Scand J Rehab Med 17: 47–52, 1985

ISOKINETIC PLANTAR FLEXION ENDURANCE

Reliability and Validity of Output/Excitation Measurements

A. R. Fugl-Meyer,[1] B. Gerdle,[1] B.-E. Eriksson[2] and B. Jonsson[2]

From the [1]Department of Physical Medicine and Rehabilitation, University of Umeå, and the [2]Division of Work Physiology, Research Department, National Board of Occupational Safety and Health, Umeå, Sweden

ABSTRACT. **The reliability and validity of isokinetic measurement of plantar flexion endurance has been studied by a method previously described by us which utilizes simultaneous measurements of mechanical contractional work (CW) and integrated electromyogram (iEMG). The reliability was gauged by test/re-test with a two year's interval; while validity was assessed by myoelectric power spectrum analyses. The output/input balance (CW/iEMG) remained unchanged for the group as well as inter-individually. Changes in myoelectric power spectrum as function of number of contractions were clearly indicative of fatigue. Under the present conditions fatigue of fast twitch motor units may explain the rapid decreases in output and excitation followed by nearly steady state levels of all registered parameters. As is the case for non-fatigued isokinetic plantar flexions, the motor unit recruitment order appears quite stereotyped during plantar flexion fatigue. The findings of significantly lower mean power spectrum during the first part of each contraction than during the second part may support the size-principle described by Henneman.**

Key words: Human, skeletal muscle, isokinetic, plantar flexion, electromyography, fatigue

Muscular endurance may adequately be defined as time to fatigue, while failure to maintain initial (or expected) force or power output characterizes fatigue (3). In our opinion there is a need for clinically applicable ways of objective assessment of muscular endurance. Plantar flexion offers good possibilities for investigations of both output and electromyographic activity. In the straight knee position, about 90% of the plantar flexor mass is contained within the triceps surae (4, 28). It is, furthermore, notably easy to gain access to the motor unit activity of all three heads of this muscle by surface electromyography which has been shown to be representative of the electromyographic activity of the muscle per se (26, 18, 34).

Recently we (6) described a method for assessment of dynamic muscular endurance. Using isokinetic dynamometry, middle-aged and elderly randomly selected healthy subjects performed up to 200 consecutive plantar flexions at 60°/s. During the initial 50–75 manoeuvres peak torques (PT) and performable contractional work (CW) decreased successively. Thereafter nearly steady state levels were generally maintained. Normalizing the integrated electromyographic signals (iEMG) from all three heads of the triceps surae for changes in range-of-motion (RoM) this measure of excitation decreased about 15–30%, concomitantly with decreases in output. The nearly steady state level was named the endurance level. Age was associated with greater relative endurance in CW but not in PT. Since changes and endurance levels of iEMG were concomitant with those of CW, close correlations were found between CW and iEMGs. A composite measure (CW/iEMG) designed to signify output/input balance was therefore virtually constant and apparently age but not gender dependent.

The goals of this investigation were (*a*) to evaluate the reliability of the isokinetic measurement of muscular endurance by test/re-test at two years' interval and (*b*) to validate the method by myoelectric power spectral analyses. The electromyographic power spectrum has been extensively studied and it appears clear that the mean or median power spectrum decreases, when initial output cannot be sustained, thus denoting fatigue (cf. 24). Furthermore, it is evident that concomitantly with development of muscular fatigue, the myoelectric power encompassed within a band of high frequency compared to that contained within a band of low frequency falls (12, 22, 27). Hence, it was felt that the validity of iEMG as a measure of "input" fatigue could be assessed by analyses of myoelectric power spectra.

