MUSCULAR ACTIVITY DURING ERGOMETER CYCLING

M. O. Ericson, R. Nisell, U. P. Arborelius and J. Ekholm

From the Kinesiology group, Departments of Physical Medicine and of Anatomy, Karolinska Institute, Stockholm and the Department of Physical Medicine and Rehabilitation, Karolinska Hospital, Stockholm, Sweden

ABSTRACT. The aim of the study was to quantify the activity as recorded by electromyography during ergometer cycling in eleven different muscles of the lower extremity. Eleven healthy subjects rode in twelve different ways at different work-load, pedalling rate, saddle height and pedal foot position. Vastus medialis and lateralis, gastrocnemius medialis and lateralis and the soleus muscle were the most activated muscles. Changes in muscle activity during different calibrations were studied in eight of the eleven muscles. An increase in work-load significantly increased the mean maximum activity in all the eight muscles investigated. An increase of the pedalling rate increased the activity in the gluteus maximus, gluteus medius, vastus medialis, medial hamstring, gastrocnemius medialis and soleus muscles. An increase of the saddle height increased the muscle activity in the gluteus medius, medial hamstring and gastrocnemius medialis muscles. Use of a posterior pedal foot position increased the activity in the gluteus medius and rectus femoris muscles, and decreased the activity in the soleus muscle.

Key words: Biomechanics, electromyography, exercise, models biological, physical therapy, rehabilitation.

The bicycle ergometer is a widely, used exercise equipment. Cycling has often been employed in the rehabilitation of patients with various dysfunctions of the lower limb (4, 16, 18, 20). In the rehabilitation of many groups of patients it is desirable to increase muscular strength and endurance. These current or possible fields of use of the bicycle ergometer make it important to investigate how cycling affects the activity of the leg muscles. The magnitude of EMG activity during cycling should be compared with the muscle activity obtained during normal level walking (6, 9, 19). Such comparison between cycling and walking may be valuable in the evaluation of cycling as an exercise in gait rehabilitation. It is also important and interesting how the muscle activity is changed with different adjustments of the bicycle or the cycling technique. Bicycle ergometer exercise may also be useful in training the circulatory and respiratory systems. In these cases one may also have to consider the loading effects on the lower limb.

The muscular activity during cycling has been studied from several points of view (1,2, 5, 15, 17, 20, 21, 26, 28, 29). As far as we know, no proper quantification of the muscular activity during cycling has been presented, nor has the change of muscular activity from different adjustments of the bicycle ergometer been studied. Hence there has been no discussion of the leg muscle training effects caused by cycling in relation to muscle activity data. Houtz et al. (15) and Carlsöö (5) used direct electromyogram to identify the muscles activated during cycling. These investigations also studied the temporal distribution of the muscular activity throughout a complete revolution. However, the EMG activity in these studies was not quantified.

The aim of the present study was to quantify the activity of the major muscle groups used during exercise on a bicycle ergometer and to study the effects of work-load, pedalling rate, saddle height or pedal foot position. Such information would be useful both in the evaluation of different effects on participating muscles, and for further study of joint mechanics during cycling.

Toe clips that fix the foot to the pedal have earlier been described as improving the pedalling efficiency (12, 30, 31). They are used by racing cyclists to make it possible to pull the pedal upwards, i.e. the pedal upstroke. Consequently, toe clips allow the cyclist to use all major lower limb muscles during nearly the entire pedal revolution. In the present investigation the use of toe clips was studied in order to quantify its effets on the muscle activity.

MATERIAL AND METHODS

Eleven subjects, all men aged between 20–32 years, participated in the study. Their average height and weight were 1.84 m (SD = 0.04) and 75.5 kg (SD = 6.5). The subjects were students with ordinary recreational cycling experience, and none were suffering from leg pain, or any other impairments of the locomotor system.

A bicycle ergometer with a weight loaded braking system (Cardionics, Stockholm, Sweden) was used. A switch was mounted on the bicycle ergometer for marking the top position of the crank on an EMG-order. Time was registered on the EMG-recorder parallel with EMG and crank top position, using signals from a specially-designed time indication panel. For purposes of control and registration of the kinematics of the lower limb the test situations were recorded using a TV camera (25 frames/second). The TV camera was mounted perpendicular to the sagittal plane of the subject at a distance of 5.0 m. The time from the time indication panel was displayed on each TV-frame. A metronome was used to enable each subject to find and keep the correct pedalling rate.

