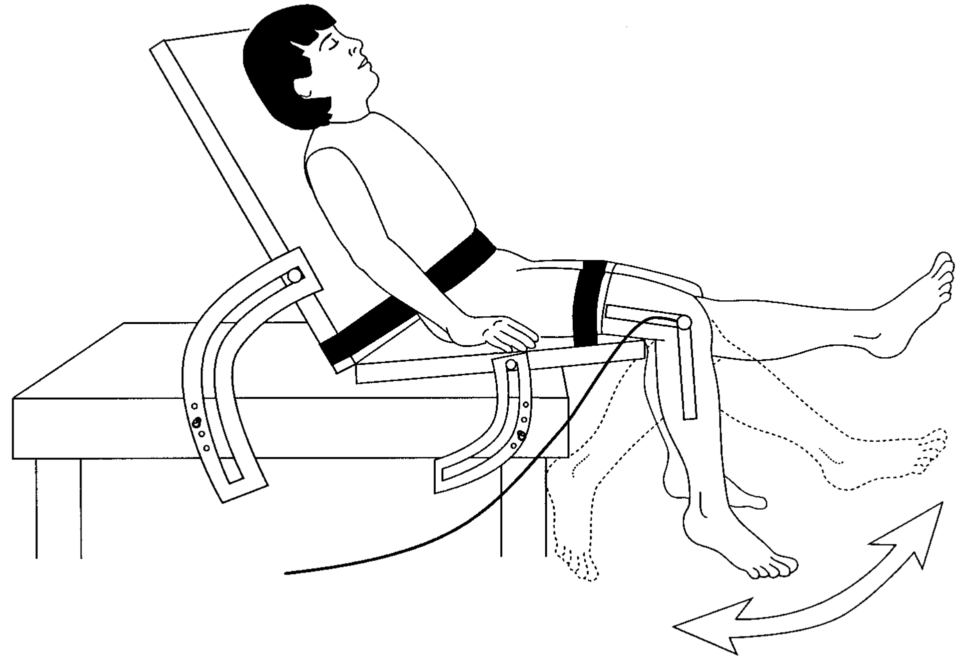

Figure 1: *Positioning of participant, placement of electrogoniometer, and right limb movement observed during pendulum test.*

goniometric data for each pendulum test, and data are presented in Figure 3. (1) The first swing excursion was the difference between the starting angle and the first angle of reversal of the swinging limb. The starting angle was the position at which the examiner released the participant's heel. (2) The number of oscillations was determined by counting the maxima of the sinusoidal waves produced by the swinging limb after the heel was released. The criterion for each oscillation was a displacement of at least 3° towards extension. (3) The duration of oscillations was determined as the duration of the pendulum swings, in seconds, from release of the lower limb to the end of the final oscillation determined by criterion 2 above. (4) The relaxation index (RI) was calculated as follows: $\mathrm{RI}=\theta_1/\theta_r$ = (starting angle – first angle)/(starting angle – resting angle) (see Fig. 3).

The resting angle was the knee joint position maintained after oscillatory movement had ceased. A mean was obtained for each participant for each outcome measure. The data were analyzed statistically using a one-way analysis of variance. Post hoc analyses were performed using the Student–Newman–Keuls method. Differences at the level $P<0.05$ were considered statistically significant.

Results

Qualitative differences can be observed in goniogram tracings from participants representing each of the four different groups (see Fig. 3). The characteristic pattern of at least six

