FLEXIBILITY OF THE USE OF RESIDUAL TIBIAL ANTERIOR MOTOR UNITS DURING WALKING IN NEUROMUSCULAR DISEASES

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ABSTRACT. The use of tibial anterior (TA) motor units in lower motoneurone disorders was studied during comfortable walking that was the main function of TA. The findings were compared to those in normal subjects. The loss of TA power was compensated either by increases of recruitment and firing rate of residual TA units or by a change from the normal plantigrade gait pattern to the infantile digitigrade pattern putting less strain on TA. Moderately paralysed subjects usually maintained plantigrade gait by excessive use of residual TA units but tended to change to digitigrade gait on fatigue thus economizing with remaining TA power. Severely paralysed subjects used digitigrade gait but plantigrade gait could be restored by application of a toe using string, i.e. the string might increase the strain on TA instead of decreasing it.

Key words: motor unit, motoneurone, muscle fibre, gait, exercise.

INTRODUCTION

Weakness of musculus tibialis anterior (TA) is a common cause of disability in patients with lower motoneurone diseases because of the long axons, relatively small power reserves during activities of daily living and possibly also because of overuse damage.

It has been shown in animal experiments that the long term use of a muscle is decisive for the properties of its muscle fibers (14, 15, 16). In man long term EMG recordings showed that most TA units were mainly used during locomotion (7). Only the motor units with the lowest thresholds had a postural role. Voluntary TA contractions were scarce. The use of a TA unit during locomotion should thus reflect its long term use.

In normal subjects about 75% of the TA muscle fibers were type I and about 25% type II. The TA units with the lowest threshold and presumably type I fibers fired each step cycle during ordinary walking and the rate and duration of firing were compatible with fused power. The TA units with the highest thresholds and presumably type II fibers, on the other hand, fired mainly during rapid corrective movements and rapid locomotion and the duration of the firing was seldom sufficient for fused power (8, 11).

Patients who had lost most of their TA units compensated for the paralyses during locomotion by increased recruitment and firing rate of remaining TA units (8). Patients with prior poliomyelitis or LV root lesion who had used remaining high threshold TA units excessively for several years had no or very few type II TA muscle fibers (1). There was no corresponding absence of those high threshold, rapidly conducting TA motoneurones, which normally innervate type II fibers (2). It was suggested that the excessive use during locomotion for several years caused a transition of muscle fibers innervated by such motoneurones.

The aim of the present paper was to study whether other compensatory mechanisms than overuse of residual TA units are available.

MATERIAL AND METHODS

1–3 single TA motor units and the integrated surface EMG of TA and triceps surae (TS) were studied during comfortable walking in 30 patients with TA paralyses (2–4 according to the Kendal scale) due to lower motoneurone lesion. The patients had no clinical signs of upper motoneurone lesion or ataxia.

Electromyographic recordings in which the potentials of single TA units could be identified were obtained by wire electrodes made from insulated silver or platinum wires 20–100 μm diam equipped with a hook for fixation in the muscle (for further description see 6, 8) or by superficially located single fiber needle electrodes (Medelec Ltd, Woking, Surrey, U.K.). Recordings in which only one motor unit had spike potentials during maximal voluntary tension were easily obtained since the number of TA units was below normal and the muscle fiber density within remaining units was greater than normal. With some luck the recordings could be maintained for many step cycles. However, sooner or later the recording electrode was dislocated so that single units could not be studied during long distance walking (cf. below).

