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QUANTIFIED ELECTROMYOGRAPHY OF LOWER-LIMB MUSCLES DURING LEVEL WALKING

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ABSTRACT. The electromyography (EMG) of eleven different lower limb muscles of ten healthy subjects was quantified during normal level walking. The surface EMGs obtained were normalized, in percentage, to the activity obtained during an isometric maximum voluntary test contraction of each subject. The mean peak activities of the gluteus maximus, gluteus medius, rectus femoris, vastus medialis, vastus lateralis, biceps femoris and medial hamstring muscles occurred at heel-strike and were between 5 and 15% of max isometric EMG. The magnitudes of tibialis anterior and triceps surae muscular activity were higher than those of the other muscles investigated. Mean peak activity in tibialis anterior was 27%, in gastrocnemius medialis 42%, in gastrocnemius lateralis 19% and in soleus 40%. The important role of the triceps surae during walking was reflected in comparatively high muscular activity at push-off.

Key words: biomechanics, gait, muscular activity, temporal distribution

The temporal distribution of muscular activity during level walking has been extensively studied (e.g. 2, 4, 5, 6, 14, 16, 21), but its magnitude (normalized EMG) during walking has hitherto received little attention. However, in some recent studies the EMGs of some lower-limb muscles have been quantified (5, 15, 23).

In rehabilitation of patients with lower-limb injuries or with gait disorders, knowledge of the magnitude and temporal distribution of lower-limb muscular activity during walking should be of clinical interest. Muscular activity recorded during normal daily activities and during training exercises has been quantified earlier (3, 7, 8, 15, 17, 20). It might be valuable to compare the magnitudes so obtained with those in normal walking. Such a comparison using quantified EMG may provide a better basis for the design of gait training exercises, where individual programmes could be adjusted to the magnitude and temporal distribution of muscular activity during normal level walking.

Dubo et al. (5) quantified the EMG of four lower-limb muscles and determined the mean peak activity for vastus lateralis to 25% of maximum isometric EMG (max EMG) at heel-strike. The medial hamstring and tibialis anterior measured 32 and 73% at heel strike, respectively, and the lateral gastrocnemius measured 63% during the push-off phase. Lyons et al. (15) recently determined mean peak activity during free walking to approximately 35% of max EMG for gluteus medius, and to 30% for gluteus maximus, adductor magnus and semimembranous. The mean peak activity of the long head of biceps femoris was determined to approximately 25% of max EMG, and that of the tensor fasciae latae to 10%.

The main purpose of the present study was to quantify muscular activity during normal walking. The magnitude of activity in eleven muscles was quantified and compared with results from earlier EMG and biomechanical studies of normal walking.

MATERIALS AND METHODS

Ten subjects, all men aged between 20–32 years (mean = 25.3), participated in the study. Their average height was 1.84 m (SD = 0.04) and weight was 76.2 kg (SD = 6.3). None had any impairments in the locomotor system.

The walkway was an ordinary level floor. The subjects walked approximately 10 m wearing their own sport shoes. They practised walking several times at their normal speed with natural and comfortable cadences before EMG was recorded.

The kinematics of the lower limb were recorded using a TV camera (25 frames/sec) mounted perpendicular to the walkway and to the sagittal plane of the subjects at a distance of 5.0 m. Time was recorded on the EMG recorder parallel to EMG using signals from a specially-designed time indication panel. The time was displayed on each TV frame.

