Scand J Rehab Med 30: 67–72, 1998

MUSCLE FATIGUE IN A STANDING HEEL-RISE TEST

Ulla Svantesson, Ulrika Österberg, Roland Thomeé and Gunnar Grimby

From the Department of Rehabilitation Medicine, Sahlgrenska University Hospital, Göteborg, Sweden

ABSTRACT. The fatigue process of the triceps surae was evaluated during a standing heel-rise test, comprising of eccentric and concentric muscle actions. Ten healthy women with a mean age of 24 years participated. The heel-rise test was performed until exhaustion. Work and electromyographic activity expressed as root mean square and mean power frequency of the gastrocnemius and soleus muscles were calculated. The average number of heel-rises performed was 25 ± 1. Work decreased significantly during the test. Mean power frequency decreased significantly in both phases. During the eccentric phase the decrease was significantly larger in the gastrocnemius than in the soleus muscle. There were no significant changes in root mean square except for a decrease in the soleus muscle during the eccentric phase. The present results, showing different fatigue patterns in the two muscles, could be used as reference when testing the fatigue process in different clinical conditions. Recommendations for standardization of a heel-rise test are given.

Key words: eccentric-concentric; electromyography; fatigue.

INTRODUCTION

A commonly employed clinical test for evaluating muscle function in the triceps surae is the standing heel-rise test, consisting of repeated eccentric and concentric muscle actions of the calf muscle. The standing heel-rise test involves the so called stretch-shortening cycle (SSC). The effect of the SSC, due to a combination of utilization of elastic energy and myoelectrical potentiation of muscle activation (3, 13, 18) may vary dependent on the velocity of movement and the coupling time between the eccentric and concentric muscle actions (13). A faster speed and a shorter coupling time will enhance the concentric muscle action (13).

To our knowledge there is no clear definition of a heel-rise test regarding neither velocity of movement or coupling time, nor standing position or height of rise. A standing position with increased dorsiflexion of the foot in the starting position, will result in a larger range of movement compared with standing on a horizontal surface. Height of rise will influence the performance, as a shorter range of movement will result in less work performed for each heel-rise and thus allow for a larger number of heel-rises. The importance of keeping a constant knee angle during a heel-rise test has not been documented, but should be considered when standardizing the test.

Furthermore, it is difficult to establish satisfactory criteria that determines when the heel-rise test should be terminated. Such a criteria as "failure to reach a certain height of rise" can be unreliable if it is impossible to document the height of the satisfactory heel-rises, specially in the clinical setting.

It is therefore not surprising that there is some disagreement about the number of heel-rises representing normal capacity. Kendall et al. (11) and Beasley (2) proposed one heel-rise, while Daniels et al. (5) suggested four or five heel-rises. Lunsford & Perry (15) recommended 25 repetitions as normal for both genders from 20 to 59 years of age. One method, used by Lunsford & Perry (15) is to monitor the heel-rises with an electro-goniometer. Along with the number of heel-rises performed, the exact height of rise can be documented and the total work for each heel-rise as well as for the whole test can be calculated. The criteria for termination of the heel-rise test can then be "when the subject is unable to continue due to exhaustion" with actual registration of the range of motion until failure to continue. In the present study we have chosen such a definition. This is also in accordance with the definition of fatigue proposed by Edwards (7) where muscular fatigue has been defined as a failure to maintain the required or expected force, a definition that will be used in this paper. One method to objectivize muscular changes related to fatigue is to follow the shift in electromyographic spectral density, being correlated to a reduction in propagation velocity along the muscle fibres (1, 14) as well as motor unit recruitment, muscle activity level, modification of the action potential, firing rate, temperature and syncronization (for review ref 9).

It was considered of interest to follow separately the changes in mean power frequency (MPF) in the gastrocnemius and soleus muscles, as they may behave differently due to differences in their contractile and metabolic characteristica (6). The results may thus, give further insight in the activation and fatigue process of the muscles in such a functional test as the heel-rise test. The aim of the present study was to investigate the fatigue process of the gastrocnemius and soleus muscles separately in a standardized heel-rise test.