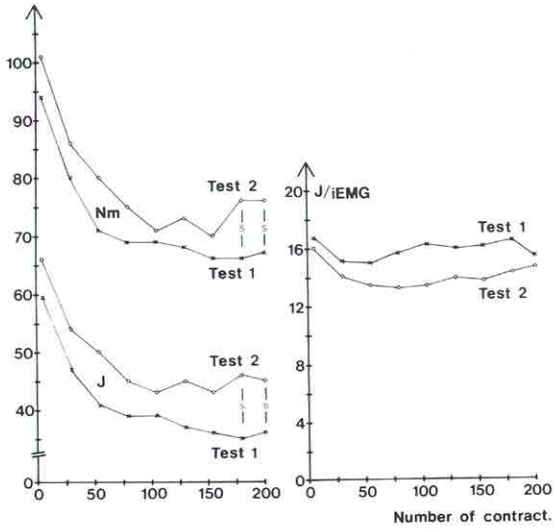

Fig. 1. The relationships between peak torque (right Y-axis, Nm), contractional work (right Y-axis, J) and electrical efficacy (left Y-axis, J/iEMG) and number of repeated isokinetic plantar flexions (X-axis). Manoeuvres were performed at 60°/s. Thirteen clinically healthy males were included. Tests were performed with about two years interval (x = test 1; o = test 2). *s* denotes significant differences between the two tests. *Nm* denotes peak torque, *J* denotes contractional work and *iEMG* denotes summed, truely integrated electromyograms of all three heads of the *m. triceps surae*.

MATERIALS

Thirteen clinically healthy, non-selected males were included. They were studied twice with two years' (range 22–25 months) interval between tests 1 and 2. At the first investigation subjects were aged between 40 and 44. Originally, at test 1, 15 males were studied. The criteria for their inclusion has been described elsewhere (8). As two were ill during the period scheduled for test 2, comparison was facilitated by including at both tests only 13 subjects.

METHODS

At both investigations isokinetic plantar flexion manoeuvres were performed using Cybex II® dynamometry (17, 32). The principles of the experimental setup have been described elsewhere (5, 6). In brief, all subjects performed 200 repetitive plantar flexions at 60°/s. For each manoeuvre PT, CW and manoeuvre time (= RoM) were registered on a digital printer. After careful skin preparation, pairs of self-attaching, disposable silver–silver chloride surface electrodes (Medico-test, Ølstykke, Denmark) were placed over the maximum bulges of the m. soleus and the musculi gastrocnemii. The electromyographic signals obtained were full wave rectified, filtered and then integrated (iEMG) and registered digitally. At test 2 frequency analyses of the EMGs were simultaneously performed in 12 subjects with high and low frequency cut offs at 10 Hz and 500 Hz, respectively. The power spectral density function (PSDF) of each manoeuvre and of the initial and the subsequent 256 ms periods were obtained using fast Fourier transform technique. The mean power frequency (MPF) of all three samples were computed through:

$$\text{MPF} = \int f\text{PSDF}\, df \Big/ \int \text{PSDF}\, df.$$

For each contraction the energy at high (≥150 Hz)/low (≤59 Hz) frequencies were registered and median ratios were calculated.

Statistics. For each calculation incorporating PT, CW, RoM and iEMG, means for sets of five consecutive contractions were used. The spectral analyses were processed for every tenth manoeuvre. To compare pairs of variables Student's *t*-test for paired observations (1) or simple regression analyses were used. All statistical tests were performed at the 5% significance level ($p \leq 0.05$, two-tailed). Statistics were based on normal theory results.

RESULTS

At both tests subjects failed to maintain initial (= "expected") output already within 10 successive isokinetic plantar flexions (Fig. 1). Throughout

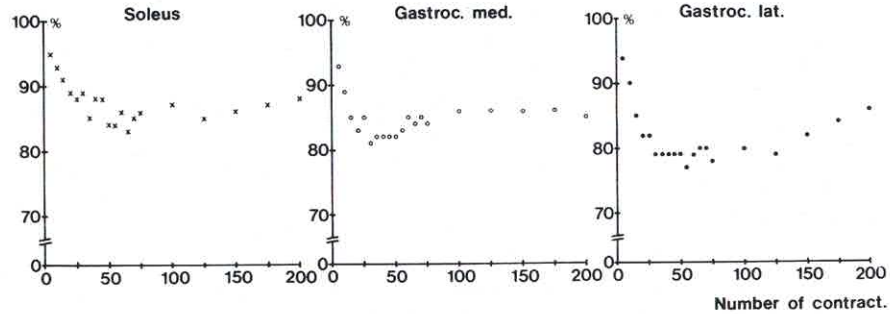

Fig. 2. The relationships between mean power frequency (MPF) of the *m. soleus*, the *m. gastrocnemius medialis* and the *m. gastrocnemius lateralis*, in per cent of contraction number one (Y-axis, %) and number of repeated isokinetic plantar flexions (X-axis) at the preset velocity 60°/s in 12 clinically healthy males.