The variables studied in the experiment were: 1) work-load, 2) pedalling rate, 3) saddle height, 4) foot position and 5) toe-clips. The different work-loads chosen were zero, 120 and 240 watt (W), and the pedalling rates were 40, 60, 80, and 100 revolutions per minute (rpm). Three different saddle heights "high, mid and low" were determined as a percentage (120, 113, 102 %) of the distance between the ischial tuberosity and the medial malleolus of the ankle measured on each subject (10). The saddle height was measured as the greatest distance from saddle surface to the centre of the upper pedal surface in a straight line along saddle pillar and crank. Two foot positions, one anterior and one posterior, were used. The anterior was defined as the position when the centre of the pedal was in contact with the head of metatarsus II (ball of foot), and the posterior foot position aproximately 10 cm backward (instep). The choice of these bicycle parameters is discussed in an earlier study of Ericson et al. (10). In one of the eleven test situations studied the subjects cycled with toe clips.

When one of the four variables was changed and studied, the other there were held constant. 120 W, 60 rpm, mid saddle and anterior foot position were chosen as constant variables. These values were also selected for the "standardized ergometer cycling" adjustment (10) studied in this experiment. All the subjects were allowed to warm up and practice for five minutes at the standardized ergometer cycling adjustment described above. In order to eliminate systemic effects of fatigue, the internal sequence of the different exercise situations was randomized. The different work-loads were regulated by adding weights (0, 2, 4 kg) to the weight braked bicycle ergometer. The saddle heights determined as previously described were adjusted to the nearest fixed saddle position with a maximum error of ±1.5 cm. The handlebars were kept level with the saddle. The cyclist's trunk was inclined forwards 20–30 degrees from the vertical.

The muscular activity during ergometer cycling was studied in the muscles listed in Table I. Two flexible disposable surface Ag-AgC1 electrodes, with a centre inter-electrode distance of approximately 40 mm, were placed in the main direction of the muscle fibres, after reducing the skin impedance with rubbing acetone. The electrode position for each muscle investigated is described in Table I. The term "medial hamstring" is used for the position of the electrode-pair over the semitendinosus and semimembranosus muscles.

The muscular activity was recorded (Devices M4, AC8 and Neurolog NL 103, 104) by means of full wave rectified, low pass filtered and time averaged electromyograms (linear envelope EMG) (8, 32). The bandwith was 10 Hz to 1.5 kHz. The time integrator constant was 100 ms. For control of disturbances caused by e.g. electrode dislocation, direct EMG was recorded in parallel on a UV-recorder (Honeywell, Visicorder 1508).

In order to quantify the muscular activity and to compare the activity between different muscles and between different subjects an EMG normalization was performed (3, 6, 7, 8, 24, 25, 27, 33). The EMG activity recorded during the test situations was related to the EMG activity recorded during a brief (5-second) maximum isometric voluntary muscular contraction (isometric MVC). The attempted movement and joint positions in which the isometric MVC of the different muscles was performed is shown in Table I. The hip extension contraction was performed in an exercise table (OB Combi Trainer device, LIC Rehab, Solna, Sweden) with the hip flexed approximately 45 degrees. This type of isometric hip extension was similar to that described by Németh et al. (23). The knee extension and flexion were also performed in the exercise table with the knee flexed approximately 45 degrees. Lying on the floor the subject abducted his leg against manual resistance. The maximum plantar flexion was performed by the subjects standing with the ankle joint in mid position and the complete sole of the foot in contact with the floor. The subjects were instructed to attempt to rise onto their toes against manual resistance applied to the shoulders. The ankle dorsiflexion was performed against manual resistance when the subjects were lying supine with the knee flexed (40–50 degrees).

The EMG activity recorded during the "standardized ergometer cycling" mode used is expressed as a percentage of the EMG activity recorded during isometric MVC. Similar EMG normalization methods have also been described and used elsewhere (3, 6, 7, 8, 24, 25, 27, 33).

The maximum EMG activity level for each of approximately 25 complete pedal revolutions was measured and analyzed for each muscle and test situation investigated. The median value of these 25 samples was used in the further analyses. The statistical significance of the differences in activation caused by changes of work-load, pedalling rate, saddle height and foot position was tested by means of ANOVA. The EMGs of vastus lateralis, gatrocnemius lateralis and tibialis anterior muscles were studied only in standardized ergometer cycling and the use of the toe clips.