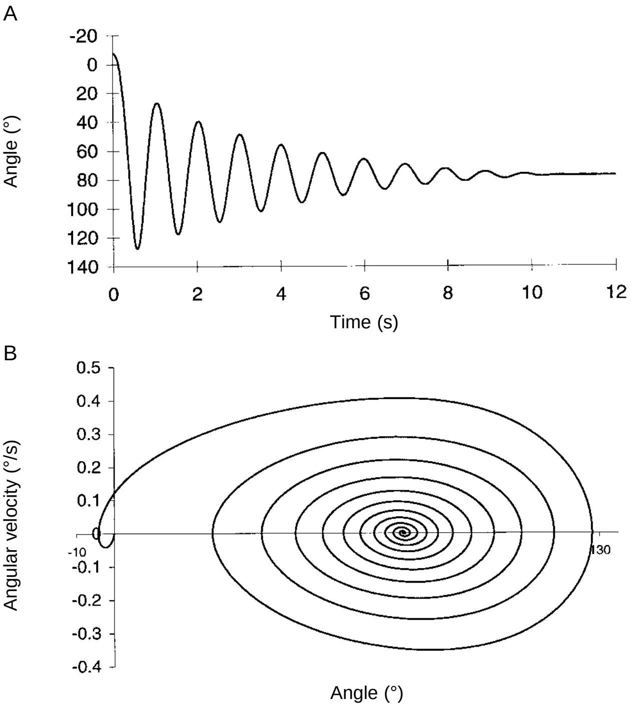

Figure 2: *(A) Goniogram tracing of a pendulum test for an unaffected participant (without CP). (B) Corresponding phase plane diagram exhibiting the typical 'whirlpool' pattern associated with relaxed unaffected participants.*

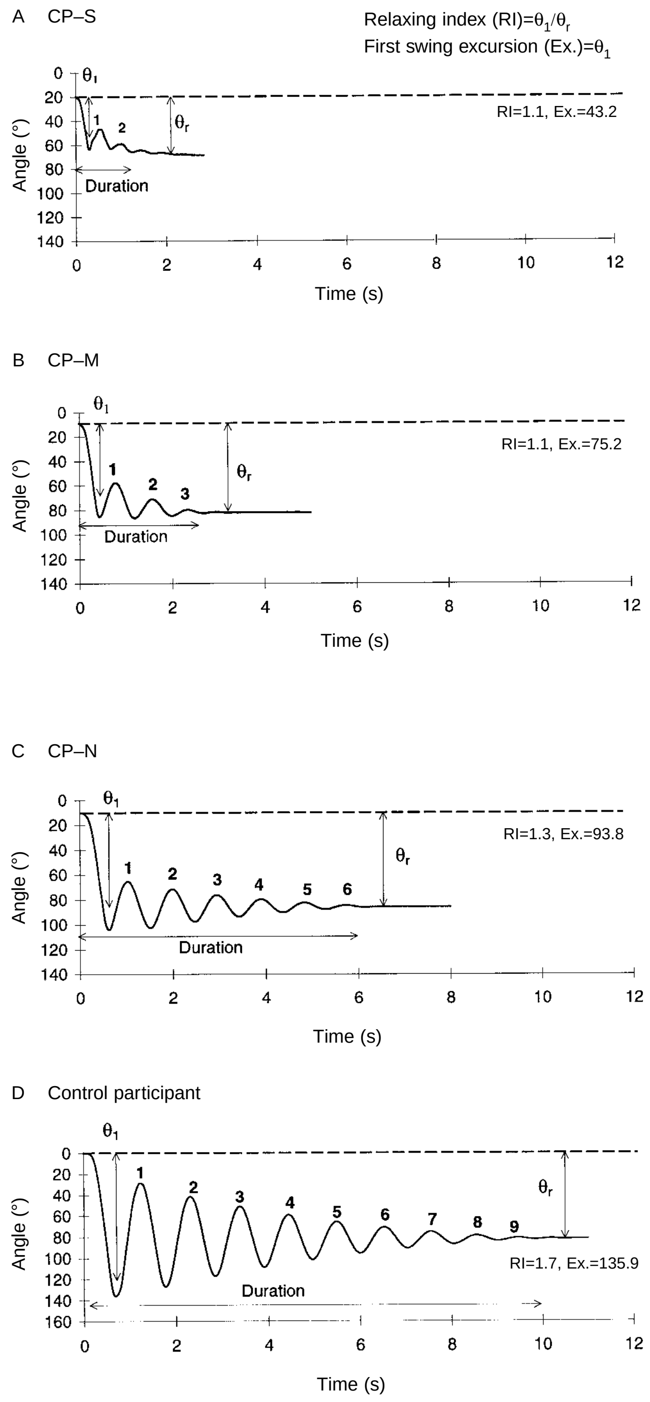

Figure 3: *Data depicting the first swing excursion, number and duration of oscillations, and relaxation index in the goniogram tracings from participants representing the four participant groups. With the exception of the relaxation index, values of outcome measure consistently increased with decreasing muscle tone. CP–N, normal quadriceps tone; CP–M, mild or moderate spasticity of quadriceps; CP–S, severe spasticity of quadriceps (as assessed on Ashworth scale).*

