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Averaged EMG profiles in jogging and running at different speeds

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Abstract

EMGs were collected from 14 muscles with surface electrodes in 10 subjects walking 1.25–2.25 m s^{-1} and running 1.25–4.5 m s^{-1}. The EMGs were rectified, interpolated in 100% of the stride, and averaged over all subjects to give an average profile. In running, these profiles could be decomposed into 10 basic patterns, 8 of which represented only a single burst. Muscles could be divided into a quadriceps, hamstrings, calf and gluteal group, the profiles of which were composed of the same basic patterns. The amplitude of some bursts was constant, but other ones varied with running speed. This speed dependency was generally different between muscles of the same group.

Many muscles show a similar profile in running as in walking. The most notable exception is the calf group, which shows activation in early stance (86–125%), together with quadriceps, instead of in late stance (26–55%) as in walking. This is also visible in low-speed running, 'jogging', where stance extends to 46% or 57%, instead of 30–37% as in normal running. Jogging shows some additional differences with normal running, related to this prolonged stance phase.

Keywords: EMG; Electromyography; Human running; Velocity

1. Introduction

In a previous paper [1] a method was presented to quantify the 'profiles' of averaged rectified EMGs for human walking in a range of walking speeds. It turned out that the timing of the profiles, when expressed as a fraction of the stride duration, was usually invariable, while their amplitude could vary with speed. The profiles of each muscle could be composed into a limited set of basic patterns, which they had in common within their functional group: calf, quadriceps, hamstrings and gluteal. The aim of the present paper is to see if a similar analysis can be made for running. The data so obtained may serve as a database for EMG analyses of running, adding to the data of Nilsson et al. [2] on a more quantitative basis. An additional point of interest is the neural control of locomotion: which changes in the activation pattern effect the switch between the walking or running modes of locomotion? [3]. On the basis of the results to be presented, it will be shown that it is practical to define an additional 'jogging' mode of human locomotion.

2. Methods

2.1. Subjects and protocol

Ten healthy male subjects took part in this study, all of whom were physically active men with no health problems. The experiments were in accordance with the guidelines of the local Medical Ethical Committee. The subject's mean and standard deviation for age, body mass, stature and leg length were 20.8 ± 1.2 years, 71.3 ± 6.3 kg, 1.84 ± 0.07 m, 0.99 ± 0.05 cm, respectively. EMGs of 14 leg muscles of the right leg were recorded, see Table 1. They wore sporting shoes.

Subjects walked and ran on a motor-driven treadmill (ENRAF Entred, belt size 0.48 m × 1.60 m) at speeds of 1.25, 1.5, 1.75, 2.0, 2.25, 2.5, 3.0, 3.5, 4.0 and 4.5 m s^{-1}.

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Table 1
Muscles and electrode positions

	Name	Electrode position	PD
1. SO	Soleus	Medial and anterior from achilles tendon	2/3
2. GM	Gastrocnemius medialis	Middle of muscle bulge	1/3
3. GL	Gastrocnemius lateralis	Middle of muscle bulge	1/3
4. PL	Peroneus longus	On line between head of fibula and lateral malleolus	1/4
5. TA	Tibialis anterior	Ventral side of lower leg, just lateral from tibia	1/3
6. VM	Vastus medialis	Anteromedial muscle bulge thigh	4/5
7. VL	Vastus lateralis	Anterolateral muscle bulge thigh	2/3
8. RF	Rectus femoris	Between VM an VL	1/2
9. BF	Biceps femoris, long head	Dorsolateral side of thigh	1/2
10. ST	Semitendinosus	Dorsomedial side of thigh	1/2
11. SM	Semimemembranosus	In fossa poplitea, between tendon of BF and ST	4/5
12. GX	Gluteus maximus	On line between greater trochanter and sacrum	1/2
13. GD	Gluteus medius	On line between greater trochanter and crista iliaca	1/2
14. AM	Adductor magnus	On line between tuberculum pubis and medial epicondylus	1/2

List of muscles used in this study, with electrode position. PD, approximate location of the electrodes as a proportion of proximo-distal length. For details see Freriks et al.

The records were made during 30 s of ‘steady state’ walking or running, after the subjects had been accustomed to the new speed for some 30 s. Between each recording one minute of rest was allowed. The subjects were first asked to walk and then to run at speeds up to 2.25 m s^{-1}. At speeds from 2.5 up to 4.5 m s^{-1} the subjects were asked to run only.

2.2. EMG recording

Surface EMGs were recorded bipolarly by Conmed disposable surface electrodes (10 mm × 10 mm electrode area, inter electrode distance 24 mm, Conmed Corporation, Utica, NY, USA). All electrodes were placed in the lengthwise direction of the muscle on the right leg. The positions of the electrodes were according to the SENIAM recommendations [4], summarized in Table 1. All 14 muscles were recorded simultaneously. The electrodes and electrode wires were wrapped on thigh and shank with an elastic bandage do prevent dislocation during fast running.

Signals were pre-amplified and A/D converted (22 bits) by a 32-channel PORTI ambulatory recording system (Twente Medical Systems, Enschede, The Netherlands). Amplifier specifications were: 100 dB common mode rejection, 2 μV pp noise level and 1 GΩ input impedance. Sampling frequency was 800 Hz. Vertical force was recorded by force transducers mounted underneath the treadmill belt. From this signal the timing of the foot contact could be calculated [5].