RESULTS

The mean maximum muscular activity values obtained during standardized ergometer cycling for the eleven muscles investigated are shown in the right column in Table I. The mean (11 subjects) muscle activation curves (normalized EMG) for a

Table I. *The muscles investigated, the approximate position of the bipolar electrodes, the attempted movement (isometric) and joint position at which the EMG normalization was performed*

d = distance. SIAS = Spina iliaca anterior superior. deg. = degrees, pos. = position

Muscle	Electrode position	EMG-normalization type of isometric contraction	Joint position	EMG as percent of max during standardized ergometer cycling (SD)
Gluteus maximus	20% of d between spinous process S2 and a point 10 cm distal to greater trochanter	Hip extension in exercise table	45 deg. hip flexion	7 (5)
Gluteus medius	10 cm distally on a line from gluteus medius insertion towards greater trochanter	Leg abduction against manual resistance lying on the floor	Mid hip joint pos.	11 (6)
Rectus femoris	50% of d between SIAS and apex of patella	Knee extension in exercise table	45 deg. knee flexion	12 (7)
Vastus medialis	20% of d between SIAS and medial knee joint space	Knee extension in exercise table	45 deg. knee flexion	54 (19)
Vastus lateralis	25% of d between SIAS and lateral knee joint space	Knee extension in exercise table	45 deg. knee flexion	50 (23)
Biceps femoris	50% of d between ischial tuberosity and caput fibulae	Knee flexion in exercise table	45 deg. knee flexion	12 (7)
Medial hamstring	50% of d between ischial tuberosity and the medial knee joint space	Knee flexion in exercise table	45 deg. knee flexion	10 (6)
Gastrocnemius medialis	35% of d between medial knee joint space and tuberosity of calcaneous	Ankle plantar flexion standing on floor rising against manual resistance	Mid ankle joint pos.	19 (9)
Gastrocnemius lateralis	30% of d between lateral knee joint space and tuberosity of calcaneous	Ankle plantar flexion standing on floor rising against manual resistance	Mid ankle joint pos.	32 (11)
Soleus	50% of d between head of fibula and tuberosity of calcaneus	Ankel plantar flexion standing on floor rising against manual resistance	Mid ankle joint pos.	37 (13)
Tibialis anterior	75% of d between lateral knee joint space and lateral malleolus	Dorsiflexion against manual resistance lying supine with 30 deg. knee flexion	Mid ankle joint pos.	9 (5)

complete 360 degree pedal revolution during standardized ergometer cycling are shown in Fig. 1.

In order to test whether one of the four variables studied significantly influenced the EMG activity, the other three variables were held constant. The muscular activity in eight of the eleven investigated muscles is shown in Table II. The activity listed in Table II is expressed as a percentage of the activity obtained during "standardized" ergometer cycling (120 W, 60 rpm, mid saddle height and anterior foot position). The statistical significances of these alterations is shown in Table III. Table III also shows whether the muscle activity generally decreased, remained equal or increased when work-load, pedalling rate, saddle height or foot position were changed.

An increased work-load significantly increased the muscle activity in all the eight muscles investigated during different work-loads. Increased pedalling rate significantly increased muscle activity with the exception of the rectus and biceps femoris muscles. An increased saddle height caused an increased muscle activity in the gluteus medius, medial hamstring and gastrocnemius medialis muscles. The other five muscles investigated were not significantly influenced by changes of saddle height.

