Quantitative assessments of elbow flexor muscle performance using twitch interpolation in post-polio patients: no evidence for deterioration

Gabrielle M. Allen, 1 S. C. Gandevia 1,2 and J. Middleton 3

1 Prince of Wales Medical Research Institute and Departments of 2 Clinical Neurophysiology and
3 Rehabilitation Medicine, Prince Henry and Prince of Wales Hospitals, Sydney, New South Wales, Australia

Correspondence to: S. C. Gandevia, Prince of Wales Medical Research Institute, High Street, Randwick NSW 2031, Sydney, Australia

Summary
A large number of patients previously affected by polio have symptoms, including increased weakness and fatigue, which are collectively known as a post-polio syndrome. Prospective measurements of strength and endurance using twitch interpolation in post-polio patients are lacking and hence the exact rate of decline in muscle function in these patients is not well defined. We therefore measured performance of the elbow flexor muscles twice, at a mean of 2.5 years apart in a group of selected post-polio subjects (Group A, n = 13) and matched control subjects (n = 11), and in a second group of unselected polio patients from a post-polio clinic (Group B, n = 40) at a mean of 1.7 years apart. All subjects performed 10 attempted maximal voluntary isometric contractions of the elbow flexor muscles, during which voluntary activation of the elbow flexor muscles was measured using a sensitive form of twitch interpolation. The first group of selected polio subjects (Group A) and matched control subjects also performed 45 min of submaximal exercise. During this time, at 5-min intervals, maximal voluntary force, voluntary activation and the amplitude of twitch responses to single and paired stimuli were measured in order to investigate central and peripheral components of muscle fatigue. There was no change in the polio patients’ strength, voluntary activation or peripheral muscle endurance between testing sessions, despite an 80% probability of detecting a 2.5% change per year in these variables. The unselected group of patients from the post-polio clinic (Group B) showed no change in maximal voluntary strength or voluntary activation between the first and second test. There was an absence of decline in muscle performance in these polio patients over the test interval, despite a subjective deterioration in muscle function consistent with the ‘post-polio syndrome’. This supports the view that the symptoms of the post-polio syndrome are not due to a progressive neuronal dysfunction.

Keywords: poliomyelitis; twitch interpolation; isometric contraction; fatigue

Abbreviation: MVC = maximal isometric voluntary contraction

Introduction
Post-polio syndrome is a much investigated clinical condition (Dalakas et al., 1995) applied to the symptoms experienced by many patients 20–40 years after their original polio infection (see also Halstead and Rossi, 1985; Dalakas et al., 1986). The syndrome includes symptoms such as a subjective decrease in strength, a subjective increase in fatigue, the presence of new muscle or joint pain and an impairment of the activities of daily living. The diagnosis is largely based on symptoms (Halstead and Rossi, 1987) and, although it is thought to be slowly progressive (Mulder et al., 1972; Wiechers, 1987), the exact rate of its progression is unknown. Several attempts to determine the factors which contribute to the post-polio symptoms have failed to define a specific cause (Dalakas, 1986; Dalakas et al., 1986; Windebank et al., 1995; Stålberg and Grimby, 1995). However, in these studies, although symptoms are often assessed and qualitative assessments of strength made, the exact rate of decline in muscle performance, especially strength and endurance, has not been measured using highly quantitative techniques. Indeed, objective evidence for a decline is, so far, lacking. Routine clinical examination of muscle strength is not sufficiently sensitive to detect small changes in strength (e.g.
Beasley et al., 1961; Gandevia, 1993). Also, measurements of strength with clinical dynamometers, although more accurate than estimates made by clinical examination, do not account for the degree of voluntary drive during the attempted maximal voluntary efforts.