2.3. Data processing

After recording, the EMG signals were high-pass filtered with a 20 Hz fourth order Butterworth high-pass filter to remove electrode artifacts, rectified and smoothed with a 24 Hz fourth order Butterworth low-pass filter, all with Matlab software. It was assumed that, because of noise from amplifier and electrodes and of cross-talk from adjacent muscles, EMG levels below 10 μV could be considered insignificant.

The smoothed rectified EMGs were linearly interpolated to 100 points p per stride, triggered by the right heel contact. The recorded steps were screened to exclude any obvious EMG artefacts or incorrect foot contacts. The number of excluded steps in a 30 s recording did not exceed two or three steps. Depending on the stride time, therefore between 25 and 45 steps were averaged for each speed.

For every subject i at every speed v the average $e(p,m,v,i)$ was calculated for the 14 leg muscles m, to get an individual mean. For the $n = 10$ subjects a grand mean was obtained at every normalised speed v for every muscle m, $E(p,m,v)$:

$$E(p,m,v) = \frac{1}{n}\sum_{i=1}^{i=n} e(p,m,v,i) \tag{1}$$

In a similar way as described for walking, the EMG patterns of all 14 muscles at all running speeds above 2.25 m s^{-1} could be described by a limited set of basic patterns FF(p, k) times a speed dependent amplitude factor $D(m,k,\hat{v})$. The profile of a certain muscle could be composed of one to three basic patterns. It will turn out that 10 basic patterns are sufficient. The speed dependence could be modelled as a linear, in some cases a quadratic relation. The complete description of all patterns thus becomes in matrix form:

$$E^{*}(p,m,\hat{v}) = \{D_0(m,k) + D_1(m,k)\hat{v} + D_2(m,k)\hat{v}^2\} * \mathrm{FF}(p,k)^{\mathrm{T}} \tag{2}$$

in which D_0, D_1 and D_2 are 14 × 10 matrices and FF(p, k) a 100 × 10 matrix, containing 10 basic patterns in a 100-point percentage scale. The ‘*’ denotes matrix multiplication. In order to be compatible to previous work and to accommodate differences in leg length, speed in (2) is expressed as normalised speed [6] $\hat{v} = v/\sqrt{gl}$, in which l is average leg length and g the acceleration of gravity (Table 2).

Table 2
Temporal data

Speed		Stride time (s)				Stance (% of stride)			
$m\ s^{-1}$	Norm.	Walk		Jog/run		Walk		Jog/run	
		Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
1.25	0.40	1.09	0.07	*0.83*	*0.06*	59.4	1.9	*57.4*	*1.1*
1.50	0.48	1.03	0.05	*0.82*	*0.10*	59.6	1.2	*56.8*	*1.7*
1.75	0.56	0.96	0.05	*0.79*	*0.06*	59.2	1.0	*51.5*	*8.2*
2.00	0.65	0.90	0.05	*0.76*	*0.05*	58.1	0.8	*46.0*	*8.7*
2.25	0.73	0.83	0.06	0.75	0.05	57.4	1.1	37.4	3.2
2.50	0.81			0.74	0.04			34.6	2.5
3.00	0.97			0.73	0.04			31.5	2.6
3.50	1.13			0.71	0.05			29.6	2.5
4.00	1.29			0.71	0.05			29.6	2.5
4.50	1.45			0.67	0.04			27.5	2.2

Normalised speed is calculated as $\hat{v} = v/\sqrt{gl}$, with l the average leg length of 0.99 m. Data for 'jogging' are italic. Note the large S.D. for relative stance in jogging at 1.75 and 2.0 m s^{-1}. In fact the range was between 32% and 60%.

First, gain factors $G(m, \hat{v}, k)$ were obtained by linear regression:

$$G(m, \hat{v}, k) = \frac{\sum_p [E(p, m, \hat{v})\,\mathrm{FF}(p, k)]}{\sum_p \mathrm{FF}(p, k)^2} \tag{3}$$

and then the speed dependence of each gain factor was fitted by least squares to obtain

$$G(m, \hat{v}, k) = D_0(m, k) + D_1(m, k)\hat{v} + D_2(m, k)\hat{v}^2 \tag{4}$$

The whole fitting procedure was done for running speeds of 2.25 m s^{-1} ($\hat{v} = 0.72$) and higher. Each basic pattern FF(k) was selected out of a representative EMG profile at the intermediate speed $\hat{v} = 1$ (3.0 m s^{-1}).

3. Results

The walking recordings at 1.25, 1.5, and 1.75 m s^{-1} were compared to the predictions according to previous results [1], obtained at the same speeds but on a different group of subjects. The patterns were identical within the limits of this group [7] but there was some difference in amplitude of the EMG, which was in this study on average 0.6 times lower than in the previous results. The present data have been corrected for this ratio, so that EMG amplitudes from this paper can be directly compared to the previous walking data. It was verified that the predictions for walking were still correct in the range of 1.75–2.25 m s^{-1}. Stride time and stance duration as a percentage of stride time have been given in Table 2.

3.1. Walking, running and jogging

Our treadmill with built-in force transducers enables walk–run detection on the basis of the vertical ground reaction force, Fig. 1. In walking it shows for each leg an M-shaped pattern, with a minimum at midstance, while the pattern in jogging and running it is unimodal, with maximum force at midstance. At the higher speeds there may be an airborne phase, with force zero. We will call this case 'running', and the case without an airborne phase 'jogging'. So the proposed division is as follows, walking: ground reaction force minimum at midstance, jogging: ground reaction force maximum at midstance, but no aerial phase, running: ground reaction force maximum at midstance with aerial phase.