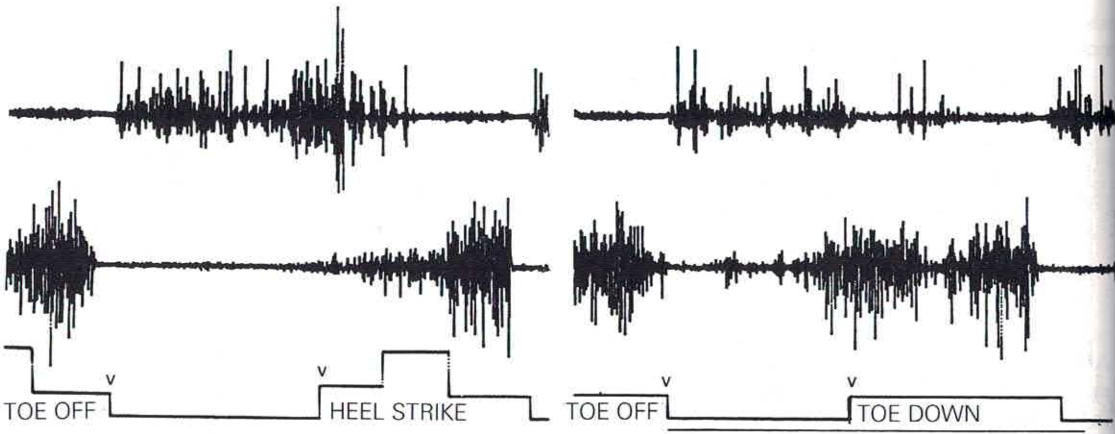

Fig. 1. Step cycle during ordinary walking with a heel strike (left) and voluntary toe walking (right) in a normal subject. Upper trace shows TA surface EMG. Middle trace shows TS surface EMG. Lower trace shows signals from foot switches; small upward deflexion denotes pressure on a switch at the plantar surface of the toes; intermediate deflexion denotes pressure on a switch at the plantar surface of the heel; large deflexion denotes pressure on both switches, i.e. stance phase. Time bar 1 s.

Single motor unit recordings could be verified by observing that the potential under study was identical to that evoked by supramaximal electrical stimulation of the peroneal nerve. In simultaneous recordings of two motor units confusion of their potentials could be avoided since they had characteristic shapes because of collateral sprouting.

The surface TA and TS EMG were recorded with Medelec (C 162 Medelec, Woking, Surrey, U.K.) or Beckman (LOT 47 Beckman Instruments Inc, Fullerton, California, USA). The signals were rectified and integrated in a linear way over periods of 80–160 ms and displayed during the following period.

The recording electrodes were connected to a small pre-amplifier strapped to the leg and connected to the main amplifier by a cable permitting 40 m of locomotion. In the studies of the surface EMG during prolonged walking the connection between the pre-amplifier and the main amplifier was wireless.

The electromyographic activities were related to the signals from two tape switches (Stig Wahlström AB, Box 64, S-123 22 Farsta, Sweden), the one strapped to the heel and the other to the anterior part of the shoe. The two switches operated at different voltages so that the signals could be distinguished when recorded simultaneously. All subjects used indoor shoes with low heels and low weight.

RESULTS

Normal subjects. During ordinary walking TA activity started at toe off and reached a short marked peak prior to the heel strike and ended at toe down. When a normal subject voluntarily changed to toe walking the use of the TA muscle was markedly decreased and there was a preparatory TS activity instead of a TA activity before touch down. Fig. 1 illustrates the change of the relative roles of the two muscles on change of mode of walking.

During ordinary walking the TA units with the lowest thresholds fired throughout the swing phase, i.e. for about half a second per step cycle. Their firing rates were 20–25 Hz during 100 ms of the heel strike peak and 10–15 Hz during the rest of the swing phase. Intermediate threshold TA units fired only a few times at the heel strike at intervals corresponding to 15–20 Hz. The TA units with the highest thresholds did not participate in the ordinary step cycle (for further normal data see 6, 8, 11).

Slight TA paralyses. Patients capable of significant TA tension at full dorsiflexion of the foot (4 according to the Kendal scale) used the normal plantigrade gait pattern with a heel strike. The loss of TA power was partly compensated by moderately increased recruitment and firing rates of remaining TA units and partly by a less marked foot dorsiflexion during the swing phase and a less marked heel strike. Increased use of remaining units predominated but relative roles of the two modes of compensation were different in different patients.

Moderate TA paralyses. During short distance walking patients barely capable of full foot dorsiflexion (Kendal 3) usually used all remaining TA units tonically at high rates to maintain a plantigrade gait pattern with some heel strike. The unit in Fig. 2 fired throughout the swing phase at 30 Hz. At such high rates there were no differences in firing between low