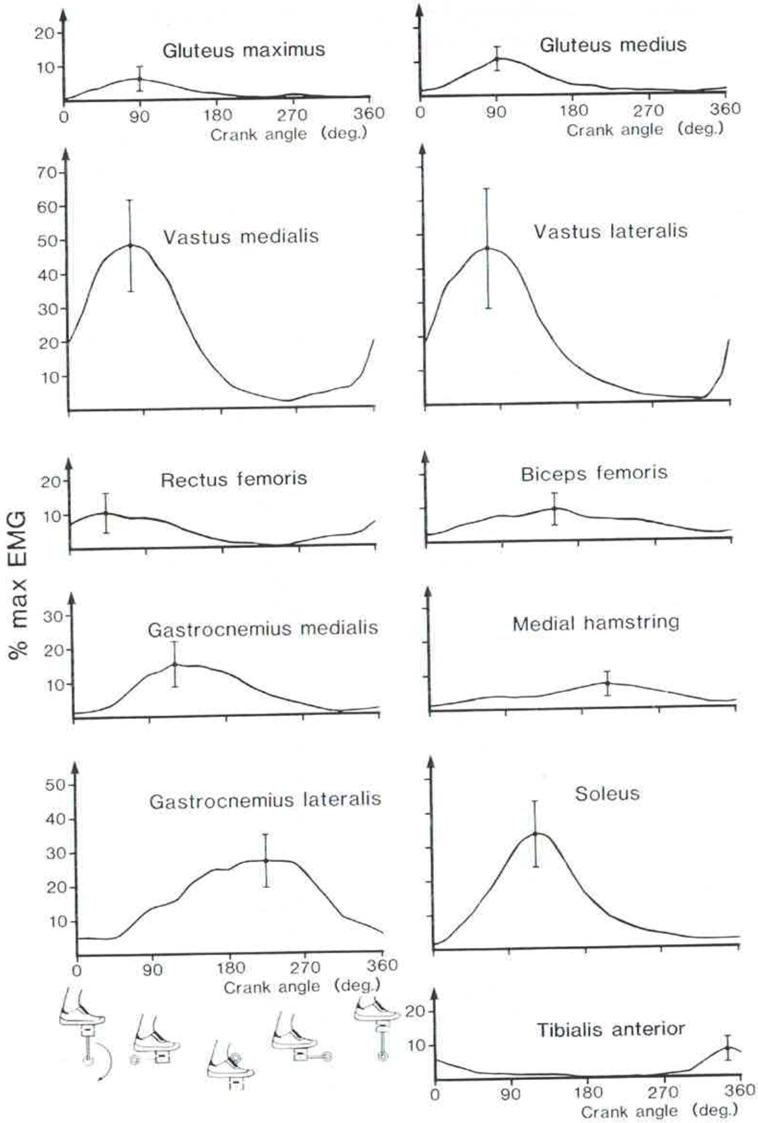

Fig. 1. Temporal distribution and mean magnitude of muscle activity in eleven lower limb muscles during ergometer cycling. X-axis: degrees crank angle. 0 and 360 degrees crank angle correspond to top position of pedal and crank. Y-axis: magnitude of muscular activity expressed as a percentage of maximum isometric EMG activity (at standardized test contraction). At the peak activity the 95 percent confidence interval of the mean is indicated.

The use of the anterior foot position (ball of foot) at the mid saddle height significantly reduced the muscle activity obtained in the gluteus medius and rectus femoris muscles. The soleus muscle was the only muscle which significantly increased its activity with a change of foot position from the posterior (instep) to the anterior.

Toe clips significantly increased the muscular activity in the rectus femoris, biceps femoris and tibialis anterior muscles (Tables II and III). The tibialis anterior activity increased from 9 to 18%. The activity was significantly decreased in the vastus medialis, vastus lateralis (from 50 to 43% of max EMG) and soleus muscles when using toe clips.

DISCUSSION

Compared to earlier studies of EMG activity and duration during cycling (5, 15, 20, 28) we did not reveal any major contradictions in the muscle activity pattern. These earlier studies were performed with direct EMG technique, providing a lower degree of quantification than can be obtained by use of the envelope EMG (6, 7, 8, 25, 32). The number

Table II. *The mean value of changes in muscular activity (EMG) due to changes of the ergometer work-load, pedalling rate, saddle height, foot position or toe clips*

Each value is expressed as percent of the EMG activity obtained during standardized ergometer cycling

Variables	Gluteus maximus	Gluteus medius	Rectus femoris	Vastus medialis	Biceps femoris	Medial hamstring	Gastroc. medialis	Soleus
Work-load								
0 W	2	14	10	7	44	64	118	17
120 W[a]	100	100	100	100	100	100	100	100
240 W	556	278	217	158	189	306	139	156
Pedalling rate								
40 rpm	53	80	121	77	115	124	72	83
60 rpm[a]	100	100	100	100	100	100	100	100
80 rpm	151	122	111	110	143	156	166	108
100 rpm	373	151	123	116	146	228	209	112
Saddle height, foot pos.								
Low saddle								
Instep	90	98	136	108	102	119	68	32
Ball of foot	105	101	116	102	144	137	75	81
Mid saddle								
Instep	108	135	152	109	98	97	90	54
Ball of foot[a]	100	100	100	100	100	100	100	100
High saddle								
Ball of foot	135	134	122	97	183	215	236	97
Toe-clips								
Toe clips, 120 W	91	98	184	82	189	171	138	86

[a] Constant variables, included in standardized ergometer cycling (120 W, 60 rpm, mid saddle height and anterior foot position).

of subjects in the present study was eleven compared to the earlier studies that included between two and six subjects.