MATERIALS AND METHODS

Subjects

The participants were systematically selected by the Swedish Social Insurance Bureau in Göteborg. The group consisted of ten healthy women with a mean age of 24 years (one SD 3, range 19–28), weight of 67 kg (one SD 8, range 53–75) and height of 167 cm (one SD 4, range 160–173). Their activity scores were documented by choosing one of six different activity levels according to participation in recreational or competitive sports (8). The activity scores of the subjects ranged from three to four on a scale from one to six, indicating a moderate physical activity level. Informed consent was obtained from the participants, and the study was approved by the Ethics Committee of the Faculty of Medicine, Göteborg University, Sweden.

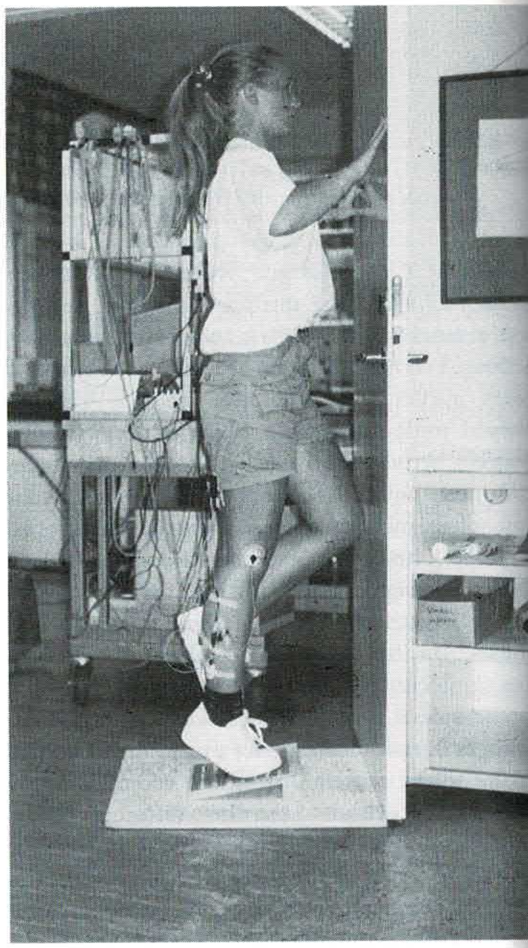

Fig. 1. Illustration of the heel-rise test.

Methods

The subjects were tested twice in the laboratory, with an interval of two to four weeks between tests.

The heel-rise test was performed with the subject standing on the right foot on a wedge tilted 10°, that is with the foot in a 10° dorsiflexed position (Fig. 1). Footwear was standardized. The subject kept her balance by touching the wall with the fingertips of both hands at shoulder level. A metronome was set at a beat corresponding to an angular velocity of approximately $60° s^{-1}$. To measure the range of motion of the ankle joint during testing, an electrogoniometer (Penny and Giles Biometrics LTD, Gwent, UK) was attached to the lower lateral part of the right leg and the lateral edge of the sole. A 90° angle of the ankle joint was defined as when the sole of the foot was perpendicular to the axis of the lower leg. Electromyographic (EMG) activity was recorded with Ag/AgCl surface electrode discs with a diameter of 9 mm (Red Dot, 2239 monitoring electrodes, 3M Medica, Borken, Westfalen, FRG). After shaving and scrubbing the skin with alcohol two electrodes at a distance of approximately 30 mm were secured to the bellies of the gastrocnemius medialis and the soleus muscle in the direction of the muscle fiberes. The reference electrodes were placed on the bony part of the medial and lateral parts of the knee, respectively. The EMG signal was preamplified with a gain of 1000, an input impedance of more than 0.5 MOhm at 50 Hz. a CMRR of more than 100 dB and a bandwidth of 0.5–400 Hz by a HDX-82 (Chattanooga Group, Inc., P. O. Box 489, Hixson, TN 37343, USA) and thereafter band-pass-filtered between 7 and 490 Hz by a KC-EMG (Chattanooga Group, Inc., P. O. Box 489, Hixson, TN 37343, USA). The angle and the EMG were sampled at a frequency of 1250 Hz with a NB-MIO-16L9 (National Instruments Corporation, 6504 Bridge Point Parkway, Austin, TX, USA) on a Macintosh computer with software developed in Lab View (National Instruments Corporation, 6504 Bridge Point Parkway, Austin, TX, USA) by Punos Electronic AB, Göteborg, Sweden. The EMG signal was then additionally band-pass-filtered using a Butterworth filter with cut-off frequencies of 10 and 300 Hz.