It is clear from neuropathological studies that the polio virus affects motor nuclei throughout the spinal cord (Bodian, 1947; Miller, 1995). Other central structures, including the motor cortex, may also be affected by the virus (Bodian, 1947; see also Bruno et al., 1991). We have previously reported that ~25% of post-polio patients have impaired voluntary activation of their elbow flexor muscles (Allen et al., 1994; Gandevia et al., 1995; see also Beelen et al., 1996), a finding which is consistent with a premotoneuronal abnormality, perhaps involving corticospinal output. Given that the degree of voluntary drive will influence the amount of force produced in an attempted maximal voluntary contraction, it is important, for the accurate detection of changes in muscle performance, to measure this central drive during longitudinal assessments of muscle strength and endurance.

In prospective studies to date, some comparing symptomatic with asymptomatic post-polio patients, the deterioration in muscle strength or endurance has either been undetected or found to be slow in its progression (e.g. Dalakas, 1986; Dalakas et al., 1986; Munsat et al., 1987; Agre and Rodriguez, 1991; Munin et al., 1991; Peach and Olejnik, 1991; Agre et al., 1995; Stålberg and Grimby, 1995; Ivanyi et al., 1996; Windebank et al., 1996). Other parameters related to EMG and analysis of muscle biopsies did not reveal specific characteristics predictive of a decline in muscle function in a polio group (e.g. Daube et al., 1995). For example, in the prospective study (over 5 years) by Windebank et al. (1995), no marked changes were detected in electrophysiological variables (e.g. the amount of jitter and blocking on single-fibre EMG), although there was clear evidence of ongoing denervation and reinnervation. Stålberg and Grimby (1995) showed that the amplitude of the macro motor-unit potential increases and fibre area decreases with time, but the findings in any one patient did not predict whether or not that particular patient would develop a decrease in muscle function (i.e. strength or endurance) as measured by isokinetic and isometric dynamometers. These results may reflect the relative insensitivity of the tests used to assess muscle function. It remains to be determined whether a quantitative technique can reveal such a change in muscle performance.

In the present study a sensitive version of the twitch-interpolation technique was used to measure both strength and endurance in post-polio subjects 2.5 years after original assessments of their strength and endurance (Allen et al., 1994). The polio subjects (Group A) were screened and they were excluded if they had any pathology other than previous polio. All of these polio subjects had some symptoms of the post-polio syndrome (Halstead and Rossi, 1987). To obtain a more representative picture of the polio population, a second group of unselected patients was studied from a post-polio clinic (Group B), but these patients were not excluded if they had other pathology. Voluntary strength and the level of voluntary activation of the elbow flexors were assessed in a follow-up study of Group B patients at a mean of 1.7 years after their first testing session. In this group of patients all reported some symptoms consistent with the diagnosis of the post-polio syndrome.

**Methods**

**Subjects**

**Selected polio subjects (Group A)**

The first group of polio subjects (Group A: n = 14; nine females, five males; see Table 1) had been previously tested with an identical protocol a mean of 2.5 years before (range 2.0–3.0 years; Allen et al., 1994). In the initial study these polio subjects (and the control subjects) were screened, using general, neurological and psychological evaluations, and excluded if they had any other pathology (e.g. asthma, hypertension). In their initial assessment, 11 of the 14 polio subjects were given the clinical diagnosis of post-polio syndrome by an independent rehabilitation physician using the criteria defined by Halstead (Halstead and Rossi, 1987), but without knowledge of results of the muscle tests.

At follow-up, all polio subjects were interviewed and examined by a rehabilitation physician (one of the two who undertook all the original assessments) who confirmed the absence of other major pathology. All patients completed a detailed questionnaire about symptoms and recent changes related to EMG and analysis of muscle...of a decline in tests. In their second assessment, none of the polio subjects reported resolution of their previous symptoms (such as increased fatigue, weakness and pain). When reviewed, 13 of the 14 polio subjects had symptoms consistent with the post-polio syndrome (i.e. two had developed these symptoms since the first test). The last polio subject remained in the subgroup which had a history of polio but did not fulfill the criteria for the post-polio syndrome. Only three of eight polio subjects in this group who were in the original study (see Allen et al., 1994) performed the follow-up study.