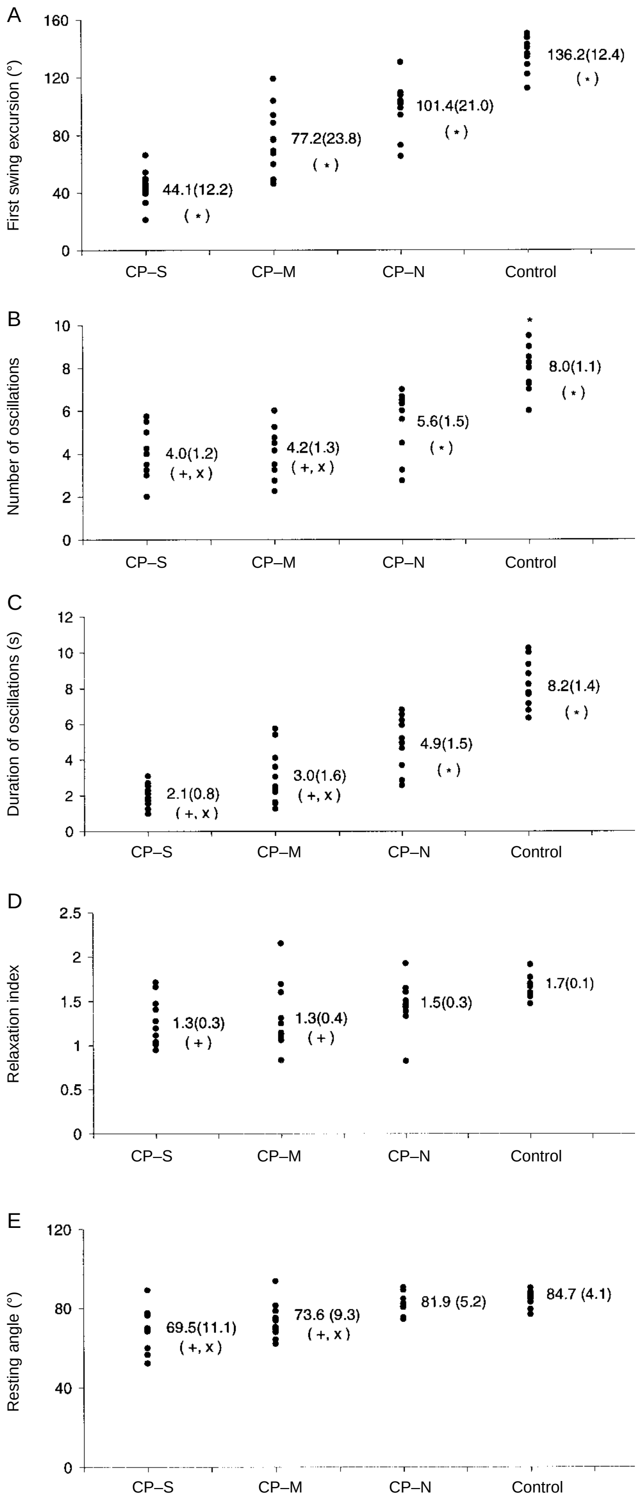

Figure 4: *Individual data for each participant are shown for all outcome measures. Mean (SD) is reported for each group. CP–N, normal quadriceps tone; CP–M, mild or moderate spasticity of quadriceps; CP–S, severe spasticity of quadriceps (as assessed on Ashworth scale). Statistically significant differences (at $P<0.05$ level): *, between each group; +, between control group and this group; X, between CP–N group and this group. First swing excursion was most sensitive measure as it was significantly different between each participant group.*

incrementally decreasing oscillations observed for control participants was not observed for most participants with CP.

FIRST SWING EXCURSION

A statistically significant difference in mean first swing excursion was found between all the groups of participants.