The gluteus maximus muscle showed the lowest EMG peak activity (7% of isometric MVC) among the muscles investigated. It was active during the force thrust phase (first 180 degrees crank angle). The activity pattern agrees with the function of this muscle as a hip extensor. The activity was significantly increased by an increase in work-load or pedalling rate.

The gluteus medius muscle had a low peak activity (11%) and might be active as a hip extensor during the force thrust phase. During this phase

Table III. *The significance of changes in muscle activity (EMG) due to changes of the ergometer work-load, pedalling rate, saddle height, foot position or toe clips statistically analyzed by means of ANOVA*

Muscle	Increased work-load	Increased pedalling rate	Increased saddle height	Anterior foot position instead of posterior	Toe-clips
Gluteus maximus	+++	+++	ns	ns	ns
Gluteus medius	+++	+++	+	Decr $p<0.05$	ns
Rectus femoris	+++	ns	ns	Decr $p<0.05$	+++
Vastus medialis	+++	+++	ns	ns	Decr $p<0.001$
Biceps femoris	+++	ns	ns	ns	+
Medial hamstring	+++	+	+	ns	ns
Gastrocnemius medialis	+	+++	+++	ns	ns
Soleus	+++	++	ns	+	Decr $p<0.05$

+ = increased activity, ns = no significant change of activity, decr = decreased activity. One plus sign = $p<0.05$, two signs = $p<0.01$, three signs = $p<0.001$.

medially directed pedal reaction forces are present producing a varus knee load moment (11). Probably the pedal reaction forces acting in the coronal plane also produce an adducting loading moment on the hip joint, counteracted by the hip-abducting gluteus medius muscle. An increase in work-load and pedalling rate were the two most important ways of increasing the gluteus medius muscle activity.

The rectus femoris muscle showed a low peak activity (12%) in comparison with the other two quadriceps muscles studied i.e. the vastus medialis and lateralis. This difference is probably explained by the fact that rectus is a two-joint muscle, and produces moments of force that tend to flex the hip and extend the knee. On the occurrence of activity during a pedal revolution, both the hip and knee are extending. Therefore it seems most likely that the rectus muscle is more important as a knee extensor during cycling. The low activity indicates that cycling is not a very effective exercise for training the rectus femoris muscle. However, it is worth noting that the rectus peak activity could be increased to approximately 25% of its isometric activity by an increase in the work-load to 240 W.

In contrast to rectus femoris the other two quadriceps muscles studied, i.e. the vastus medialis and lateralis, were the two most activated muscles with a mean peak activity of 54 and 50% respectively. These muscles were active during the phase where the knee was extending and the pedal forces were greatest (14) (from approximately 330 to 180 degrees crank angle). Based upon the present data it can be concluded that the vastus muscles are very important muscles for the cycling motion. However, the present study has shown that rectus femoris is less activated than the vasti. The vastus lateralis muscle was not investigated at all the different adjustments, but most probably vastus lateralis reacts mainly as vastus medialis to adjustments. The activity of the vastus medialis muscle was increased by an increase in work-load or pedalling rate, and was also significantly higher, at level $p<0.10$ when using the posterior foot position instead of the anterior.

The biceps femoris muscle had a low peak activity (12%) and was active during the whole revolution except for a short period when the pedal passed its highest position at approximately zero degrees crank angle. The biceps muscle activity was changed only by a change of the work-load.

The medial hamstring muscles, i.e. the semitendinous and semimembranous muscles, showed low peak activity (10%). They were mainly active during 150 to 270 degrees crank angle. The activity in the medial hamstring was significantly increased with an increase of the work-load, pedalling rate or saddle height.