3.2. Grouping of muscles

In running the muscles could be grouped into a number of functional groups on the basis of their EMG profiles, similar to walking: (1) a quadriceps group: VM, VL and RF; (2) a hamstring group: BF, ST and SM; (3) a calf group: SO, GM, GL and PL; (4) a gluteal group: GX and GD. TA and AM are to be classified separately. We will present the results groupwise, first describe the findings for running and then report differences with walking and jogging.

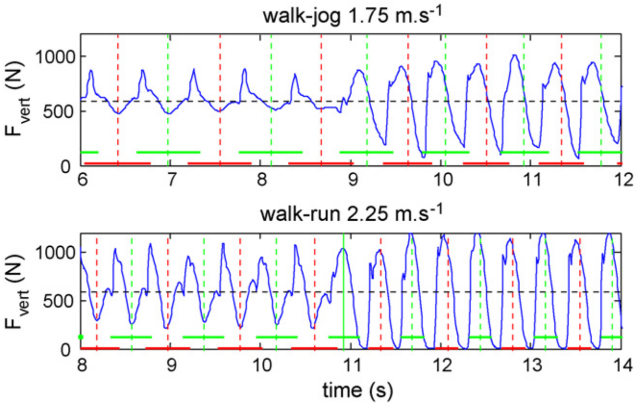

Fig. 1. Vertical component of ground reaction force, recorded with the instrumented treadmill, sum of left and right feet. The subject changed from walking into jogging at 1.25 m s^{-1} (above) and from walking into running at 2.25 m s^{-1} (below). The lower and upper horizontal bars indicate foot contact of each leg. The vertical dotted lines correspond with midstance, the horizontal dotted line equals body weight. In walking, midstance corresponds with a minimum of the ground reaction force, in jogging and running with a maximum. In jogging the ground reaction force is minimum in double stance, but it does not reach zero, so there is still ground contact.

3.3. Quadriceps group

This group consists of VM, VL and RF muscles. Vastus intermedius is located below RF and not directly accessible to surface EMG. The profiles in running were all very similar, Fig. 2a. The basic pattern is included in the FF range as pattern FF(2), Fig. 3. It starts before foot contact (80%) and ends at about midstance (15% or 115%) with a maximum around 7% of stance, Fig. 3. While the profiles were identical, the speed dependence was not: in VM the amplitude hardly changed with speed, Fig. 2c, in VL it showed a minor increase, in RF a more substantial increase, about two-fold. This is reflected in the entries in D_0, D_1, and D_2 (Table 3).

In the vasti the EMG profile was essentially the same for walking and for running, Fig. 2b. The minor peak around 40% is unique for walking. In jogging the profile was different from both walking and running. The period of activity lasted longer, up to 35%, and peak height was lower than running, see Fig. 2c.

RF has an additional peak from about 40–70%, FF(3). In fact the onset shifts somewhat earlier, from 47% at 2.25 m s^{-1} to 37% at 4.5 m s^{-1}. The amplitude increases quadratically with speed, with the result that at 4.5 m s^{-1} it is higher than the first peak. This peak corresponds to a similar pattern in walking. At the same speed, the peak in walking is considerably higher.

3.4. Hamstring group

EMG profiles in the hamstring group, BF, ST and SM, show two peaks, one in the second half of swing, 70–100%, and a double-peaked activity in stance, 6–30% (Fig. 4a). These two basic patterns are represented in FF(4) and FF(5). The speed dependence is quite different for the three hamstring muscles, see Fig. 4c. In SM both peaks are constant, the first peak increased in BF and ST, as did the second peak in ST. In BF the second peak showed maximum activity at 3 m s^{-1}, and decreased at higher speeds. The latter finding is reflected in a negative entry in the quadratic term D_2 (Table 3).

Walking showed largely the same two-peaked pattern as running, but some 10% later, Fig. 4b. The jogging profile has essentially the timing of walking, but at a higher amplitude. There is not a gradual shift in timing with speed; at 2.25 m s^{-1} the profile just switches to the timing of running.