Testing procedure

Before testing, the subject warmed up for ten minutes with submaximal bicycling. After a couple of trials with the left foot to allow the subject to become familiar with the testing procedure, the heel-rise test was performed with the right foot. The subject was instructed to lift the heel as high as

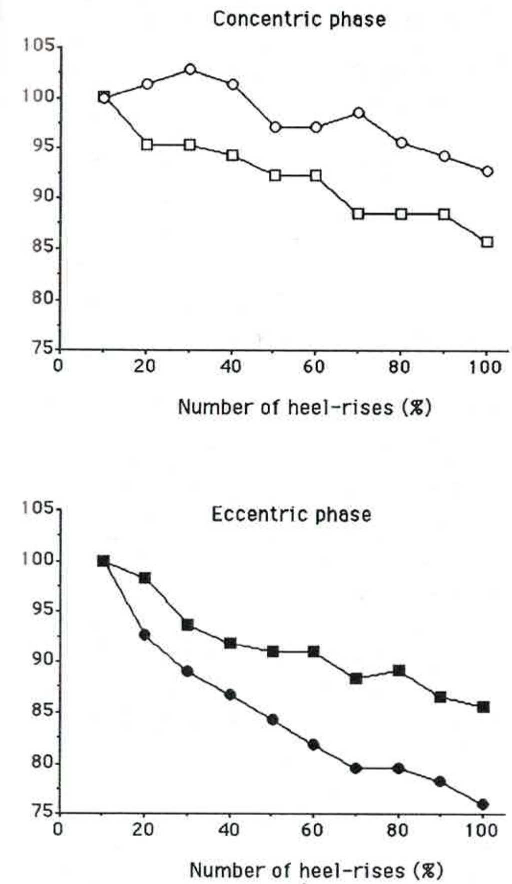

Fig. 2. Mean values for mean power frequency (MPF) in % in both the concentric and the eccentric phases for the gastrocnemius and soleus muscles. The values are normalized to the initial value for each phase and muscle. The abscissa is in % of number of heel-rises performed.

possible at the preset frequency until no further heel-rises could be performed due to exhaustion.

Analysis

The total work for each 10% of the heel-rises performed was calculated according to the formula

$$W = m * g * l * \sum_{t=t_{start}}^{t_{stop}} \omega_t * t$$

where m is the weight of the subject, $g = 9.81\ ms^{-2}$, l is the length of the foot between the axis of rotation of the ankle joint and the metatarsophalangeal joints and ω_t is the angular velocity between each sample. Δt is the time interval between each sample. The interval between t_{stop} and t_{start} is the time during which the calculation was made. Only the calculated work in the concentric phase was used in the analysis. Decrease in work between the first 10 and last 10% of the total number of heel-rises performed and the total amount of work were calculated.

The part of the EMG signal recorded when a velocity of approximately $60° s^{-1}$ was reached was *separately* derived for the concentric and the eccentric phases, by observing the angle of the ankle joint from the goniometer. The same range of motion was derived for all heel-rises for the same test. For each such part, the average of the amplitude of the rectified signal was calculated using the root mean square (RMS) method. Each part was modified by a Hanning window and a zero padder before Fast Fourier Transformation was used to obtain the mean power frequency (MPF). The development of the MPF and RMS was calculated with simple regression analysis, and then reported as percent decrease from the initial value. This was done separately for the concentric and eccentric phases. For all subjects the mean MPF and RMS value for each ten percent of the test was calculated. The mean values for every ten percent from all subjects were then normalized to the initial ten percent value for each phase and muscle and plotted.