The gastrocnemius medialis and lateralis muscles were moderately activated during standardized ergometer cycling (19% and 32% respectively). Their function seems to be to push the pedal through its lowest position, placing the contralateral pedal at the starting position of its force thrust phase, and together with other plantar flexors counteracting the dorsiflexing ankle load moment during the force thrust phase (10). The activity in the gastrocnemius medialis muscle was mainly increased by an increased pedalling rate or saddle height. The soleus muscle was rather active (37%) during standardized ergometer cycling, and mainly during the force thrust phase. The activity was significantly increased by an increase in work-load, pedalling rate or the use of the anterior foot position. The activity was increased (significance level $p<0.10$) by an increased saddle height.

We wish to stress that the gastrocnemius medialis activity was not changed by a change of foot position. This is remarkable because the mean maximum ankle load moment is increased by approximately 100% when changing from the posterior to the anterior foot position (10). In contrast to gastrocnemius medialis, the activity in soleus was influenced by change of foot position. The difference in behaviour between soleus and gastrocnemius muscles may be explained by the fact that soleus is a postural muscle (13) and that the ankle load moment is rather low and static in nature (10). Another complicating factor is that gatrocnemius is a two-joint muscle, with mechanical possibilities to act either as knee joint flexor or extensor (22).

The tibialis anterior muscle exhibited low activity (9%), and was active only during 300 to 60 degrees crank angle, i.e. when the pedal was passing its highest position. During this phase of the pedal revolution, the ankle joint was in its most dorsiflexed position.

The increase in rectus and biceps femoris and tibialis anterior muscle activity during the pedal upstroke when introducing toe clips is most likely caused by these muscles helping to pull the pedal up (30). The rectus muscle is also acting as a hip flexor, the biceps muscle as a knee flexor and the

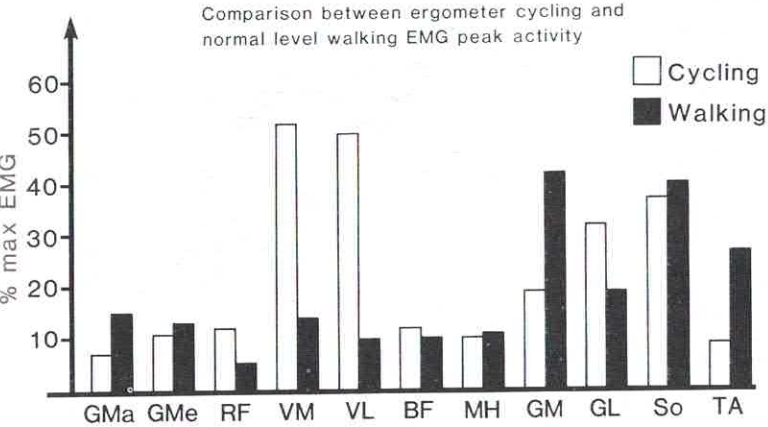

Fig. 2. Mean EMG peak activity (as % of max test contraction) during ergometer cycling determined in the present study compared to mean peak activity during level walking reported by Ericson et al. 1985. GMa = Gluteus maximus, GMe = Gluteus medius, RF = Rectus femoris, VM = Vastus medialis, VL = Vastus lateralis, BF = Biceps femoris, MH = Medical hamstring, GM = Gastrocnemius medialis, GL = Gastrocnemius lateralis, So = Soleus, TA = Tibialis anterior. (n=10, same subjects in both studies.)

tibialis anterior muscle as a dorsiflexor of the foot. The use toe-clips during the pedal upstroke probably decreases the simultaneous joint load in the contralateral limb. This decrease in joint load during the force thrust phase is then reflected in significantly decreased activity in the vastus medialis, vastus lateralis and soleus muscles. Thus it is likely that the knee and ankle joint load is decreased during the downstroke when toe clips are used. Actively used toe clips alter the mechanical situation and potential of some muscles. The present study shows that some of the muscles with a low activity during ordinary cycling obtained a higher activity through the use of toe clips and some muscles with high activity decreased their activity. However, the use of toe clips needs further investigation concerning loading moment of force in the hip, knee and ankle joints.

In spite of the fact that cycling is a reciprocal movement (28), the peak amplitude of the electromyographic activity changed from revolution to revolution. The activity for each subject was therefore computed as the median value of a sequence of peak values from 25 pedal revolutions. The temporal pattern of the muscle activation was much more regular and consistent than the amplitude.