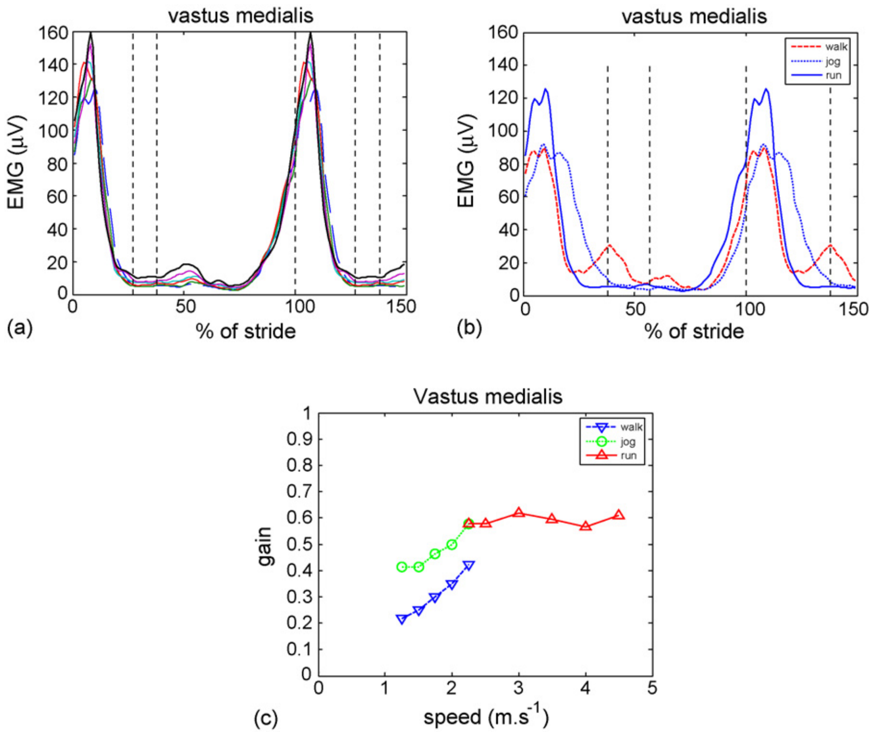

Fig. 2. (a) Quadriceps group. Profiles of rectified and smoothed EMG of VM for running at speeds from 2.25 m s^{-1} (dashed line) to 4.5 m s^{-1} (thick line) plotted as a percentage of stride time, 0%–100%–50%. The temporal pattern, FF(2), is identical over the range of speeds, in VM the amplitude is constant as well. Vertical dotted lines show foot contact (0/100%) and the range of toe-off, which is between 37% at 2.25 m s^{-1} and 28% at 4.5 m s^{-1}. (b) EMG profiles for VM for walking at 2.25 m s^{-1} (dashed line), jogging at 1.25 m s^{-1} (dotted) and running at 2.25 m s^{-1} (drawn line). Profiles for walking and running are identical. In jogging activity extends over most of stance. Vertical dotted lines correspond to toe-off for running (37%), walking/jogging (57%), and to foot contact (100%), respectively. (c) EMG amplitude factor as a function of speed for VM in walking (dashed), jogging (dotted) and running (drawn line). The amplitude increases in walking and jogging, but is largely constant in running. The amplitude in jogging and running is always higher than in walking.

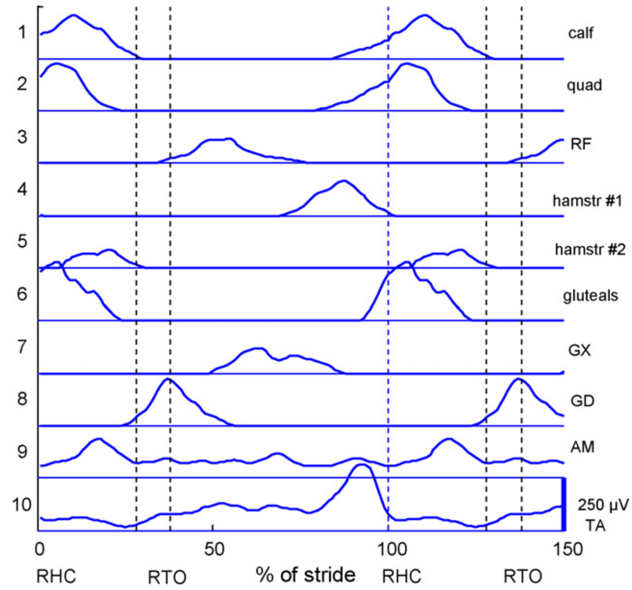

Fig. 3. Basic patterns of running EMG, represented in the FF functions. The number k of the FF function is given on the left, the name on the right. Vertical dotted lines show foot contact (0/100%) and the range of toe-off, which is between 37% at 2.25 m s^{-1} and 28% at 4.5 m s^{-1}.

3.5. *Calf group*

All four calf muscles, SO, GM, GL and PL, showed a single peak starting shortly before stance (86%) and ending before toe-off (125%), represented as FF(1), see Fig. 5a. The form of this peak is closely alike the quadriceps peak FF(2), but shifted about 10% later. The amplitudes of SO and PL were about constant, while GM and GL increased some 40% over the speed range 2.25–4.5 m s^{-1}, see Table 3.

Table 3
Gain factors

No. m	Muscle	Profile (FF) k	D_0	D_1	D_2
1	**SO**	1	0.15	0.63	−0.24
2	GM	1	0.54	0.28	0
3	GL	1	0.06	1.11	−0.37
4	PL	1	0.49	0	0
5	**TA**	10	0.28	0.25	0
6	**VM**	2	0.59	0	0
7	VL	2	0.46	0.17	0
8	**RF**	2	−0.17	0.64	0.018
8	RF	3	0.16	−0.37	0.50
9	BF	4	0.68	−0.61	0.50
9	**BF**	5	−0.22	2.13	−1.14
10	**ST**	4	0.23	0.55	0
10	ST	5	−0.20	0.61	0
11	SM	4	0.32	0	0
11	SM	5	0.23	0	0
12	GX	6	0	0.093	0
12	**GX**	7	0.046	0.13	0
13	**GD**	6	0.28	0	0
13	**GD**	8	0	0.29	0
14	**AM**	9	−0.19	0.69	0

D-matrices, with coefficients of speed dependent gain factors. Gain factor $g = D_0 + \hat{v}D_1 + \hat{v}^2 D_2$. Only entries in which at least one of the D's was nonzero are included. The muscle from which the profile was taken is printed bold. When $D_2 = 0$, the dependence of profile amplitude with speed was linear, when both $D_1 = 0$ and $D_2 = 0$ it is constant.

In this muscle group there were major differences between walking and running, Fig. 5b. Walking has a major peak, increasing with speed, in late stance (26–55%) and a lower and speed-independent activity in early stance, 86–126%. At the highest walking speed, 2.25 m s^{-1}, the peak amplitude in walking was higher than in running. Jogging showed a profile in between: starting at 86% with a similar and equally high peak as running, but continuing over almost the whole stance period, up to about 150%.