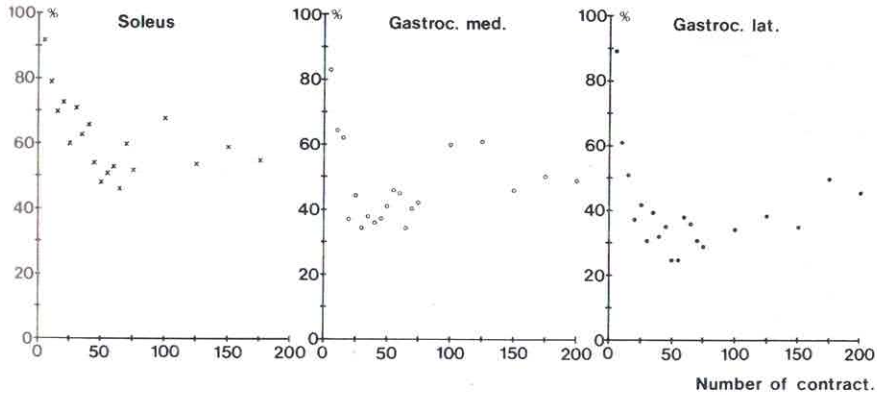

Fig. 3. The relationships between high (≥150 Hz)/low (≤59 Hz) median ratios of the *m. soleus*, the *m. gastrocnemius medialis* and the *m. gastrocnemius lateralis*, in per cent of contraction number one (*Y*-axis, %) and number of repeated isokinetic plantar flexions (*X*-axis) at the preset velocity 60°/s in 12 clinically healthy males.

the subsequent approximately 50 contractions both PT and CW were successively and significantly reduced. After about 70 plantar flexions no further significant reductions occurred. Not until the final 30 manoeuvres were there significant differences between output at tests 1 and 2. During these last manoeuvres torque production at test 2 increased to a level significantly greater than that of test 1. Initially, RoM did not differ significantly between tests. After about 100 contractions RoM was, though, systematically and significantly greatest at the re-test, providing part of the explanation for the relatively greater test/re-test differences in CW than in PT. Since, at both tests, CW and the summed iEMG of all three heads of the triceps surae were closely associated (r between 0.82 and 0.95) the CW/iEMG ratio was constant at both tests. Within the group a rank analysis demonstrated significant test/re-test inter-individual conformity of this ratio. In this context it is worth emphasizing that during the 2-year span of time, vocational and leisure physical activities were uniformly unaltered.

During the initial 25 plantar flexions the MPFs of all three plantar flexors fell about 15–25% (Fig. 2) but had a tendency to increase when 50–75 manoeuvres had been performed. Increases were, though, not statistically separable from minimum values reached. In contrast to the moderate reductions in MPF, high/low median ratios (Fig. 3) fell drastically until about the 50th repetition and in particular so for the m. gastrocnemius lateralis in which this measure of fatigue dropped nearly 80%. The ratios, however, again increased after about 100 contractions. In analogy with MPF the increased ratios were not significantly separable from the minimum values previously attained.

The MPFs registered for the initial 256 ms fragment of each manoeuvre were, in all three muscles and throughout the experiment (Fig. 4) significantly lower than those of the subsequent 256 ms fragment, during which PT consistently occurred. For all three heads of the triceps surae the MPF of this second part of the plantar flexion manoeuvre had fallen significantly after 10 contractions. MPFs of this part of the manoeuvre were similar to the MPF of the total manoeuvre (cf. Fig. 2). In contrast the MPFs of the first 256 ms did not change systematically throughout the experiment.

DISCUSSION

Reliability

It appears that in randomly selected middle-aged males with stabilized levels of physical activites, maximum supine isokinetic plantar flexor output (Nm, J) varies only slightly at two years' interval. Moreover, the chosen expression of dynamic electrical efficacy (CW/iEMG) is remarkably constant under the present experimental conditions.