Our results show that the vastus medialis and lateralis, gastrocnemius medialis and lateralis and the soleus muscles were the most activated muscles during standardized ergometer cycling. A change of the ergometer work-load was the most effective way to change the level of activity. For the gluteus maximus, gluteus medius, medial hamstring and gastrocnemius medialis muscles, an increase in pedalling rate was effective to increase the muscular activity. An increase in saddle height effectively increased the activity in the medial hamstring and gastrocnemius medialis muscles. The use of the posterior foot position significantly increased the activity in the gluteus medius, rectus femoris and vastus medialis muscles. The use of the anterior foot position instead significantly increased the activity in the soleus muscle. Toe clips significantly increased the activity in the rectus and biceps femoris and tibialis anterior muscles and decreased the activity in the vastus medialis, vastus lateralis and soleus muscles.

Prior to the bicycling experiments, ten of the eleven subjects participating in the present study was also allowed to walk at their natural speed and stride length. The temporal distribution and magnitude of EMG activity obtained during level walking for these ten subjects has been reported elsewhere (9). In the evaluation of cycling as an exercise in medical rehabilitation, a comparison between level walking and cycling might be of interest. A comparison between the magnitudes of muscular activity obtained during level walking and standardized ergometer cycling is shown in Fig. 2. The major difference in muscle activity between cycling and walking was the 4-to-5-times-greater activity in the vastus medialis and vastus lateralis muscles obtained during cycling. The tibialis muscle was 3 times more activated during walking than during cycling. There were also significant differences ($p<0.05$) in muscle activity in the rectus femoris and the two gastrocnemius muscles. The gastrocnemius medialis was more active during walking and gastrocnemius lateralis more activated during cycling. The soleus muscle showed no difference in mean peak activity between cycling and walking. The two-joint function (knee and ankle joint) of the gastrocnemius muscles may have influenced the difference in activity between the two gastrocnemius muscles during cycling and walking. Thus, differences in knee and ankle joint motion utilized during cycling and walking influenced the activity pattern found in the two gastrocnemius muscle bellies. However, the significant difference between the gatrocnemius medialis and lateralis is uncertain and needs further investigation. For the other five muscles investigated there was no major difference in magnitude of peak activity. The activity in the two vastus muscles investigated was far more activated during the cycling exercise than during walking, which supports the general opinion of cycling being good for strengthening the knee extensor muscles. To increase the activation of tibialis anterior during cycling, toe-clips can be used. It can be concluded that during standardized ergometer cycling the magnitude of muscle activity in all major lower limb muscles, except the tibialis anterior, is approximately level with, or greater than, that exhibited during normal level walking.

ACKNOWLEDGEMENTS

This study was supported by grants from the Swedish Medical Research Council (5720) and the Karolinska Institute.