3.6. *Gluteal group*

Both glutei showed a profile with two peaks, Fig. 6a. The first peak FF(6) is identical, it runs from 88% to 118%. In GD it is constant in amplitude, while it linearly increases with speed in GX, Table 3. In GX the second peak FF(7) is at midswing, 60–84%, in GD it is at the transition from stance to swing, 30–50%, FF(8). Both increase with speed.

The GX the pattern in walking is essentially the same as in running, both in profile as in amplitude, with the reservation that the second peak is rather low, and hard to discern. In GD the profiles of walking and running are identically timed as well, Fig. 6b, but the amplitude is considerably higher in jogging and running. In walking and in jogging there is an additional third peak present, corresponding to FF(7).

3.7. *Tibialis anterior*

TA activity FF(10) extended over the complete swing phase, starting slightly before toe-off, around 27%, and ending abruptly at heel contact (100%), Fig. 7a. The prominent peak is at 90% and there is a moderate increase with running speed. In the first half of stance, 0–15%, there is a minor activity.

The profile in walking also starts just before swing, which is later at about 60%. The peak activity in walking is later, corresponding with foot contact, and sharply descending at 10%. At higher walking speeds the TA peak is higher than in running. For jogging at 1.25 m s^{-1} activity starts again at toe-off, which is around 55%, and ends at foot contact, but there is no prominent peak. At higher jogging speeds TA activity always corresponds with toe-off and thus starts earlier.

3.8. *Adductor magnus*

AM shows a profile in which three peaks can be discerned, in midstance at 18%, in midswing at 68%, and in final swing at 90%, Fig. 8a. These peaks become prominent only at 3 m s^{-1} and higher, at lower running speeds and in jogging the EMG is low and irregular, even to the extent that it is hard to see a periodicity. In walking the pattern is very different from running, with peaks at foot contact (0%) and toe-off (60%), Fig. 8b.

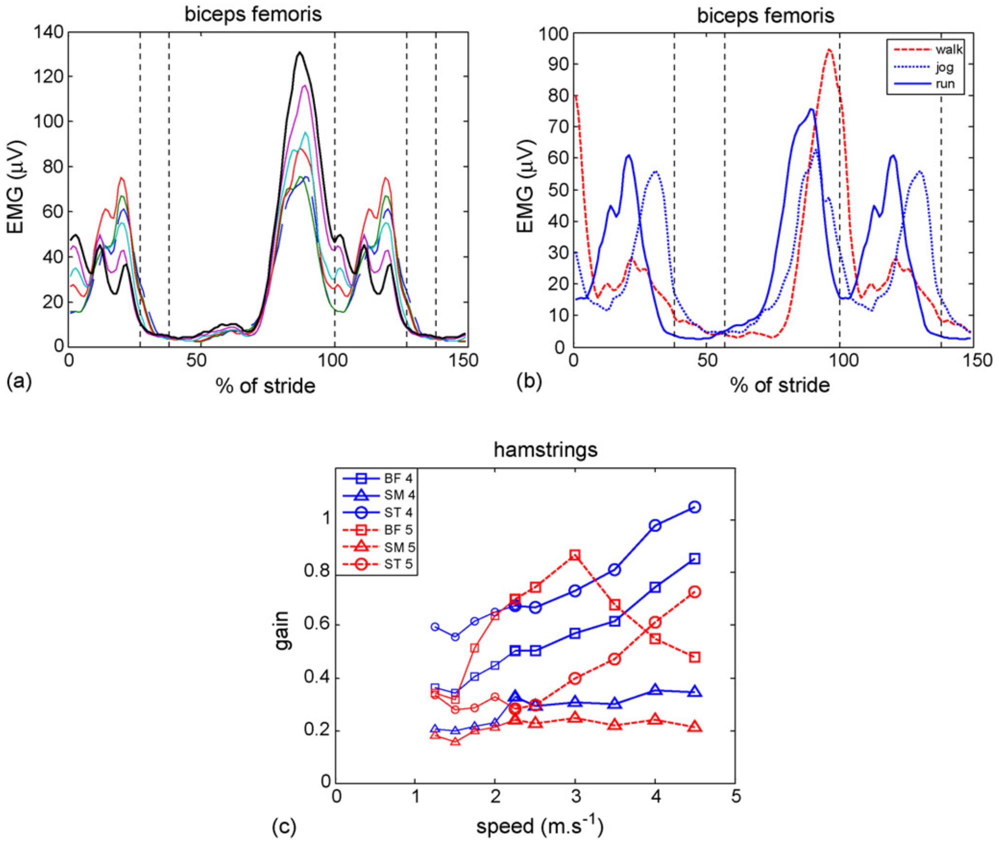

Fig. 4. (a) Hamstrings group. Profiles of rectified and smoothed EMG of BF for running at speeds from 2.25 m s^{-1} (dashed line) to 4.5 m s^{-1}(thick line) plotted as a percentage of stride time, 0%–100%–50%. The profile shows two peaks, corresponding to FF(4) and FF(5). In BF the first peak increases with speed, the second is maximal at 3 m s^{-1}. Vertical dotted lines show foot contact (0/100%) and the range of toe-off, which is between 37% at 2.25 m s^{-1} and 28% at 4.5 m s^{-1}. (b) EMG profiles for BF for walking at 2.25 m s^{-1} (dashed line), jogging at 1.25 m s^{-1} (dotted) and running at 2.25 m s^{-1} (drawn line). Profiles for walking and running are similar, but in running both peaks are about 10% earlier. Vertical dotted lines correspond to toe-off for running (37%), walking/jogging (57%), and to foot contact (100%), respectively. (c) EMG amplitude factor for pattern FF(4), drawn lines, and pattern FF(5), dashed lines, for the hamstring muscles as a function of speed for jogging (thin dotted lines) and running. Note that the gain-speed relations are quite different between muscles and patterns.