Of the 13 polio subjects with symptoms of the post-polio syndrome in their second assessment, six felt that their symptoms were relatively stable as a result of lifestyle changes designed to minimize their symptoms. The muscle performance in these two subgroups of polio subjects (i.e. ‘progressive’ versus ‘stable’ symptoms) was compared. In addition, the changes in muscle performance in these polio subjects as a group were compared to those of the original age- and sex-matched control group who were also reassessed after 2.5 years (n = 11; six females, five males; see Table 1; Allen et al., 1994).

**Unselected polio subjects (Group B)**

The second, unselected, group of polio subjects (Group B) consisted of patients who were referred from a post-polio...
Strength change in post-polio patients

Approximately two-thirds of these Group B patients had attended the post-polio clinic because they had noticed new symptoms consistent with the post-polio syndrome and the remainder attended the clinic concerned about a possible future deterioration in function. However, when interviewed all reported some symptoms of the post-polio syndrome. Eleven of these patients had one or two of the key symptoms associated with the syndrome (i.e. increased pain, increased weakness, increased fatigue or a reduction in the activities of daily living). The remaining 29 subjects had three or four of these symptoms.

Patients from the post-polio clinic were also studied twice, at a mean of 1.7 years apart (range 0.6–2.4 years), and only performed tests of strength and voluntary activation. Data for age, height, weight and muscle function in these patients are shown in Table 1 (Polio, Group B). All testing procedures were approved by the local ethics committee and all subjects gave informed consent.

### Table 1 Characteristics of subjects (data from second test)

<table>
<thead>
<tr>
<th></th>
<th>Control subjects</th>
<th>Polio patients (Group A)</th>
<th>Polio patients (Group B)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Male (n = 5)</td>
<td>Female (n = 6)</td>
<td>Male (n = 5)</td>
</tr>
<tr>
<td>Age (years)</td>
<td>52 ± 6</td>
<td>51 ± 7</td>
<td>53 ± 8</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>174.9 ± 3.6</td>
<td>166.4 ± 3.3</td>
<td>169.0 ± 8.5</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>69.1 ± 7.1</td>
<td>65.0 ± 4.0</td>
<td>83.1 ± 16.2</td>
</tr>
<tr>
<td>MVC (N m)</td>
<td>66.4 ± 6.4</td>
<td>44.1 ± 7.4</td>
<td>63.8 ± 13.8</td>
</tr>
<tr>
<td>Twitch amplitude (Nm)</td>
<td>9.0 ± 1.9</td>
<td>6.7 ± 1.2</td>
<td>8.3 ± 4.1</td>
</tr>
<tr>
<td>Voluntary activation (%)</td>
<td>Median</td>
<td>97.6</td>
<td>92.5*</td>
</tr>
<tr>
<td></td>
<td>Interquartile range</td>
<td>97.2–97.8</td>
<td>91.9–94.2</td>
</tr>
<tr>
<td></td>
<td>Full range</td>
<td>96.9–97.8</td>
<td>89.0–94.7</td>
</tr>
<tr>
<td>Cases with median &lt;92%</td>
<td>0/5</td>
<td>0/6</td>
<td>2/5</td>
</tr>
</tbody>
</table>

*Significant difference in means between polio and control subjects.

Clinic for tests of muscle performance (n = 40; 19 females, 21 males). These patients were studied because of the selection bias in the choice of polio subjects for Group A, in whom there was no additional pathology which may have contributed to their symptoms. Although patients in Group B were also screened extensively, they were not excluded from the study if they had other pathology (such as hypertension or asthma), but they were excluded if they had other major pathology affecting the tested limb (e.g. trauma). Patients with severe psychiatric disturbances were not referred for the tests of muscle performance. Of all patients attending the post-polio clinic <5% were excluded.