REFERENCES

1. Benecke, R., Conrad, B., Meinck, H. M. & Höhne, J.: Electromyographic analysis of bicycling on an ergometer for evaluation of spasticity of lower limbs in man. *In* Advances in Neurology (ed. J. E. Desmedt), *39*: 1035, 1983.
2. Bigland-Ritchie, B. & Woods, J. J.: Integrated EMG and oxygen uptake during dynamic contractions of human muscles. J Appl Physiol *36*: 475, 1974.
3. Brask, B., Lueke, R. H. & Soderberg, G. L.: Electromyographic analysis of selected muscles during the lateral step-up exercise. Phys Ther *64*: 324, 1984.
4. Campbell, D. E. & Glenn, W.: Rehabilitation of knee flexor and knee extensor muscle strength in patients with meniscectomies, ligamentous repairs, and chondromalacia. Phys Ther *62*: 10, 1982.
5. Carlsöö, S. & Molbech, S.: The functions of certain two-joint muscles in a closed muscular chain. Acta Morph Neerl Scand *6*: 377, 1966.
6. Dubo, H. I. C., Peat, M., Winter, D. A., Quanbury, A. O., Hobson, D. A., Steinke, T. & Reimer, G.: Electromyographic temporal analysis of gait: normal human locomotion. Arch Phys Med Rehabil *57*: 415, 1976.
7. Dvir, Z. & Trousil, T.: Electromyographic study of several lower limb muscles during maintenance of dynamic balance in frontal plane. Agressologie *23*: 71, 1982.
8. Ekholm, J., Arborelius, U. P & Németh, G.: The load on the lumb-sacral joint and trunk muscle activity during lifting. Ergonomics *25*: 145, 1982.
9. Ericson, M. O., Nisell, R. & Ekholm, J.: Quantified electromyography of lower limb muscles during level walking. To be submitted to Scand J Rehab Med.
10. Ericson, M. O., Ekholm, J., Svensson, O. & Nisell, R.: Load on ankle joint structures during ergometer cycling. Submitted to Foot & Ankle.
11. Ericson, M. O., Nisell, R. & Ekholm, J.: Varus and valgus loads on the knee joint during ergometer cycling. Scand J Sports Sci. In press.
12. Faria, I. E. & Cavanagh, P. R.: The Physiology and Biomechanics of Cycling. Wiley, New York, 1978.
13. Gollnick, P. D., Sjödin, B., Karlsson, J., Jansson, E. & Saltin, B.: Human soleus muscle: a comparison of fiber composition and enzyme activities with other leg muscles. Plügers Arch *348*: 247, 1974.
14. Hoes, M. J. A., Binkhorst, R. A., Smeekes-Kuyl, A. E. M. & Wissers, A. C. A.: Measurement of forces exerted on pedal and crank during work on a bicycle ergometer at different loads. Int Z Angew Physiol *26*: 33, 1968.
15. Houtz, S. J. & Fischer, F. J.: An analysis of muscle action and joint excursion during exercise on a stationary bicycle. J Bone Joint Surg *41-A*: 123, 1959.
16. Indelicato, P. A.: Non-operative treatment of complete tears of the medial collateral ligament of the knee. J Bone Joint Surg *65-A*: 323, 1983.
17. Kostka, C. E. & Cafarelli, E.: Effect of pH on sensation and vastus lateralis electromyogram during cycling exercise. J Appl Physiol *52*: 1181, 1982.
18. Leach, R. E., James, S. & Wasilewski, S.: Achilles tendinitis. Am J Sports Med *2*: 93, 1981.
19. Lyons, K., Perry, J., Gronley, J. K., Barnes, L. & Antonelli, D.: Timing and relative intensity of hip extensor and abductor muscle action during level and stair ambulation. Phys Therap *63*: 1597, 1983.
20. McLeod, W. D.: Biomechanics of knee rehabilitation with cycling. Am J Sports Med *8*: 175, 1980.
21. Miller, N. & Seireg, A.: Effect of load, speed and activity history on the EMG signals from intact human muscle. J Bioengin *1*: 147, 1977.
22. Molbech, S.: On the paradoxical effect of some two joint muscles. Acta Morph Neerl Scand *6*: 171, 1965.
23. Németh, G., Arborelius, U. P., Harms-Ringdahl, K. & Schüldt, K.: Influence of knee flexion on isometric hip extensor strength. Scand J Rehab Med *15*: 97, 1983.
24. Németh, G., Ekholm, J., Arborelius, U. P., Schüldt, K. & Harms-Ringdahl, K.: Hip joint load and muscular activation during rising exercises. Scand J Rehab Med *16*: 93, 1984.
25. Perry, J. & Bekey, G. A.: EMG-force relationships in skeletal muscle. Crit Rev Biomed Engin *7*: 1, 1981.

26. Petrofsky, J. S.: Frequency and amplitude analysis of the EMG during exercise on the bicycle ergometer. Eur J Appl Physiol *41*: 1, 1979.
27. Soderberg, G. L. & Cook, T. M.: An electromyographic analysis of quadriceps femoris muscle setting and straight leg raising. Phys Ther *63*: 1434, 1983.
28. Suzuki, S., Watanabe, S. & Homma, S.: EMG activity and kinematics of human cycling movements at different constant velocities. Brain *240:* 245, 1982.
29. Suzuki, Y.: Mechanical efficiency of fast- and slow-twitch muscle fibers in man during cycling. J Appl Physiol *47*: 263, 1979.
30. Tate, J. & Shierman, G.: Toe clips. How they increase pedalling efficiency. Bicycling *57*: 18, 1977.
31. Whitt, F. R. & Wilson, D. G.: Bicycling Science: Ergonomics and Mechanics. London, England, 1974.
32. Winter, D. A.: Biomechanics of Human Movement. Wile, New York, 1979.
33. Woods, J. J. & Bigland-Ritchie, B.: Linear and nonlinear surface EMG/force relationships in human muscles. Am J Phys Med *62*: 287, 1983.

Address for offprints:

Mats Ericson
Kinesiology group
Department of Physical Medicine
Karolinska Institute
Box 60 500
S-104 01 Stockholm
Sweden