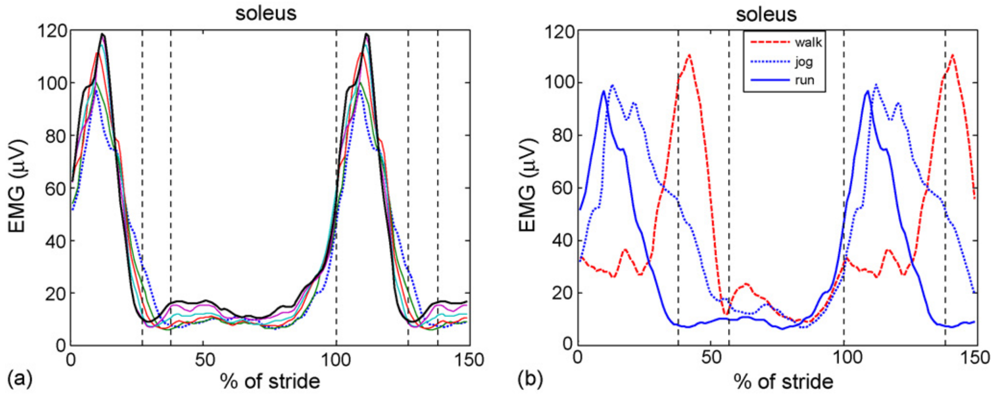

Fig. 5. (a) Calf group, triceps surae and peroneus. Profiles of rectified and smoothed EMG of SO for running at speeds from 2.25 m s^{-1} (dashed line) to 4.5 m s^{-1} (thick line) plotted as a percentage of stride time, 0%–100%–50%. The temporal pattern is identical over the range of speeds, in SO there is a minor increase in amplitude with speed. Vertical dotted lines show foot contact (0/100%) and the range of toe-off, which is between 37% at 2.25 m s^{-1} and 28% at 4.5 m s^{-1}. (b) EMG profiles for SO for walking at 2.25 m s^{-1} (dashed line), jogging at 1.25 m s^{-1} (dotted) and running at 2.25 m s^{-1} (drawn line). Note the major differences between walking and running: in running peak activity in early stance, in walking in late stance. In jogging the main activity is identical with running, but the activity is extended to cover most of stance, which is up to 57% at this low speed. Vertical dotted lines correspond to toe-off for running (37%), walking/jogging (57%), and to foot contact (100%), respectively.

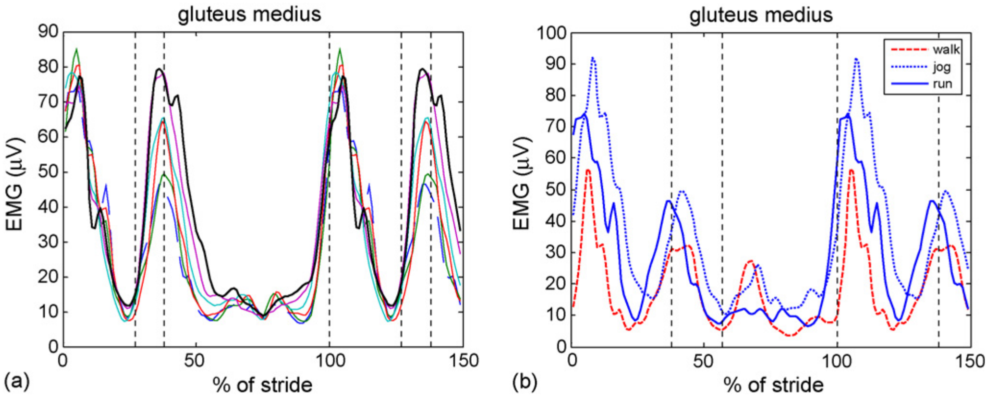

Fig. 6. (a) Gluteal group. Profiles of rectified and smoothed EMG of GD for running at speeds from 2.25 m s^{-1} (dashed line) to 4.5 m s^{-1}(thick line) plotted as a percentage of stride time, 0%–100%–50%. The GD profile shows two peaks, corresponding to FF(6) and FF(8). In GD the first peak is constant, the second increases with speed. Profile of GX has the same first peak, but the second peak, FF(7) is from 60% to 84%. Vertical dotted lines show foot contact (0/100%) and the range of toe-off, which is between 37% at 2.25 m s^{-1} and 28% at 4.5 m s^{-1}. (b) EMG profiles of GD for walking at 2.0 m s^{-1} (dashed line), jogging at 1.25 m s^{-1} (dotted) and running at 2.25 m s^{-1} (drawn line). Profiles for walking, jogging, and running are the same, with the addition that a minor third peak, corresponding to FF(7), is visible in walking and jogging. A walking speed of 2.0 m s^{-1} was chosen, because the profile at 2.25 m s^{-1} was not representative for the lower speeds. Vertical dotted lines correspond to toe-off for running (37%) walking/jogging (57%), and to foot contact (100%), respectively.

4. Discussion

4.1. Walking, running and jogging

In this study we have used the shape of the vertical ground reaction force as the feature which discriminates running from walking. The conventional criterion is the occurrence of an airborne phase. As has been observed earlier, this criterion is not generally valid. When a subject walking on a treadmill at a moderate walking speed (up to 1.75 m s^{-1}) is asked to change into a run, the duration of the stance phase is indeed reduced, but remains over 50% of the stride (Table 2), so there is no aerial phase. Only at higher speeds stance decreases below 50%.