The muscular activity during walking was studied in the following muscles: gluteus maximus, gluteus medius, rectus femoris, vastus medialis, vastus lateralis, biceps femoris, medial hamstring, gastrocnemius medialis, gastrocnemius lateralis, soleus and tibialis anterior. For each muscle two

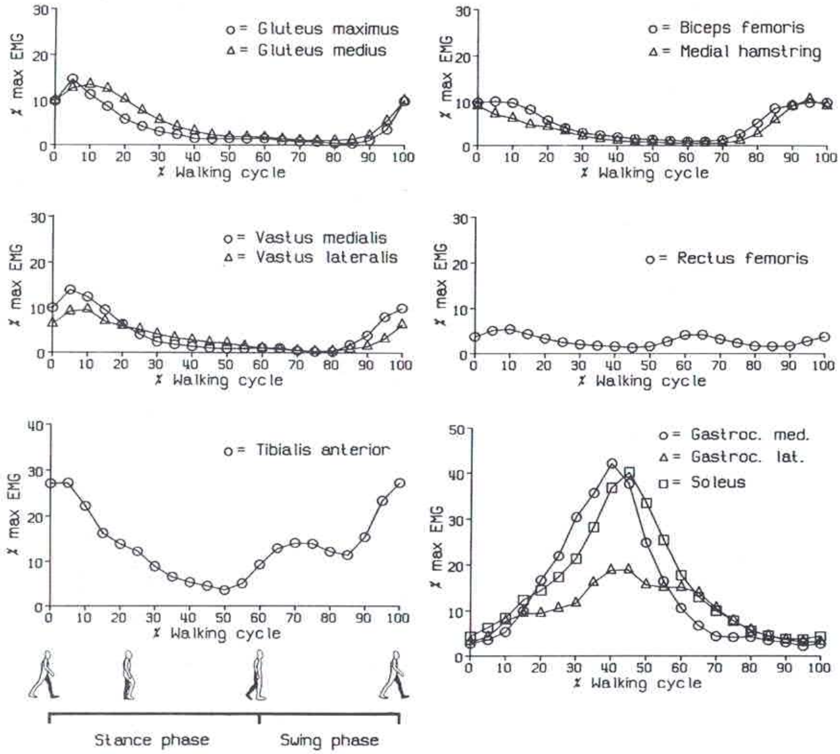

Fig. 1. Temporal distribution and mean magnitude of lower limb muscles during normal walking. Abscissa: % walking cycle. 0% corresponids to heel strike. Stance phase is between 0 and approximately 60% walking cycle and swing phase between 60 and 100%. 100% walking cycle corresponds to following heel strike of the same limb. Ordinate: magnitude of muscular activity expressed as % of max isometric EMG activity.

flexible disposable Ag–AgCl surface electrodes were placed with their centres approximately 40 mm apart, in the main direction of the muscle fibres, after reducing skin impedance with rubbing acetone. The electrode position for each muscle investigated is described in detail elsewhere (8). The term "medial hamstring" is used for the position of the electrode pair over the semitendinous and semimembranous muscles.

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

To quantify muscular activity for comparison between different muscles and different subjects, an EMG normalization was performed. The EMG activity recorded during the test situations was related to that recorded separately during 5-sec maximum isometric voluntary muscular contraction (isometric MVC). The attempted movements and joint position for these contractions have earlier been described (8).

The EMGs recorded during normal level walking were expressed as a percentage of the isometric MVC values (normalized EMG). The EMG level was analysed 25 times per second. The walking cycle was analysed from heel strike to heel strike measured in the left lower limb. Stride time was normalized in such a way that heel contact was considered 100% stride time. Because of inter-individual differences in cadence, the recorded EMG values were interpolated and means computed for every five percent of the walking cycle.

RESULTS

The mean natural cadence of the 10 subjects was 110.3 steps per minute (SD = 6.5). Their mean stride velocity and mean stride length were 1.43 m/sec (SD = 0.13) and 1.56 m (SD = 0.14), respectively.

The mean EMGs during one complete walking cycle for the eleven muscles investigated are shown in Fig. 1. Gluteus maximus was active mainly during retardation at the end of the swing phase and at the beginning of the stance phase. Peak activity measured 15% of max isometric EMG (SD = 13) and occurred shortly after heel strike (5% of the walking cycle). Gluteus medius was active from the retardation at the end of the swing phase, during the heel-strike period and up to the time of the contralateral limb toe-off. Mean peak activity of 13% (SD=7) occurred at 10% walking cycle, i.e. at the beginning of the opposite lower-limb swing phase.