The significantly greater mechanical output at test 2 than at test 1 towards the end of the experiment, when endurance level had been reached, probably implies that at the re-test subjects remembered the total number of contractions they were expected to perform, while at test 1 they were not informed about this maximum number. Hence, at test 2, they at least for a short while increased their

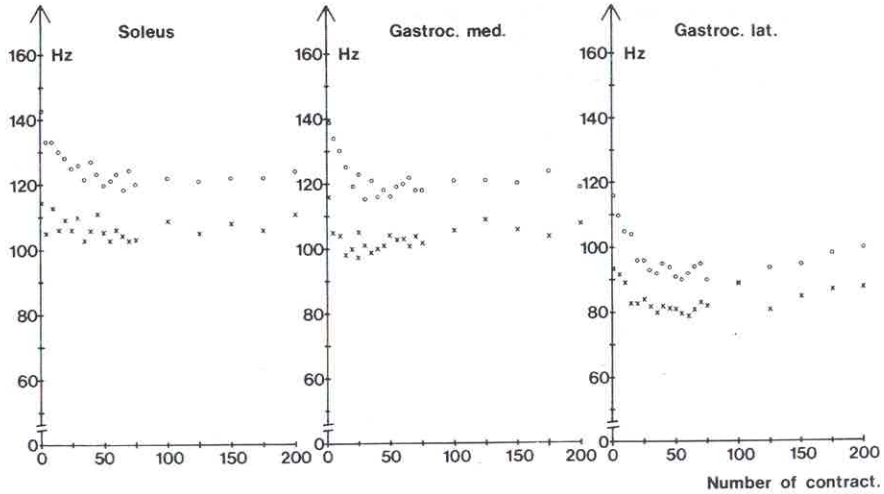

Fig. 4. The relationships between mean power frequency of initial 256 ms (denoted x) and subsequent 256 ms (denoted o) for the *m. soleus*, the *m. gastrocnemius medialis* and the *m. gastrocnemius lateralis* (*Y*-axis, Hz) and number of repeated isokinetic plantar flexions (*X*-axis) at the preset velocity 60°/s in 12 clinically healthy males.

level of performance. The fact that output increased somewhat, but electrical efficacy decreased slightly, from test 1 to test 2 may signify that, due to—correct—expectations as regards number of contractions, the subjects could modify, slightly, their input/output balance.

The repeatability of the close association between CW and iEMG emphasizes that under relatively stereotyped dynamic concentric conditions, surface iEMG can give reliable information as regards performed contractional work, at least in clinically healthy not specifically trained subjects. In principle this agrees with the findings of Hof & Van den Bergh (19) of static force/iEMG relationships in plantar flexion. The fact that, at least for the triceps surae, iEMG can be obtained with adequate reliability at two years interval is of particular interest. In isometric contraction Viitasalo & Komi (34) found acceptable day-to-day reliability of iEMG registrations obtained by surface electrodes.

Validity

Previously (6) it was suggested that the fall in iEMG/manoeuvre time occurring during the initial fatigue phase of this experiment signified decrease in excitation, possibly due to decrease in mean firing frequency. The decrease in iEMG/manoeuvre time then reported appears to be of the same magnitude and follow the same time course as the decreases in MPF for the total manoeuvres reported here. The initial falls in MPF and in high/low frequency ratios are in good agreement with other reports on progressive muscular fatigue, whether static or dynamic (13, 14, 21, 27). Hence, we feel that the previously described method for assessment of plantar flexion endurance is adequately validated.

A considerable part of the available literature (cf. 6) lead us to suggest that the type of fatigue measured reflects fatigue of fast twitch (FT) motor units. For example, during supposedly fatiguing static (35) and isokinetic (22) knee extension experiments, decreases in MPF are more pronounced in richly than in sparsely FT-fibre populated musculi vasti lateralii. Furthermore, in the present investigation mean MPFs and high/low frequency ratios of the musculi gastrocnemii decreased more, particularly those of the m. soleus. Although rather small, these differences appear to reflect the well-known relative fibre composition of these muscles (2, 7, 20) similar to the findings from Komi's group.

Recruitment of motor units during non-fatigued plantar flexions at different velocities of angular motion has been described to be independent of velocity of angular motion (5, 8). The MPF of the first 256 ms period of each manoeuvre in all three muscles was significantly lower than the MPF of the subsequent 256 ms. Since slow-twitch (ST) fi-

bres have lower firing frequencies than have FT fibres (10) the finding implies that, systematically, ST motor units are recruited prior to FT units during isokinetic plantar flexions. A suggestion which is congruent with the size principle of Henneman (15, 16). Recently, however, Secher et al. (30) using tubocurarine to partially block ST motor units presented some evidence that in isokinetic knee extension at different velocities of angular motion FT fibres may be highly contributory to initial torque development. In line with our previous suggestion that under the present conditions fatigue is mainly caused by failure of FT motor unit function, the MPF of the second but not of the first 256 ms fragment decreased with the time course similar to other decreases. Furthermore, several authors (9, 31, 33) have found that peak torque is positively associated with relative FT fibre content and/or area and, consistently peak torques occurred during the second 256 ms period of contractions.