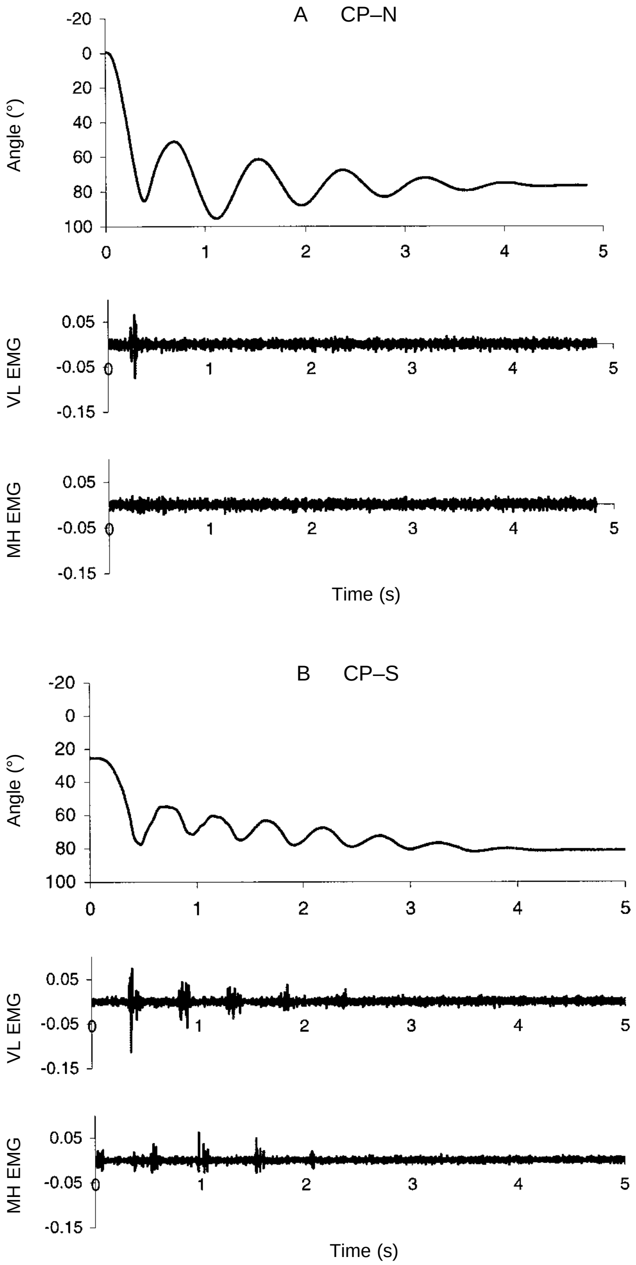

Figure 5: *Goniogram (top) and EMG tracings (bottom). (A) Participant with CP and normal quadriceps tone assessed on the Ashworth scale: a quadriceps EMG burst, in response to stretch, was observed during the first downward swing. (B) Participant with CP and severe quadriceps spasticity on the Ashworth scale. Quadriceps and hamstring EMG bursts were observed, in response to stretch, for most oscillations.*

The first swing excursion was greatest in control participants and lowest in the CP–S group (Fig. 4A). Most of the control participants had initial first swing excursions of more than 130° from the horizontal, while most participants in the CP–S group had less than 50°.

NUMBER AND DURATION OF OSCILLATIONS

The mean number and duration of oscillations decreased with increasing muscle tone (see Fig. 3; Fig. 4B,C). The control participants had a significantly larger number and longer duration of oscillations than any of the groups with CP (see Fig. 4B,C). The CP–N group had a significantly larger number and longer duration of oscillations than the participants in the CP–M and CP–S groups. The latter two groups did not differ significantly; in fact, some participants with severe spasticity had more and longer-lasting oscillations than many participants with mild to moderate spasticity. Several participants in the CP–S group exhibited repeated, rapid oscillations similar to the movement of a bouncing ball. Quadriceps and hamstring EMG bursts were observed during muscle lengthening for most of the oscillations, implying that the lower velocities of stretch during oscillations beyond the first swing were sufficient to elicit additional stretch reflexes (Fig. 5B). In contrast, most participants in the CP–N and CP–M groups exhibited quadriceps EMG signals during the first swing only, resulting in an overall damping of subsequent oscillations (Fig. 5A).