The elbow flexor muscles were tested in all subjects. Although polio may have had marked effects on the lower limbs in many of these patients, we studied the upper limb to look for a global change in muscle performance as it is known that the original polio infection affects most motor nuclei (Bodian, 1947). This is also indicated by the extensive changes in single-fibre EMG and muscle biopsies (Dalakas, 1988; Ravits et al., 1990; Luciano et al., 1996). In addition, we chose to study the upper limb as a number of other changes secondary to the original effects of polio render strength changes in the lower limb difficult to interpret, (e.g. scoliosis, orthopaedic surgery to the lower limbs and caliper use). Many of these patients actually had clinical and historical evidence for original involvement of the upper limb.

Maximal elbow-flexor torque was assessed with the elbow flexed at 90° and the fully supinated forearm attached to an isometric myograph by a strap at the wrist (usually the dominant arm unless this could not be tested). Torque was measured by a load cell (see Allen et al., 1995). Each subject performed 10 brief, maximal isometric voluntary contractions (MVCs), 2–3 s in duration and separated by 1 min to avoid fatigue. During these efforts, the subjects were encouraged verbally and given visual feedback to encourage maximal performance. At the peak force during each attempted maximal effort (see Fig. 1) a supramaximal electrical stimulus was delivered through surface electrodes (saline soaked, gauze covered aluminium, 1×1 cm) which were positioned over biceps brachii and brachioradialis (for details, see Allen et al., 1994). The cathode was positioned over the motor point of the muscle and the anode over the distal tendon. Stimuli (100 μs duration and 100–300 mA stimulus intensity) were delivered through a modified Digitimer DS7 stimulator (Digitimer Ltd, Welwyn Garden City, Herts, UK). Five seconds after the first stimulus an additional stimulus was delivered over the relaxed muscle to evoke a ‘control’ twitch potentiated by the previous contraction (McKenzie et al., 1992). The reliability of measurements made with these procedures is high (i.e. for five subjects tested on five different days intraclass correlation coefficients for voluntary activation, MVC and twitch amplitude were 0.86, 0.99 and 0.97, respectively; Allen et al., 1995).

Increments in torque evoked by the stimulus during the maximal efforts were measured by a sample-and-hold amplifier (Hales and Gandevia, 1988). To calculate the level of voluntary activation any increment produced by the stimulus during the maximal effort was expressed as a fraction of the amplitude of the response evoked by the same
Statistical analysis

All data are displayed as mean ± SD except voluntary activation data which are not normally distributed and are therefore presented as median and interquartile range. Comparisons between maximal voluntary force and twitch amplitude in the first and second tests were made with paired Student’s t tests. Based on the standard variability of the results from control subjects in the first study, a power calculation was performed to determine the percentage change that could be detected in 1 year with a probability of 80% for maximal voluntary force, and voluntary activation; it was possible to detect a 2.5% change per year. However, twitch amplitudes were more variable between subjects and between tests (Allen et al., 1995) and therefore only a 12% change per year in twitch amplitude was detectable with an 80% probability. Changes in voluntary activation between first and second tests were assessed by Wilcoxon signed-ranks test. Associations between parametric variables were assessed using Pearson’s correlations and non-parametric associations were assessed using Spearman’s rank correlations.

Differences between maximal voluntary force and twitch amplitude in polio (Groups A and B) and control subjects in the first study were assessed by analysis of variance. Analysis of variance was also used for the comparison of the change in muscle performance between the subgroups of polio subjects in Group A. Voluntary activation in polio subjects (Group A) was compared with that in control subjects by Mann–Whitney rank test. From laboratory data for control subjects, the lower 95% confidence limit for the median level of voluntary activation was set at 92% (see Gandevia et al., 1995). Post-polio clinic patients with median voluntary activation below this level were considered abnormal. Statistical significance was set at the 5% level.