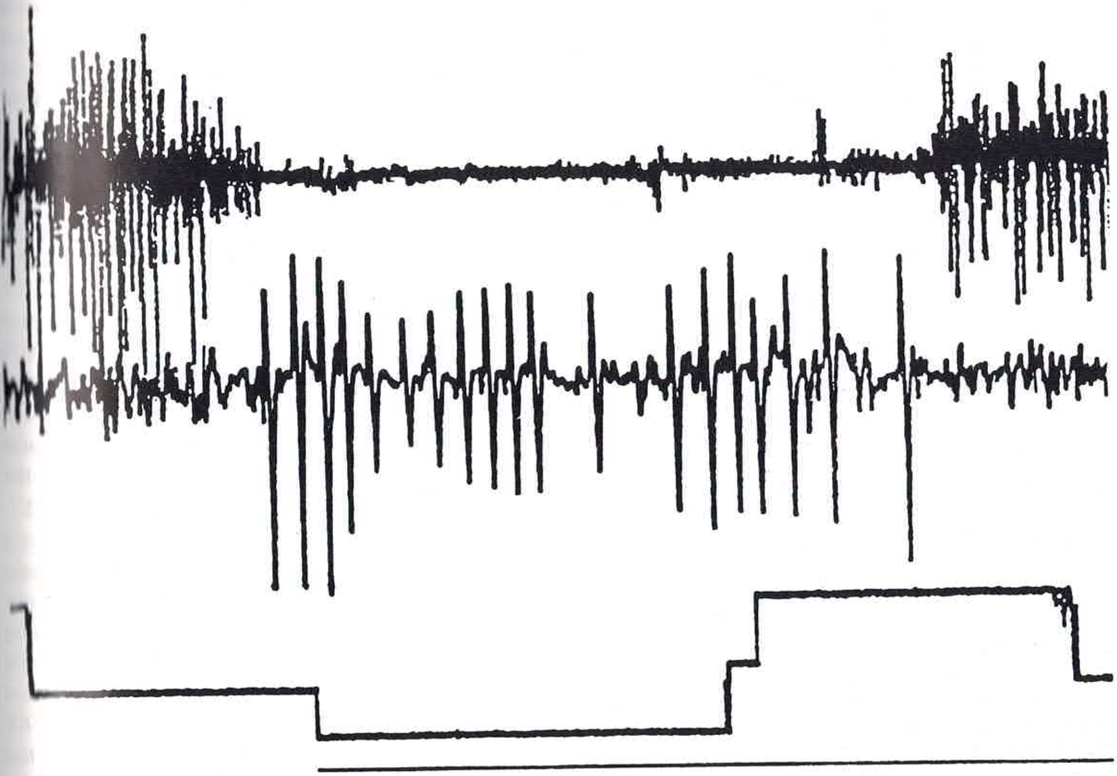

Fig. 2. Ordinary step cycle in a subject with moderate TA paralysis. Upper trace shows TS surface EMG. Middle trace shows the discharge of a single TA unit. Variation of the amplitude of the single motor unit potential could not be avoided since the muscle was shortened and lengthened during the step cycle. Lower trace shows signals from foot switches as in Fig. 1. Time bar 1 s.

and high threshold units. The TA firing rates were about those recorded when maximal TA tension was maintained voluntarily (9). The TS activity was restricted to the stance phase.

Prolonged walking. When moderately paralysed patients walked long distances there was, however, a tendency towards to touch down with the toes and a preparatory TS activity instead of TA activity prior to touch down. Thereby the activity of remaining TA units decreased. In the experiment illustrated in Fig. 3

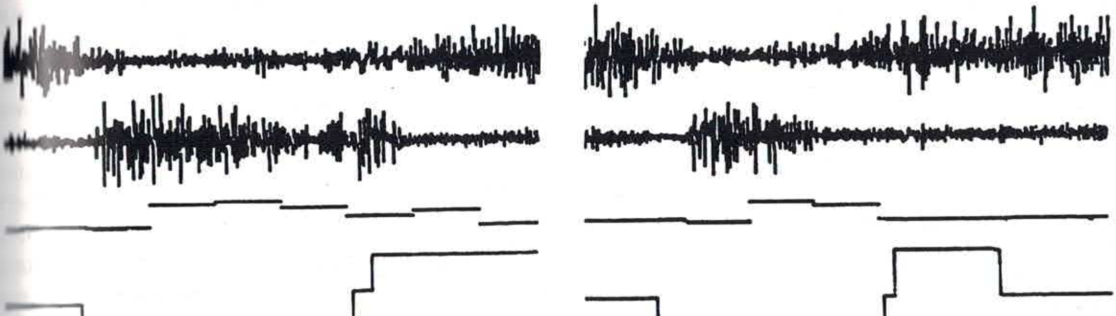

Fig. 3. Step cycle after rest (left) and on fatigue (right) in a subject with moderate TA paralysis. Upper trace shows TS surface EMG, second trace the TA surface EMG, third trace the TA surface EMG integrated during each period of 160 ms and displayed during the following period, lower trace signals from foot switches as in Fig. 1. Time bar 1 s.