The increases in total manoeuvre MPF during the second half of the experiment may be caused by re-recruitment of FT motor units. Several speculative mechanisms shall be offered. Thus, increased intramuscular temperature will lead not only to increased output (29) but also to increase in MPF and in the high frequency content of the myoelectric power spectrum (cf. 24). The effect of temperature may however be dampened by increased intramuscular pressure (23). Another explanation for the tendency towards right shifts of the power spectrum may be that a central exhaustion protective mechanism such as that found for at least some FT motor units (11) and possibly elicited by some feedback mechanism, cf. Komi (22), is overruled by cortical command. As previously pointed out subjects probably expected the amount of manoeuvres maximally required. Hence, by will they might overcome peripheral signs of fatigue. This suggestion appears to agree with the findings of Merton et al. (25) who found that during voluntary skeletal muscle fatigue, pre-fatigue action potentials can be evoked by appropriate external cortical stimulation.

REFERENCES

1. Diem, K. & Lentner C.: Scientific Tables (ed. K. Diem & C. Lentner). Ciba-Geigy, Basel, 1970.
2. Edgerton, V. R., Smith, J. L. & Simpson, D. R.: Muscle fibre type populations of human leg muscles. Histochem J *7:*259, 1975.
3. Edwards, R. H. T.: Biochemical bases of fatigue in exercise performance: Catastrophe theory of muscular fatigue. *In* Biochemistry in Exercise (ed. H. G. Knuttgen, J. A. Vogel, J. Poortmans). International series on sport sciences, vol. 13, pp. 3–28. Human Kinetics Publishers Inc., Champaign, 1983.
4. Fick, R.: Anatomie und Mechanik der Gelenke. Teil III. Spezielle Gelenk- und Muskelmechanik. Fischer, Jena, 1911.
5. Fugl-Meyer, A. R., Mild, K. H. & Hörnsten, J.: Output of skeletal muscle contractions. A study of isokinetic plantar flexion in athletes. Acta Physiol Scand *115:* 193, 1982.
6. Fugl-Meyer, A. R., Gerdle, B. & Långström, M.: Mechanical output and EMG of repeated isokinetic plantar flexions in 40–64-year old subjects. Acta Physiol Scand, 1985. In press.
7. Fugl-Meyer, A. R., Sjöström, M. and Wählby, L.: Human plantar flexion strength and structure. Acta Physiol Scand *107:*47, 1979.
8. Gerdle, B. and Fugl-Meyer A. R.: Mechanical output and iEMG of isokinetic plantar flexion in 40–64-year old subjects. Acta Physiol Scand, 1985. In press.
9. Gregor, R. J., Edgerton, V. R., Perrine, J. J., Campain, D. S. & DeBus, C.: Torque–velocity relationships and muscle fiber composition in elite female athletes. J Appl Physiol *47:*388, 1979.
10. Grimby, L., Hannerz, J. & Hedman, B.: Contraction time and voluntary discharge properties of individual short toe extensor motor units in man. J Physiol *289:*191, 1979.
11. Grimby, L., Hannerz, J., Borg, J. & Hedman, B.: Firing properties of single human motor units on maintained maximal voluntary effort. *In* Human Muscle Fatigue: Physiological Mechanisms. Pitman Medical, London, 1981 (Ciba Foundation Symposium, 82).
12. Gross, D., Grassino, A., Ross, W. R. D. & Macklem, P. T.: Electromyogram pattern of diaphragmatic fatigue. J Appl Physiol Respirat Environ Exercise Physiol *46:*1, 1979.
13. Gross, D., Ladd, H. W., Riley, E. J., Macklem, P. T. & Grassino, A.: The effect of training on strength and endurance of the diaphragm in quadriplegia. Am J Med *68:*27, 1980.
14. Hagberg, M.: Muscular endurance and surface electromyogram in isometric and dynamic exercise. J Appl Respirat Environ Exercise Physiol *1:*1, 1981.
15. Henneman, E., Sojmen, G. & Carpenter, D. O.: Functional significance of cell size in spinal motoneurones. J Neurolophysiol *28:*560, 1965.
16. Henneman, E. & Mendell, L. M.: Functional organization of motoneuron pool and its inputs. *In* Handbook of Physiology. The Nervous System. Vol II, part 1. 1980.
17. Hislop, H. J. & Perrine, J. J.: The isokinetic concept of exercise. Phys Ther *47:*114, 1967.
18. Hof, A. L. & Van den Bergh, J. W.: Linearity between the weighted sum of the EMGs of the human triceps surae and the total torque. J Biomech *10:*329, 1977.
19. Hof, A. L. & Van den Bergh, J. W.: EMG to force