The ground reaction force gives a more generally valid criterion. In walking it shows for each leg an M-shaped pattern, with a minimum at midstance, while the pattern in running is unimodal, with maximum force at midstance [8]. This effect is related to the trajectory of the body centre of mass, which at midstance shows a maximum in walking and a minimum in running [9]. In our research we used a treadmill with built-in force transducers, which simply enables walk–jog–run detection on the basis of the ground reaction force, Fig. 1.

Jogging or running at slow speeds can easily be performed on a treadmill, but the question is whether it corresponds to a real-life situation. Minetti et al. [10] found with a speed-controlled treadmill that subjects do not voluntarily choose high walking and low running speeds. He found a maximum walking speed of 2.0 ± 0.2 m s^{-1} and a minimum running speed of 2.3 ± 0.3 m s^{-1}. This suggests that running at speeds below 2.25 m s^{-1} is more or less

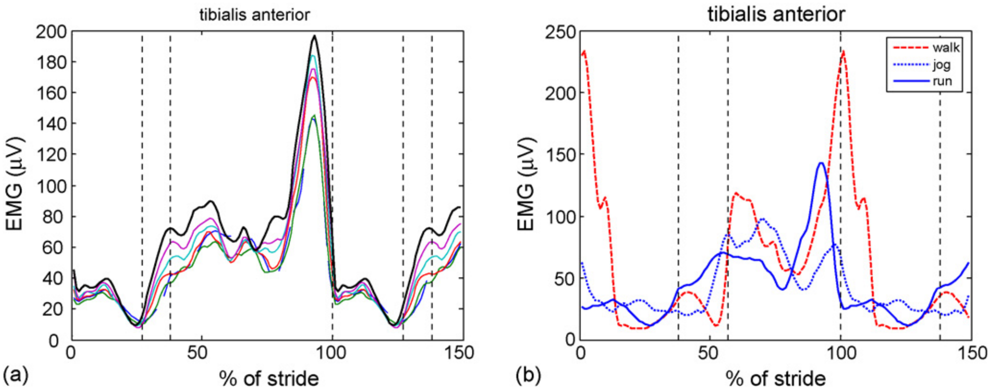

Fig. 7. (a) Tibialis anterior. Profiles of rectified and smoothed EMG of TA for running at speeds from 2.25 m s^{-1} (dashed line) to 4.5 m s^{-1} (thick line) plotted as a percentage of stride time, 0%–100%–50%. EMG activity extends over the complete swing phase, 27–100%, with a peak in final swing at 90%. Vertical dotted lines show foot contact (0/100%) and the range of toe-off, which is between 37% at 2.25 m s^{-1} and 28% at 4.5 m s^{-1}. (b) EMG profiles of TA for walking at 2.25 m s^{-1} (dashed line), jogging at 1.25 m s^{-1} (dotted) and running at 2.25 m s^{-1} (drawn line). In walking TA activity starts later, in correspondence with the later toe-off and extends into stance (10%), with a peak at heel contact. Vertical dotted lines correspond to toe-off for running (37%) walking/jogging (57%), and to foot contact (100%), respectively.

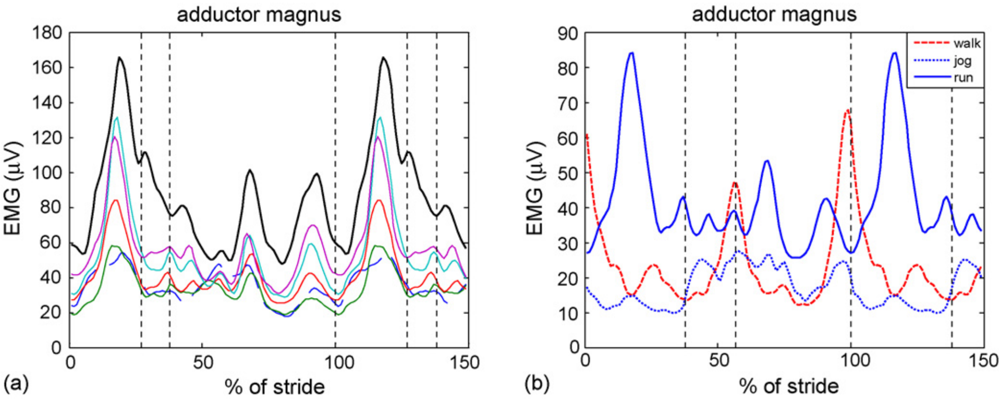

Fig. 8. (a) Adductor magnus. Profiles of rectified and smoothed EMG of AM for running at speeds from 2.25 m s^{-1} (dashed line) to 4.5 m s^{-1} (thick line) plotted as a percentage of stride time, 0%–100%–50%. At higher speeds three peaks can be discerned, at low speeds activity is low and irregular. Vertical dotted lines show foot contact (0/100%) and the range of toe-off, which is between 37% at 2.25 m s^{-1} and 28% at 4.5 m s^{-1}. (b) EMG profiles of AM for walking at 2.25 m s^{-1} (dashed line), jogging at 1.25 m s^{-1} (dotted) and running at 3.0 m s^{-1} (drawn line). The walking profile shows peaks at foot contact (0%) and toe-off (57%). A running speed of 3.0 m s^{-1} was chosen, because the profile at 2.25 m s^{-1} was too low to show a distinct pattern, see (a).

artificial. In this paper we have called it ‘jogging’ (admitting that this term is not sharply defined) and have considered it separately from walking and running. This separate treatment was justified by the deviant EMG patterns, which reflected the longer stance phase.