Results

Table 1 summarizes the post-polio and control subjects. Females previously affected by polio in the selected group (Group A) had significantly lower height and weight than the control female subjects. This reflects the reduced stature and atrophy of lower limbs in some polio subjects. Male polio subjects in the selected group (Group A) were well matched to the control subjects. The unmatched post-polio clinic patients (Group B) were also of similar age, height and weight to the control subjects.

Follow-up studies on selected polio subjects (Group A)

Voluntary activation and strength in unfatigued muscles

Figure 2 illustrates the maximal strength and voluntary activation of the elbow flexors without the influence of fatigue from the first group of selected post-polio subjects (Group A) and matched control subjects. The maximal

stirnulus in the relaxed muscle. This was subtracted from 1 and converted to a percentage (see Fig. 1; Bellemare and Bigland-Ritchie, 1984; McKenzie et al., 1992). If small increments in torque were produced by the interpolated stimuli then not all motor neurons were recruited or they were not firing at fusion frequencies.

The first group of selected polio subjects (Group A) and matched control subjects also performed 45 min of submaximal exercise (see Allen et al., 1994). This consisted of repeated contractions at 30% of each subject’s individual maximal force (6 s contraction, 4 s relaxation). At 5-min intervals during the exercise a maximal voluntary contraction was performed. During the effort, at the peak force, paired stimuli (10 ms interval) were delivered over the muscle to determine voluntary activation. Following this contraction, paired and single stimuli were delivered over the relaxed muscle during the rest periods between the subsequent submaximal voluntary contractions. This protocol enables maximal voluntary force, the level of voluntary drive (and thus ‘central’ fatigue) and peripheral force generating capacity (amplitude of the responses to paired and single stimuli) to be monitored during the 45 min of exercise. This submaximal exercise, aimed to assess muscle endurance is especially designed to mimic the normal level of exercise required to carry out the activities of daily living and therefore to stress excitation–contraction coupling, rather than to cause fatigue via ischaemia (Vøllestad et al., 1988). Perceived effort was measured just prior to each maximal voluntary effort at 5-min intervals using a modified Borg scale ranging from 0 (infinitesimally small amount) to 10 (extremely large amount: maximal; see Lloyd et al., 1991; Allen et al., 1994).
follow up assessment. Those polio subjects who were affected more severely initially (i.e. affected in all four limbs or who had been mechanically ventilated) did not have a greater change in muscle strength over the testing interval than those who were less severely affected initially. Five polio subjects had a decrease in strength which was >10% and in two of these subjects, the decrease in strength occurred despite a slight increase in voluntary activation. In the other three subjects voluntary activation decreased only 1.1%, 2.0%, and 4.0%, while in these subjects there were decreases in strength of 13%, 15% and 16%, respectively.

Endurance study

Data from the endurance study in the selected polio subjects (Group A) and the matched control subjects are shown in Fig. 3. The decline in maximal voluntary torque across the 45 min of exercise was not significantly different in the first compared with the second test in male or female polio subjects or the male control subjects. These results occurred despite reports by all the polio subjects and some control subjects of a subjective deterioration in muscle function over the 2.5 years between the studies. However, the maximal voluntary torque decline during the endurance test in the control female subjects was slightly greater in the second test ($P = 0.032$). This occurred despite there being no difference in the decline in voluntary drive across the 45 min between the polio and control subjects ($P = 0.310$).

When the peripheral force-generating capacity of the muscle was considered by comparing the decline in twitch amplitude in the two endurance tests, there was also no evidence for a deterioration in this aspect of the polio subjects’ muscle function. For example, in male polio subjects the amplitude of the response to a single stimulus declined to 63.0 ± 12.0% of the initial value at the end of the first endurance test and to 66.8 ± 16.3% of the initial value in the second test ($P = 0.210$; see Fig. 3). However, the amplitude of the response to single and paired stimuli is more variable than maximal voluntary torque and voluntary drive when tested on different days (Allen et al., 1995).