processing. IV. Eccentric-concentric contractions on a spring-fly wheel setup. J Biomechanics *14* (11): 781, 1981.
20. Johnsson, M. A. Polgar, J., Werghtman, D. & Appleton, D.: Data on the distribution of fibre types in thirty-six human muscles. An autopsy study. J Neurol Sci *18:* 111, 1973.
21. Komi, P. V. & Tesch, P.: EMG frequency spectrum, muscle structure and fatigue during dynamic contractions in man. Eur J Appl Phsiol *42:* 41, 1979
22. Komi, P. V.: Fatigue and recovery of neuromuscular function. In press, 1984.
23. Körner, L., Parker, P., Almström, C., Herberts, P. & Kadefors, R.: The relation between spectral changes of the myoelectric signal and the intramuscular pressure of human skeletal muscle. Eur J Appl Physiol 52: 202, 1984.
24. Lindström, L. & Petersén, I.: Power spectrum analysis of EMG signals and its application. *In* Progress in Clinical Neurophysiology. Vol 10. Computer-Aided Electromyography (ed. J. E. Edsmedt), pp. 1–53. Karger, Basel, 1983.
25. Merton, P. A., Hill, D. K. & Merton, H. B.: Indirect and direct stimulation of fatigued human muscles. *In* Human Muscle Fatigue: Physiological Mechanisms. Pitman Medical, London, 1981 (Ciba Foundation Symposium 1982).
26. Milner-Brown, H. S. & Stein, R. B.: The relation between the surface electromyogram and muscular force. J Physiol *246:* 549, 1975.
27. Moxham, J., Edwards, R. H. T., Aubrei, M., DeTroyer, A., Farkas, G., Macklem, P. T. & Roussos, C.: Changes in EMG power spectrum (high to low ratio) with forced fatigue in humans. J Appl Physiol *53*(5): 1094, 1982.
28. Murray, M. P., Guten, G. N., Baldwin, J. M. & Gardner, G. M.: A comparison of plantar flexion torque with and without the triceps surae. Acta Orthop Scand *47:* 122, 1976.
29. Sargeant, A. J.: Velocity dependent effect of muscle temperature on short term power output in humans. *In* Biochemistry of Exercise (ed. Knuttgen, Vogel, Pootmans), pp. 612. Human Kinetics, 1983.
30. Secher, N. H., Petersen, S. & Grimby, G.: Effect of tubocurarine on static and dynamic muscle contractions in man. Acta Physiol Scand *120:* 251, 1984.
31. Tesch, P., Sjödin, B., Thorstensson, A. & Karlsson, J.: Muscle fatigue and its relation to lactate accumulation and LDH activity in man. Acta Physiol Scand *103:* 413, 1978.
32. Thistle, H. G., Hislop, H. J., Moffroid, M. & Lowman, E. W.: Isokinetic contraction: A new concept of resistive exercise. Arch Phys Med Rehab 279–282, 1967.
33. Thorstensson, A., Grimby, G. & Karlsson, J.: Force–velocity relations and fibre composition in human knee extensor muscles. J Appl Physiol *40:* 12, 1976.
34. Viitasalo, J. H. T. & Komi, P. V.: Signal characteristics of EMG with special reference to reproducibility of measurements. Acta Physiol Scand *93:* 531, 1975.
35. Viitasalo, J. H. T. & Komi, P. V.: Isometric endurance, EMG power spectrum and fiber composition in human quadriceps muscle. *In* Biomechanics, vol. VI–A (ed. Asmussen, Jørgensen), pp. 244–250. University Park Press, Baltimore, 1978.

Address for reprints:

B. Gerdle, MD
Dept. of Physical Medicine and Rehabilitation
University of Umeå
S-901 85 Umeå, Sweden