The rectus femoris muscle had low activity but showed two peaks. The first peak, 5% (SD = 3) of max isometric EMG, occurred at 10% walking cycle, i.e. during the heel-to-strike-to-foot-flat period. The other peak, also 5% (SD = 4), occurred at the beginning of the swing phase. Vastus medialis and vastus lateralis activity peaked at the time of limb retardation, heel strike and foot flat. Mean peak activity measured 14% (SD = 6) for vastus medialis and 10% (SD = 7) for vastus lateralis, and occurred at 5% and 10% walking cycle respectively.

The biceps femoris and medial hamstrings, were active during the mid swing, limb retardation, heel strike and foot flat phases. Biceps femoris and medial hamstring mean activity peaks were 10% (SD = 8) and 11% (SD = 8) repectively, occuring at 5% and 95% walking cycle.

The three bellies of triceps surae were active mainly in the phases of mid stance, heel off and toe off. The mean peaks for gastorcnemius medialis gastrocnemius lateralis and soleus measured 42% (SD = 18), 19% (SD = 16) and 40% (SD = 11) of max isometric EMG repectively. Their peak activities occurred at 40–45% walking cycle, i.e. at the beginning of the push-off phase.

The tibialis anterior muscle showed two peaks: at the time of heel strike (5% walking cycle) and at the beginning of acceleration in the swing phase (70% walking cycle). Mean peak activity during the heel-strike period was 27% (SD = 16) of max isometric EMG. Moreover, tibialis anterior was active during the whole walking cycle except for a short period at toe-off when its activity decreased.

DISCUSSION

Because the electromyography of level walking has been well studied, few of the temporal distribution observations here are original. Nevertheless, quantitative EMG technique permits improved integration and explanation of muscle function. Compared to earlier studies concerning temporal distribution of lower-limb muscular activity during level walking (2, 4, 5, 6, 14, 16, 21), we found no major contradictions in the muscular activity pattern. Our quantified EMG data showed that only the three different muscle bellies of triceps surae and tibialis anterior attained a mean muscular activity peak greater than 15% of maximum isometric EMG. The gluteus maximus, gluteus medius, quadriceps and hamstring muscles showed lower activity throughout the complete walking cycle.

The magnitudes of muscular activity recorded for the gluteus maximus (15%) and for gluteus medius (13%) in the present study are lower than the peaks of 30 and 35%, respectively, reported by Lyons et al. (15). These authors also measured higher activity for the biceps femoris and medial hamstring: approximately 25 and 30% compared to our 10 and 11%. Dubo et al. (5) reported a medial hamstring peak activity measuring 27% of max EMG. Their vastus lateralis peak activity (25%) was higher than the 10% mean peak activity measured in the present study. Also, they obtained higher peak activities for the gastrocnemius lateralis (73%) and tibialis anterior muscles (63%), compared to our 19 and 27%, respectively.

The muscular activity found in the present study was generally lower and in contrast to the quantified EMG data presented by Dubo et al. (5) and Lyons et al. (15), but differences in age, sex, physical fitness and EMG normalization methods may have influenced the results. Our subjects were young (mean = 25.3 years), healthy and well-trained men. The subjects in Dubo's study were of both sexes and aged between 8 and 72 years, with a mean of 37 years. Lyons et al. (15) used five men and six women between 25 and 34 years of age (mean = 27.6 years). The gait characteristics (cadence, stride velocity and stride length) in the present study closely resembled those reported by Lyons et al. (15). Gait characteristics were not presented by Dubo et al. (5). Their subjects were instructed to walk at normal and comfortable walking speed. Minor differences in EMG normalization methods, e.g. joint position, type of resistance applied (manual or dynamometers) may also have influenced the magnitude of EMG level. However, there are no major differences between the studies regarding temporal distribution and relative EMG levels.