Deterioration in muscle performance was not augmented in those patients who had impaired endurance or voluntary activation in the initial assessment (those patients with median voluntary activation <92% and a decline in the response to the single stimulus during the submaximal exercise of >50%). In these polio patients (four out of 14, Group A), the largest change in strength, voluntary activation or muscle endurance was a 13% decrease in maximal voluntary force. This occurred in the oldest polio subject (72 years) and was possibly enhanced by the decrease in strength which is associated with ageing (Brooks and Faulkner, 1994). However, for all patients there was no correlation between age and voluntary activation.

Given that 13 of these 14 polio patients had reported symptoms associated with the post-polio syndrome, it was impossible to examine statistically whether deteriorating voluntary torque in the polio females was lower than in the control females (32.7 ± 4.8 Nm polio, 44.1 ± 7.4 Nm control; $P = 0.003$) which confirms the findings in our previous study (Allen et al., 1994). Voluntary activation was significantly lower in male polio subjects (range of median values from 10 MVCs: 89.0–94.7% polio, 96.8–97.8% control; $P < 0.05$) and female polio subjects had decreased voluntary activation, although this was on the borderline for statistical significance (range of medians: 78.0–98.7% polio, 94.3–99.5% control; $P = 0.052$). For this group of subjects, neither the level of voluntary activation, the amplitude of the resting twitch, nor MVC torque changed during the 2.5 years between the two tests (see Fig. 2).

These results were obtained despite the clinical diagnosis of post-polio syndrome in 13 of the 14 subjects in their
Unselected post-polio clinic patients (Group B)
Voluntary activation and strength in unfatigued muscles

These post-polio clinic patients were studied to avoid the potential bias in the Group A patients whose selection was based on the absence of other pathology which could explain their symptoms. Data from the clinic group of patients (Group B) are shown in Fig. 4. Their maximal voluntary strength covered a wide range (14.5–49.3 N m in females; 3.8–90.1 N m in males). Nineteen patients (10 females, nine males) reported that they were initially affected in the tested arm (see Fig. 4B). Based on our normal lower limit of voluntary activation (median 92%; see Methods), seven patients had impaired voluntary drive to their elbow flexor muscles in both assessments. Five patients had markedly reduced strength in their elbow flexor muscles (<20 Nm in females, <35 Nm in males). Despite variations in the performance of individuals between the testing sessions (especially for the maximal voluntary torque in females, see Fig. 4A), even in this unselected ‘clinic’ group there was no overall decline in the level of maximal voluntary force over 1.7 years. In addition, the level of voluntary drive over this time did not decline, even in those patients with initially impaired voluntary drive. The median level of voluntary activation in those patients with reduced drive on their first assessment was 64.5% and on their second test was 70.5%. There were no significant differences in the amplitude of the twitch responses (without the influence of fatigue) between the two tests (change in males = –5.5 ± 23.2%, change in females = –0.3 ± 29.9%).

Two patients showed a decrease in maximal voluntary force which was >10% (see asterisks in Fig. 4A). The level of voluntary drive was similar in the first and second test in these two patients (medians 94.8% and 98.7%, respectively, in the first test; medians 94.1% and 98.7%, respectively, in the second test) and thus their decline in force must reflect peripheral factors. The presence of weak elbow flexor muscles did not predict a change in muscle function in the group of patients (see also Fig. 4B). All of these patients reported some symptoms of the post-polio syndrome. However, there was no significant change in the muscle function of those who reported one or two of the key symptoms (see Methods), compared with those patients who reported three or four of these symptoms.