Statistical methods

Mean and standard errors of the mean (±) are given and calculated with conventional methods. Wilcoxon's one-sample non-parametric test was used for differences. The Spearman Rank correlation coefficient was calculated. The level of significance used in this paper was 0.05, with two-tailed test. The mean values of the two tests were used. For calculations of methodological error in percent, the following formula (4) was used:

$$\frac{\sqrt{\sum(D^2)/2n}}{\bar{x}}$$

where D is the difference between the tests, n is the number of subjects and $\bar{x}$ is the mean value. The errors for duplicate determinations were 19% for the total amount of work and 8% for the number of heel-rises.

RESULTS

Work

The average number of heel-rises performed before exhaustion was 25 ± 1 (range 15–32). The total amount of work produced during the concentric phases was calculated to be 1449 ± 118 J. The decrease in work in the concentric phase was significant and $26 \pm 7\%$ due to a successively shorter range of motion starting with $36 \pm 2°$ and ending with $25 \pm 3°$.

Electromyographic activity

All decreases of MPF were significant. In the concentric phase the decreases were $13 \pm 2\%$ in the soleus and $9 \pm 3\%$ in the gastrocnemius muscle with

Table I. *Start values of MPF (SEM) in Hz and RMS (SEM) in µV for each muscle and phase in the heel-rise test*

	Start values of MPF		Start values of RMS	
	Concentric	Eccentric	Concentric	Eccentric
m. Soleus	106 (5)	114 (4)	1728 (221)	848 (78)
m. Gastrocnemius	75 (2)	82 (3)	2715 (279)	1170 (146)

no significant difference ($p = 0.20$) between the two muscles. In the eccentric phase the decreases were $15 \pm 2\%$ in the soleus and $20 \pm 2\%$ in the gastrocnemius muscle. The MPF decreased significantly more during the eccentric phase ($p = 0.04$) in the gastrocnemius than in the soleus muscle (Fig. 2). Start values of the MPF are seen in Table I.

The correlation between the decreases of work and MPF was significant ($r = 0.57$; $p = 0.02$). The correlation between the number of heel-rises and the decrease of MPF was non-significant ($r = 0.23$; $p = 0.37$). In the concentric phase there were no significant changes in RMS concomitant with the reduction in work. However, there was a tendency towards an initial increase in RMS. In the eccentric phase the pattern was different, where the soleus showed a significant successive fall in RMS, whereas there was no significant change in the gastrocnemius muscle (Fig. 3). Start values of the RMS are seen in Table I.

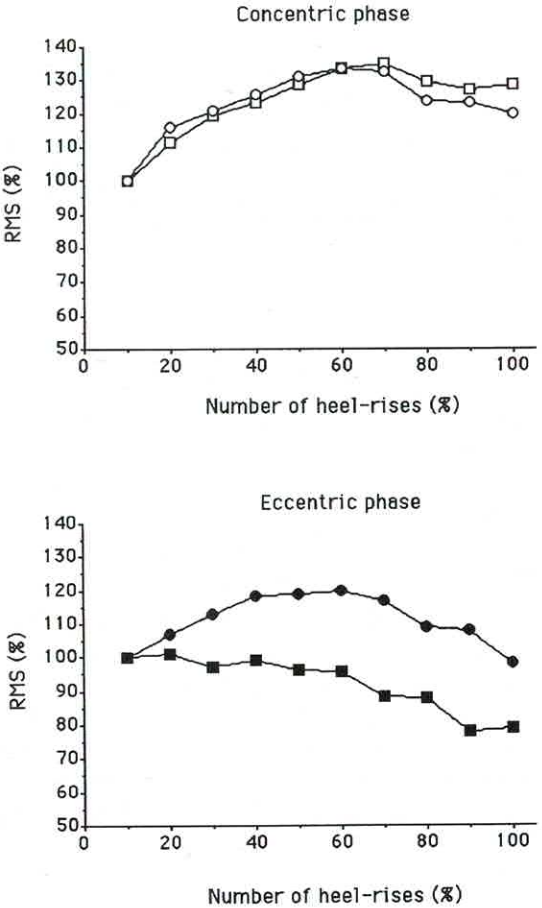

Fig. 3. Mean values for RMS in % in both the concentric and the eccentric phases for the gastrocnemius and soleus muscles. The values are normalized to the initial value for each phase and muscle. The abscissa is in % of number of heel-rises performed.