Yang & Winter (23) recently investigated different types of EMG amplitude normalization method for clinical gait analysis. They stated that normalization to 50 or 100% MVC causes high intersubject variability. In the present study, normalization was performed using 100% MVC. However, our main purpose was to quantify the magnitude of muscular activity—useful when comparing different training exercises with normal walking—not to provide specific temporal EMG data for clinical gait analysis.

The gluteus, quadriceps and hamstring muscles were active predominantly during the period of transition from swing phase to stance phase, i.e. shortly before and after heel strike with following weight acceptance. At the end of the swing phase, the hip-extending gluteus and hamstring muscles increased their activity, most probably due to their action as limb decelerators (13). During this retardation period of the swing phase these muscles probably contract eccentrically, absorbing energy from the swinging leg (22). In the carry-over into heel strike and weight acceptance, the gluteus and hamstring muscles contract concentrically, producing a hip-extending moment of force (22). The gluteus medius—the most important hip abductor (12)—is also active for most of the stance phase (4), counteracting the adducting moment of force and muscle force. Shortly after heel strike, the hip-extending muscles contract concentrically, generating a hip-extending power. Zarrugh (24) determined hip joint power at a cadence of 100 steps/min to approximately 150 W.

The quadriceps femoris muscle bellies had a relatively low peak activity (5 to 14% of max EMG) at the beginning of the stance phase. The quadriceps peak activity coincides with the phase of negative work done by this muscle, which lengthens in an eccentric contraction during weight acceptance (22). At heel strike, the foot plantar flexes to the floor under control of the pretibial muscles, mainly tibialis anterior. During the beginning of the stance phase, tibialis anterior contracts eccentrically against gravity, presumably to prevent the foot from slapping down during the transition from swing to stance (16).

At mid-stance, the muscular activity decreased in all the lower limb muscles investigated except for the triceps surae. These mucles showed a high level of peak activity, between 19 and 42% of max EMG during the push off phase, which is where the most important increase in mechanical energy during walking occurs (9, 11, 16, 22). The mean power peak during normal level walking has been estimated to 430 watts by Winter et al. (22). These authors stated that the positive work done during this push-off is the major "new" energy that propels the body forward. The high level of triceps surae muscular activity determined in the present study is in agreement with the finding that during the push-off phase, the function of the ankle plantar flexor is to supply the larger part of the energy necessary for moving legs and body.

At the transition from stance to swing phase, triceps surae activity decreased, whereupon rectus femoris and tibialis anterior increased their activity, rectus femoris to a second peak also reported by others (4, 6). The rectus muscle probably helps to accelerate the lower limb forward during the start of the swing phase. Quanbury et al. (18) reported that during the initial part of the swing phase, shank movement results almost entirely from the power developed at the hip, i.e. in the hip flexors. In the present study tibialis anterior was active during the whole period of leg swing: the muscle lifts the toes to clear the ground. At mid-swing, EMG activity decreased to 11%, which is similar to the slight fall reported by Sheffield et al. (19). Dubo et al. (5) measured the lowest tibialis anterior activity during mid-swing, and similar findings are reported by Gray & Basmajian (10) and Battye & Joseph (1). The difference reported in mid-swing activity in tibialis anterior is unclear, and this part of the walking cycle, probably needs further investigation. At the end of the swing phase, tibialis anterior increased its activity in preparation for the heel strike. Before heel strike, the other lower-limb muscles investigated (except for triceps surae) also increased their activity.

Winter (22) suggests that the major exercises for the quadriceps muscle should be eccentric rather than concentric, while ankle joint exercises should be directed toward strengthening the plantar flexors by concentric work. The high level of activity recorded from the plantar flexors during walking in the present study supports the opinion that triceps surae is an important muscle for normal level walking. When training patients with lower-extremity injuries or gait dysfunctions, it is valuable to know which muscles are activated and to what degree, their temporal distribution, and type of contraction (concentric, static or eccentric), and also to understand the joint motions occurring during normal level walking. We hope that the quantified EMGs reported in the present study may contribute to this knowledge.

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