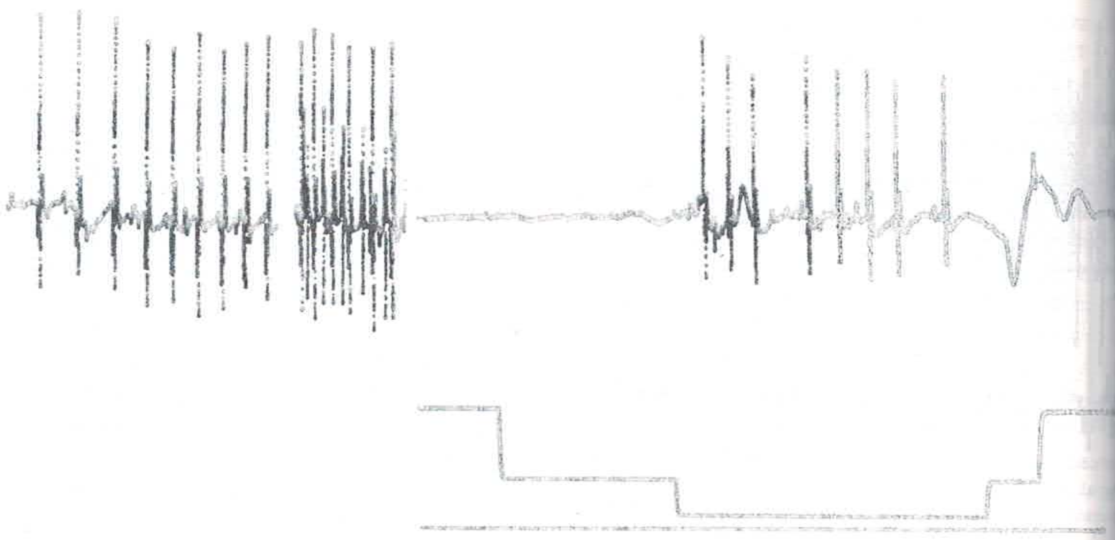

Fig. 4. Voluntary contraction (left) and ordinary step cycle (right) in a subject with severe TA paralysis. Upper trace shows a simultaneous recording of one low threshold unit (large potential) and one high threshold unit (small potential). Lower trace shows signals from foot switches as in Fig. 1. Time bar 1 s.