RELAXATION INDEX

The mean RI in the unaffected participants was significantly higher than in the CP–M and CP–S groups (Fig. 4D) and was slightly but not significantly higher than in the CP–N group. Two participants in the CP–S group and three in the CP–M group exhibited normal RI values of at least 1.6 despite a decreased number and duration of oscillations, and/or decreased first swing excursion. Data (Fig. 6) illustrate how two very different pendulum tests can result in the calculation of similar RIs. The RI is the ratio of the first swing excursion divided by the resting angle. Participants in the CP–M and CP–S groups did not always exhibit gravity-neutral resting angles, even though they had adequate passive range of motion. When the heel of these participants was released, the force of gravity caused the limb to flex beyond this 'resting' angle. Though the first swing excursion was significantly decreased, the RI was within normal limits because the resting angle was also smaller. Because of these unexpected results, we analysed the resting angle and found that it was significantly less in the CP–M and CP–S groups than in the control and CP–N groups (Fig. 4E).

Discussion

First swing excursion was the parameter that quantified the effect of the initial quadriceps stretch and was the most sensitive to differences in muscle tone between the four participant groups. The greatest velocity of musculotendinous stretch occurred during the first downward swing after the heel was released from its highest point, when the effect of gravity was greatest. As spasticity is velocity-dependent, most participants with CP who had 'normal' quadriceps muscle tone, as shown by a modified version of the Ashworth scale (Ashworth 1964, Bohannon and Smith 1987, Peacock and Staudt 1991), were sensitive to this initial stretch and exhibited smaller first swing excursions than the control participants. Other investigators have reported first swing excursion to be a good indicator of spasticity in individuals with spinal cord injury (Boczko and Mumenthaler 1958).

Most researchers have provided minimal data about the number and duration of oscillations. Instead, they have described the first swing in greater detail (Boczko and Mumenthaler 1958, Bajd and Bowman 1982, Bajd and Vodovnik 1984, Bohannon and Larkin 1985), and made general statements about the number of oscillations (Wartenberg 1951; Boczko and Mumenthaler 1958; Bajd and Vodovnik 1984; Bohannon and Larkin 1985; Brown et al. 1988a, b). Boczko and Mumenthaler (1958) used the number and duration of oscillations as a primary outcome measure; however, the limb was released from 45° of knee flexion rather than full extension, preventing direct comparisons of the data. The mean of eight oscillations reported in the present study for unaffected participants was slightly greater than the previously reported averages of five to six (Bohannon and Larkin 1985) and six to seven (Wartenberg 1951, Boczko and Mumenthaler 1958, Bajd and Vodovnik 1984). The difference is probably due to differences in the criteria used to define an oscillation. In the present study, we observed barely perceptible oscillations, e.g. of 1° or 2°, in some participants with spasticity; therefore, we defined an oscillation as a motion of at least 3° towards extension. If others used specific criteria, they did not report them.

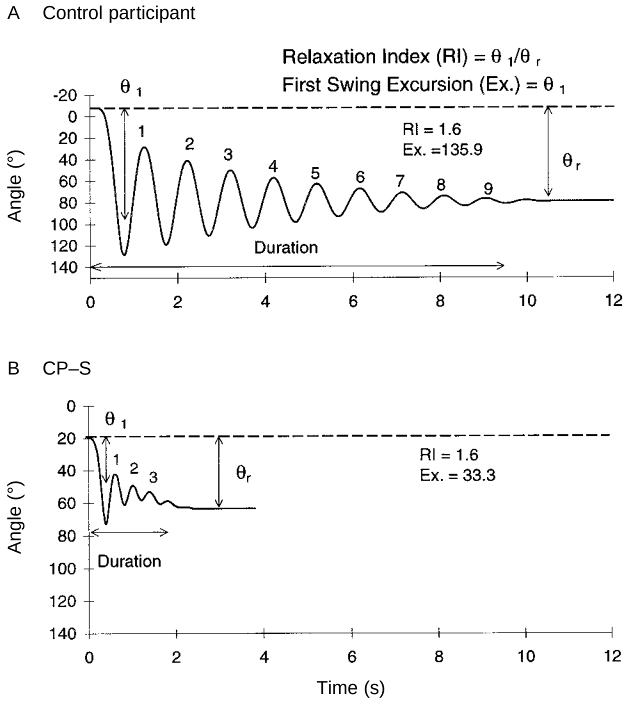

Figure 6: *Goniogram tracing. (A) Unaffected participant with a normal relaxation index of 1.6. (B) Participant with severe spasticity with a normal relaxation index of 1.6 despite decreased number and duration of oscillations and first swing excursion.*