Discussion
These results provide the first demonstration of a lack of detectable change in muscle function in post-polio subjects over time using the twitch-interpolation technique. In this prospective study of selected post-polio subjects with no other pathology and a more heterogeneous group of post-polio clinic patients, there was no evidence for a decline in maximal voluntary force, voluntary activation or peripheral muscle endurance, even though patients frequently reported
Strength change in post-polio patients

Fig. 4 (A) Percentage change in maximal voluntary force and voluntary activation in female (n = 19) and male (n = 21) unselected polio subjects (Group B, from a post-polio clinic). Each line represents the change in muscle performance for an individual. A positive value indicates an improvement in performance and a negative value indicates a deterioration in performance. Overall, there was no significant change in either maximal voluntary force or voluntary activation over the period between studies. Asterisks denote the two patients who had a decline in maximal force of >10% and their corresponding change in voluntary activation (see text). (B) Maximal voluntary torque in the second test plotted against maximal voluntary torque for the first test. Note that over a wide range of voluntary strength there is little deviation from the line of identity. (C) Percentage change in voluntary activation plotted against the % change in maximal voluntary force for each patient (R² = 0.018, P = 0.455). Closed circles = male patients; open circles = female patients.

Strength and endurance changes in post-polio patients

Studies of muscle performance in post-polio patients 20–40 years after their initial infection led to the belief that the symptoms of late neuromuscular deterioration were progressive, although this progression was probably slow (e.g. Mulder, 1972; see Introduction). Several groups of investigators have measured strength over time in post-polio patients with either self-report questionnaires or manual clinical assessment (Dalakas, 1986; Dalakas et al., 1986; Munsat et al., 1987; Peach and Olejnik, 1991; Windebank et al., 1995, 1996). In some studies isometric dynamometers have been used (Agre and Rodriguez, 1991; Munin et al., 1991; Agre et al., 1995; Stålberg and Grimby, 1995; Ivanyi et al., 1996).

Dalakas (1986) found relatively stable strength over 3 years in post-polio patients with residual disability after their original illness. However, a slow decline in ‘functional capacity’ was observed in a subgroup of patients with wasting and fasciculations, although the method of determining functional capacity was not defined (Dalakas, 1986). Based on a qualitative rating of neuromuscular ‘function’ in a group...
of patients studied 8 years apart, a decrease in function of 1% per year was estimated (Dalakas et al., 1986). Windebank et al. (1995) reported, in a follow-up of 5 years, that there was no deterioration in neurological disability based on a score which included a measure of strength made with a dynamometer; however, no data for the isometric and isokinetic tests were given.

The present results indicate no significant deterioration in muscle endurance over 2.5 years in post-polio patients. Few investigators have studied the change in muscle endurance in these patients. In one other prospective study, muscle endurance was measured as the maximal time for which a patient could maintain a contraction at 40% MVC force (Agre and Rodriguez, 1991). There was no significant change in this measure of ‘endurance’, the level of voluntary drive to the muscle was not checked, and only 12 months separated the tests. Windebank et al. (1995, 1996) found functional performance was stable (measured as the time to walk 100 m and to perform a manual dexterity task), although specific muscle endurance was not assessed. One confounding factor in such studies is that patients with long-standing neuromuscular disease are notably adept at using trick movements and strategies to optimize their functional performance.

Although some post-polio patients have an impaired ability to drive their muscle voluntarily (Allen et al., 1994) and some have decreased strength, in the present study there was no change in the voluntary activation of the elbow flexor muscles during the endurance test. This suggests there was no deterioration in the central drive to the muscles or development of excessive ‘central’ fatigue. Likewise there was no significant deterioration in the twitch amplitude during the endurance protocol. In addition, the patients with more severely affected muscle performed similarly in both tests of endurance. This result was surprising given the frequent subjective reports of a decrease in muscle endurance in these patients.

**Correlations with symptoms of the post-polio syndrome**

Muscles in post-polio patients have abnormal electrophysiological and histological features, but the presence and degree of the abnormalities do not distinguish those patients with symptoms of the post-polio syndrome (e.g. pain, weakness, fatigue) from those who do not have these symptoms (e.g. Windebank et al., 1995, 1996; see also Cashman et al., 1987; Daube et al., 1995).