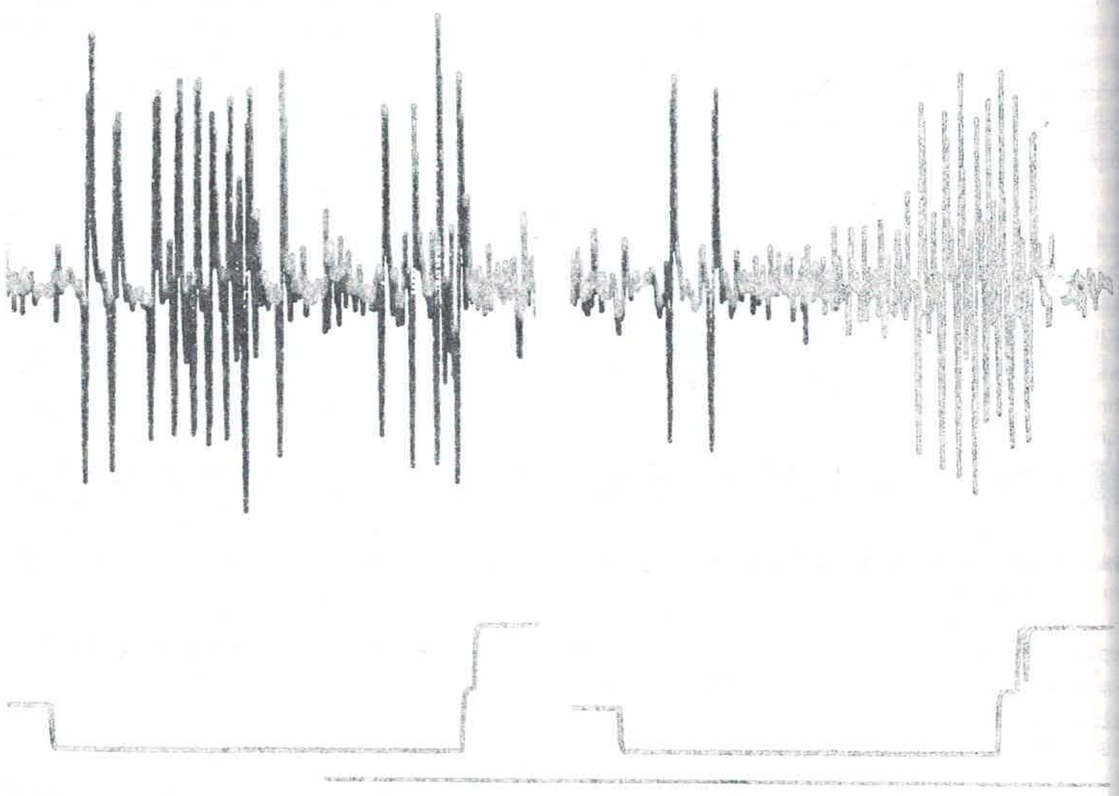

Fig. 5. Ordinary step cycle (left) and step cycle when a toe rising string is used (right). Upper trace shows a single TA unit, lower trace signals from foot switches as in Fig. 1. Time bar 1 s.

the mood of walking changed during prolonged walking. The integrated TA surface EMG during toe walking was only about one third of that during walking with a heel strike.

Severe TA paralyses. In patients incapable of foot dorsiflexion (Kendal scale 1–2) the toes hit the ground before the heel and there was a preparatory triceps surae activity. TA activity was recorded mainly during the first part of the swing phase. Remaining TA units were even then often not fully used. In the experiment illustrated in Fig. 4 the low threshold unit (high amplitude potential) and one high threshold unit (low amplitude potential) were recorded simultaneously (left). During walking (right) only the low threshold unit fired and mainly during the first part of the swing.

Effects of toe rising strings. A toe rising string decreased TA activity during the first part of the swing phase while the effects on the TA heel strike peak were complicated. When the string did not change the mode of walking also the TA heel strike peak decreased. However, the string often caused a more marked heel strike and a more marked preparatory TA activity. In the experiment illustrated in Fig. 5 the test unit fired one high-frequency burst just after toe off and one just before heel strike. Application of a string resulted in a decrease of the first burst but an increase of the firing rate and duration of the second burst.

DISCUSSION

In patients with TA paralyses because of prior poliomyelitis or traumatic LV lesion excessive use of remaining high threshold motor units resulted in transition of type II to type I fibers and in muscle fiber hypertrophy (1). There was, however, no structural abnormalities of the muscle fibers (1) suggesting harmful effects.

These findings in non-progressing disorders do not necessarily mean that overuse of remaining motor units is harmless in progressing neuromuscular disease. In normal subjects hard training programs caused severe structural abnormalities of the muscle fibers (4, 10, 13) but there was a rapid and complete recovery. However, the recovery process might be disturbed in pathological states and more so in progressing than in non-progressing disorders.

Further, maximal use of all remaining TA units in the ordinary step cycle must be a disadvantage when there is a need of compensation for contractile fatigue during long distance locomotion or a need of corrective movements, e.g. to avoid obstacles and unevenness of the ground. In normal sedentary subjects high threshold units seemed to be used mainly during such corrective movements (6).

Infants use a digitigrade pattern of walking with a touch down with the toes and a preparatory TS activity (5). When the adult plantigrade pattern with a heel strike and a preparatory TA contraction develops the role the TA muscle increases.

Patients compensated for a slight to moderate TA paralysis mainly by increasing recruitment and firing rates of remaining TA units but for a severe paralysis mainly by decreasing the level of foot dorsiflexion. When the ground was hit with the toes there was a preparatory TS activity, i.e. there was an active toe walking rather than a passive foot drop. It seems as though chronic patients with a severe TA paralysis returned to the infantile digitigrade pattern of walking thus economizing with remaining TA power.

The TA contraction at the heel strike during plantigrade walking is eccentric, i.e. the muscle lengthens during the contraction (12). During digitigrade walking, however, the TA contraction is concentric, i.e. the muscle shortens during the contraction. Excessive eccentric work causes more structural damage to the muscle fibers than does concentric work (4, 13).

A toe rising string, supposed to decrease the work of the TA muscle, tended to restore the plantigrade pattern and thus to increase the eccentric work. To avoid the potential overuse damage the string should either be so strong that it actually protects the TA muscle or so weak that it does not change the mode of walking.

In the paralysed subjects a change from plantigrade to digitigrade gait occurred during prolonged walking. The transformed and hypertrophic TA muscle fibers in prior polio had a low oxidative capacity and a low capillarization (Borg & Henriksson, in prep.) suggesting that they were not endurance trained. The explanation might be that they were excessively used mainly during short distance walking and protected by a change of gait pattern during long distance walking.

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