Although the RI has been reported as a reliable outcome measure from the pendulum test, we did not find it so in our participants with CP, and we found that a reduced resting angle was the mathematical explanation. If the limb did not rest in a gravity-neutral position, a small knee extensor moment must have been present. As previously stated, nonvoluntary resistance to joint movement may be due not only to spasticity but also to central reflexes and biomechanical restraint. The centrally mediated tonic labyrinthine reflexes, for example, may have been elicited and recruited knee extensor musculature due to the semireclined trunk position. The effect would have been a constant undetected elevation in our baseline EMG recordings. In contrast, biomechanical restraint is an electrically silent resistance to stretch, due to musculoskeletal abnormalities. Central nervous system insults can result in secondary abnormalities of muscle, tendon, and bone, especially in the growing child (Leonard 1994). Joint contractures are common in persons with CP; however, all of our participants had more than 90° range of motion on passive flexion of the knee. Several participants exhibited a passive knee joint moment due to patella alta. These participants had passive tendinous restraint causing their limb to rest in an antigravity position. The pendulum test was developed and tested using patients diagnosed with adult-onset neurological disorders. Our results indicate that in persons with CP, the use of the RI as an outcome measure can lead to erroneous conclusions about the degree of spasticity.

Some investigators have proposed that passive joint resistance in CP is primarily biomechanical, and is due to 'muscle transformation' of contractile or adjacent non-contractile elements (Berger et al. 1982; Dietz and Berger 1983; Lin and Brown 1992; Lin et al. 1994a, b). Using different methods, Lin et al. (1994a) documented an electrically silent resistance to quadriceps and hamstring stretch in the involved limb of children with the spastic hemiplegic form of CP. Muscle activity recorded during gait also has led researchers to believe that changes in the mechanical properties of muscle fiber are mainly responsible for clinical signs of hypertonia in adults with spasticity (Dietz et al. 1981, Dietz and Berger 1983) and children with CP (Berger et al. 1982, Dietz and Berger 1983).

In the present study, we recorded EMGs for the primary purpose of screening for voluntary interference with the pendulum test. These EMGs, however, indicated that reflexes were elicited. All participants in the CP–S group, six in the CP–M group, and seven in the CP–N group exhibited quadriceps EMG bursts during the first downward swing (see Fig. 5A, B). Participants in the CP–M group not exhibiting quadriceps EMG bursts did exhibit hamstring activity during upward swings (knee extension). While passive biomechanical restraint may have contributed to the damping of pendulum swings, the EMG records indicate that spasticity was elicited.

We were able to distinguish differences between the control group and the CP–N group using the pendulum test method, although all of these participants had normal quadriceps tone on the Ashworth scale. Using that scale, the clinician passively moves the limb as rapidly as possible to feel for resistance. During the pendulum test, the force of gravity can move the limb at a higher velocity, which may be more likely to elicit a quadriceps stretch reflex in persons with mild spasticity. Similarly, when Brown and colleagues used the pendulum test to assess the seemingly unaffected limb in patients who had had cerebral vascular accidents, they observed increased muscle tone even though an Ashworth score had indicated normal tone (Brown et al. 1988b).

The ability to quantify the presence and severity of spasticity is essential to understanding and treating spastic CP. We have shown that the pendulum test is a simple and useful tool for this purpose in the lower extremities of patients with spastic CP. First swing excursion was the most sensitive measure of the degree of spasticity, while the *RI* was not a good indicator in this population. The simplicity and objectivity of the pendulum test, and the basic outcome measures that result, make the pendulum test applicable for clinical use, especially in children with spastic CP, who are often treated to reduce spasticity. We are using this tool at present in research to test the premise that the performance of strengthening exercises will increase spasticity. It may also prove useful as an outcome measure to examine changes in spasticity after systemic interventions, such as intrathecal baclofen or rhizotomy, or after local treatments to the quadriceps musculature, such as botulinum toxin injections or orthopedic surgery.

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Mac Keith Meetings

Management and Treatment of Autism (Closed meeting)
Royal Society of Medicine, London. 20th to 21st March 2000
Organised by G O'Brien

Young Adults with Disability: Where Are the Services? (Open meeting)
Royal Society of Medicine, London. 22nd May 2000
Organised by Richard Morton

Incontinence Management: Practical Aspects of an Important Quality of Life Issue (Open meeting)
Royal Society of Medicine, London. 16th June 2000
Organised by Martin Bax

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