Agre et al. (1995) reported a significant decline in knee extensor strength (8%) in patients studied 4 years apart, but the decline was not different in patients with and without symptoms of the post-polio syndrome. With strength measured using the twitch-interpolation technique in the present study, the change in muscle performance in those patients with symptoms of the post-polio syndrome was the same as in those without these symptoms. This could not be assessed for the selected Group A polio subjects as 11 of the 14 had been diagnosed clinically as having all symptoms of the post-polio syndrome on their first test and thus a comparison of symptomatic and asymptomatic groups could not be made. When those polio subjects who had noticed a deterioration in their symptoms were compared with those in whom the symptoms were stable, there was no difference in changes of elbow flexor strength. Furthermore, in the unselected post-polio clinic patients (Group B), there was no difference in the change in muscle performance of those patients with one or two symptoms (usually increased pain and weakness) compared with patients with three or four of the main symptoms of the post-polio syndrome.

**Limitations**

It is difficult to find significant correlations between variables associated with original polio (such as the number of limbs affected) and marked weakness or deterioration in muscle function, as only a small proportion of patients have abnormal tests of muscle performance and patients affected by the original illness before the age of 5 years may have only a limited history of their original illness. Also, in many patients, new symptoms and some atrophy are noticed in limbs seemingly ‘unaffected’ by the original infection. Other factors which may influence prospective studies of muscle performance in post-polio patients include the effects of surgical, rehabilitation and medical interventions [e.g. exercise and walking aids (Agre et al., 1991); in females, hormone replacement therapy may stabilize muscle strength (Phillips et al., 1992)]. Patients who attend a post-polio clinic may increase their exercise and adapt their lifestyle to minimize any deterioration in muscle function. Many of the patients in the post-polio clinic sample had pathology other than previous polio and therefore explanations for their new symptoms are likely to be multifactorial. This problem is also reported by Windebank et al. (1995, 1996) who suggested that the majority of the symptoms which patients had recently developed were explicable by other factors such as degenerative joint disease, secondary problems resulting from residual weakness or other medical conditions.

Although poliomyelitis may appear clinically focal, there is evidence that the infection is widespread throughout the neuraxis (e.g. Bodian, 1947). There is therefore good reason to believe that a progressive loss of motor neuronal function would be detectable using our testing system if it occurred. However, to obtain an overall view of the symptoms, and the post-polio syndrome in particular, it may be necessary to assess muscle performance of the lower limbs. Unfortunately, the difficulty in dissociating lower limb pathology (due to the original infection) from the secondary dysfunction due to other degenerative disorders such as scoliosis and arthritis may render such results difficult to interpret. Furthermore, large sample sizes will be required.
Implications and conclusions

In the present study, no deterioration in muscle performance was detected in post-polio patients using objective tests, although many patients report evolving symptoms, consistent with the diagnosis of the post-polio syndrome. Some control subjects also reported decreased muscle performance over the interval between the tests. Thus it is likely that any change in muscle performance in the majority of post-polio patients is a very slow process which may not be faster than the decline in muscle performance that occurs with ageing. However, for patients with low strength, a slight decrease in absolute strength may produce a large change in functional performance. However, to detect the magnitude and time course of such a gradual change in muscle performance it would be necessary to follow patients over many years. There are some patients (5% of the total sample) with a more rapid decline in maximal voluntary strength, and in them, other possible contributory causes should be sought.

In the present study, we found no evidence for a deterioration in voluntary activation with ageing in post-polio subjects (see also Phillips et al., 1992). This implies that the impairment in voluntary drive previously documented in some of these polio subjects (Allen et al., 1994; see also Beelen et al., 1996) is not progressive, at least over 2.5 years. Furthermore, patients with already impaired strength and endurance are not predisposed to a more rapid deterioration in these parameters. These results imply that any deterioration in muscle function associated with previous polio is slow and that the symptoms of the post-polio syndrome (and in particular the perception that muscle function is worsening) are not necessarily associated with a change in muscle performance.

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