DISCUSSION

In the present study we have demonstrated that during a standing heel-rise test, performed until exhaustion, there is a decrease in work and MPF of the EMG. The gastrocnemius muscle developed a larger fall in MPF in the eccentric phase, while there was a tendency towards a larger fall in the soleus muscle during the concentric phase, most likely due to different activation patterns of the two muscles in these two phases. The subjects in the present study could on an average perform 25 heel-rises, which is in agreement with Lunsford & Perry (15), who recommended that 25 repetitions represent normal capacity in healthy subjects.

As the muscular activity was submaximal at the beginning of the heel-rise test, both muscles showed successively increased EMG activity during the concentric phase, seen in Fig. 3 as an increase in the RMS during the first part of the test. Also Löscher et al. (16) found increasing RMS values during submaximal contractions of the plantar flexion. The gastrocnemius muscle showed then in the concentric phase a tendency towards a later decrease in MPF than the soleus muscle, which may depend on a lower initial activation in the gastrocnemius muscle in this phase.

In contrast to its activity in the concentric phase, the soleus showed successive reduction in EMG activity in the eccentric phase. In the gastrocnemius muscle less reduction in RMS values and a larger reduction in MPF were recorded. The MPF values indicated that, in the eccentric phase, the soleus muscle would be less fatigued than the gastrocnemius muscle, to which reduction in muscle activation as well as its muscle fiber characteristics with the dominance of type I fibers (6) might contribute.

It is important to recognize that the design of the test, with repeated eccentric-concentric muscle actions, limits the possibility of comparing the development of fatigue during these two types of muscle activities. As the metabolic changes in the muscle fibers during one phase also have an effect on the following phase, it is difficult to separate the conditions in the different phases in the present setting. This also limits any effect of the differences in energy consumption between eccentric and concentric muscle work (12) on the measurements in the present study. On the other hand, a rhythmic type of muscle activity normally occurs in different types of daily activities such as walking. The pattern of fatigue development in the present study is therefore representative of such situations, even though the angular velocities are different.

In many functional settings, such as the heel-rise test, the close chain exercise is used and is characterized by complex movements. The present results are in accordance with the findings of Jacobs et al. (10), who demonstrated that, in a closed-chain activity as in running, a mono-articular muscle (soleus) appears to be more active than a biarticular muscle (gastrocnemius) in concentric work. During the eccentric phase, however, the estimated muscle force was low in a mono-articular muscle (soleus) and high in a biarticular muscle (gastrocnemius) (10). Moritani et al. (17) also concluded that the gastrocnemius muscle was specially affected by fatigue-induced changes during the eccentric phase of repeated maximal stretch-shortening cycles of the ankle extensors.

The findings in the present study are in contrast to those obtained with an isokinetic dynamometer test, which is an open chain activity, using repeated eccentric and concentric muscle actions, where the gastrocnemius muscle tended to show larger reductions in MPF than the soleus muscle, both in the eccentric and the concentric phases (unpublished observations). Thus, it seems that there are differences between open and closed-chain muscle activities with respect to activation and fatigue patterns of the two muscles. Further studies are necessary to understand the nature of the changes in motor neuron activation.

The present results, showing significant decreases of work concomitantly with decreases in MPF, indicate that the standing heel-rise test causes fatigue in the calf muscle. Also the correlation between the decreases of work and MPF indicates that the development of fatigue is related to changes in the internal environment of the muscle fibers. The lack of correlation between the reduction in MPF and number of heel-rises may indicate that the tests were performed until fatigue irrespective of number of repetitions. Our recommendation is therefore that the standing heel-rise test should be performed as described in the present study with maximal heel-rises until exhaustion. It is important to standardize both range and rate of motion, keeping in mind that a faster speed and shorter coupling time favour a better utilization of the stretch-shortening cycle (13).

CONCLUSIONS

For research purposes measurements of performed work, EMG and joint motion should be included, whereas for clinical use the test can be carried out in a standardized manner with determination of maximal number of heel-rises. Our results point towards differences in activation patterns for the gastrocnemius and the soleus muscles, which can be of importance in different clinical conditions, such as calf muscle atrophy and changes in the motor control.

ACKNOWLEDGEMENTS

This study was supported by grants from the Swedish Medical Research Council (Project No. 03888), Asker's Foundation, Hjalmar Svensson's Foundation, the Swedish Centre for Sport Research and the Dr Gunnar Svantesson Foundation. Thanks are due Ms Marielle Peeters for valuable cooperation and for skillful technical assistance.

REFERENCES

1. Basmaijan, J. V. & DeLuca, C. J.: Muscles alive. Their functions revealed by electromyography. Baltimore, USA. Williams & Wilkins, 1985.

2. Beasley, W. C.: Quantitative muscle testing: principles and applications to research and clinical services. Arch Phys Med Rehabil June: 398–425, 1961.
3. Bosco, C., Tarkka, I. & Komi, P. V.: Effect of elastic energy and myoelectrical potentiation of triceps surae during stretch-shortening cycle exercise. Int J Sports Med *3:* 137–140, 1982.
4. Dahlberg, G.: Statistical methods for medical and biological students. Allen and Unwin, London, 1940.
5. Daniels, L., Williams, M. & Worthingham, C.: Muscle testing: Techniques of manual examination. 2nd ed. Philadelphia, Pa: WB Saunders Co, 1956.
6. Edgerton, V. R., Smith, J. L. & Simpson, D. R.: Muscle fiber type populations in human leg muscles. Histochem J *7:* 259–266, 1975.
7. Edwards, R. H. S.: Human muscle function and fatigue: physiological mechanisms. In: Ciba Foundation Symposium. Pitman Medical London *82:* 1–18, 1981.
8. Grimby, G.: Physical activity and muscle training in the elderly. Acta Med Scand Suppl 711: 233–237.
9. Hägg, G.: Interpretation of EMG spectral alteration and alteration indexes at sustained contraction. Am Physiol Soc *73:* 1211–1217, 1992.
10. Jacobs, R., Bobbert, M. F. & van Ingen Schenau, G. J.: Function of mono- and biarticular muscles in running. Med Sci Sports Exerc *25:* 1163–1173, 1993.
11. Kendall, H. O., Kendall, F. P. & Wadsworth, G. E.: Muscles: testing and function. 2nd ed. Baltimore, Williams & Wilkins Company, 1971.
12. Knuttgen, H. G.: Human performance in high-intensity exercise with concentric and eccentric muscle contractions. Int J Sports Med (Suppl.) 7: 6, 1986.
13. Komi, P. V.: Physiological and biomechanical correlates of muscle function: effects of muscle structure and stretch-shortening cycle on force and speed. *In* Exerc Sport Sci Rev (ed. R. L. Terjung), New York, USA. pp 81–121, 1984.
14. Lindström, L., Magnusson, R. & Petersén, I.: Muscular fatigue and action potential conduction velocity changes studied with frequency analysis of EMG signals. Electromyography *4:* 341–353, 1970.
15. Lunsford, B. R. & Perry, J.: The standing heel-rise test for ankle plantar flexion: Criterion for normal. Phys Ther *75:* 8, 49–53, 1995.
16. Löscher, W. N., Cresswell, A. G. & Thorstensson, A.: Electromyographic responses of the human triceps surae and force tremor during sustained submaximal isometric plantar flexion. Acta Physiol Scand *152:* 73–82, 1994.
17. Moritani, T., Oddsson, L. & Thorstensson, A.: Electromyographic evidence of selective fatigue during the eccentric phase of stretch/shortening cycles in man. Eur J Appl Physiol *60:* 425–429.
18. Svantesson, U., Grimby, G. & Thomée, R.: Potentiation of concentric plantar flexion torque following eccentric and isometric muscle actions. Acta Physiol Scand *152:* 287–293, 1994.

Accepted May 27, 1997

Address for offprints:

Ulla Svantesson
Department of Rehabilitation Medicine
Sahlgrenska University Hospital
Guldhedsgatan 19
SE-413 45 Göteborg
Sweden