As the above suggests, there are a number of disadvantages in using a treadmill in studies of running. These do not outweigh the practical advantages. To record a considerable number of EMGs of steady running for 30 s would have required an outdoor track and data logging, although in principle this would have been possible with the available apparatus. Next to this, it is quite difficult to make the subjects run at a prescribed range of speeds, as done here. It has been shown [11] that walking or running on a treadmill is mechanically equivalent to overground, as long as it is ensured that the treadmill speed does not fluctuate. In our brand of treadmill speed was constant within 5%. A second argument is that the profiles in walking of the present study were found identical to those of a previous one, which were recorded on an indoor track.

4.2. EMG profiles

The profiles of the EMG in running can be decomposed in a set of no more than 10 basic patterns, most of which have a constant timing, and the amplitude of which varies in a simple way with running speed. This representation resembles closely the corresponding procedure for walking. The differences are that walking required 16 basic patterns, and that walking patterns either were constant or increased steeply with speed, proportional to $(\hat{v} - 0.16)$ or $(\hat{v} - 0.16)^2$. In running several intermediate cases were seen, amplitudes could be constant, increase slowly, or even decline with speed. Within the calf quadriceps and hamstring groups, general patterns are closely identical, but the relative amplitude of the peaks could vary considerably with speed and within muscles of the group.

Several of the basic patterns in running (FF) correspond with those for walking as found earlier ($F0$, $F1$ and $F2$). Quadriceps FF(2) is identical with $F1(2)$, RF pattern FF(3) is equal to $F2$, gluteals FF(6) with $F1(4)$. For the hamstrings peak 1, FF(5) is very much like $F1(3)$, but activity starts slightly earlier in running, at 70% instead of 77%. Hamstrings peak 2, FF(6), is in stance when running (6–30%), but considerably earlier in walking, $F0(3)$ 91–19%.

The protocol of these experiments is closely equal to that of Nilsson and Thorstensson [12]. Differences are the number of muscles studied, 14 versus 7, and the more quantitative description in the present work. Nilsson et al. were able to measure at speeds up to 9 m s^{-1}, well into the sprinting range. As far as could be seen, the results are in good agreement with the present, also at the highest speeds. One difference is that Nilsson et al. observed a monophasic activity in GX, while we saw a biphasic pattern.

A disadvantage of using profiles averaged over a sample of subjects is that neither step-to-step variations nor different patterns within the subject group can be discerned. The latter problem has be studied for walking [7]. As to the step-to-step variability, only a global impression can be given. In most muscles the EMG in each step follows closely the temporal pattern of the average profile, while the amplitudes vary some 15–25% per step. Where the average profile is zero, there is as a rule no activity except some noise or cross-talk. In running this on-off contrast is generally better than in walking, where muscles like PL or GX could show irregular background activity. AM as an exception, shows a rather irregular EMG throughout, both in walking as in running.

4.3. EMGs of hip flexors

In our study we were restricted to surface EMG recording. This excludes several muscles, especially the functionally important hip flexors. For these we have to refer to studies where indwelling (fine-wire) electrodes have been used.

Nene et al. [13] investigated RF activity in walking with fine-wire electrodes. Their results clearly showed that the second peak FF(3)/$F2$, in early swing, was RF activity proper. The first 'quadriceps' peak FF(2)/$F1(2)$, as found in surface EMG, did not correspond to activity of RF, but was probably cross-talk from the underlying m. vastus intermedius.

An extensive study of the hip flexors, iliacus, psoas, sartorius, rectus femoris and tensor fasciae latae, was undertaken by Andersson et al. [14]. In running all hip flexors were active from about 30–65%, RF starting slightly later, 45–65%. Psoas has a second burst in late swing, 80–100%. Tensor fasciae latae seems not a hip flexor, showing activity during stance and early swing, 0–50%. Amplitude of iliacus and psoas sharply increased with running speed, about three-fold over the range of 2–4 m s^{-1}. Both timing and amplitude agree with our findings for the second peak of RF. The results of Andersson and Nene, taken together, support the view that RF functions not as a part of quadriceps (knee extensor) but as a hip flexor.

4.4. Similarities and differences between walking, jogging, and running

The EMG profiles in walking and running show many similarities. GX shows essentially the same profile and amplitude in walking as in running. The quadriceps group and GD have identical profiles, but a considerably higher amplitude in running (Figs. 2c and 6b). The hip flexors are reported to have almost identical profiles but lower amplitudes at the same speed in running. The walking and running profiles for the hamstrings show minor differences. TA timing is adapted to the longer swing duration in running and the final peak is now before foot contact.

The major difference between walking and running is found in the calf muscles, with the main peak 26–55% in walking and much earlier, 86–125% in jogging and running. In all cases muscles from this group are active over the complete stance, so there is additional activity 0–26% in walking and 25–50% in jogging, Fig. 5b. In fast running stance duration is so short that no additional activity is necessary.

4.5. Muscle function in running versus walking

Muscle function in walking has been discussed extensively in the past [15–17] and to a lesser degree for running as well [18]. Within the scope of this paper we can only point to a few issues.

Two major actions can be discriminated in running: a stance action and an alternating hip flexion–extension action. The stance action encompasses a more or less simultaneous activation burst of all leg extensors: glutei, quadriceps and calf, FF(1, 2, 6). With this simultaneous activation, and with hip, knee and ankle all slightly flexed, the leg is made into an elastic element [19]. In the first half of stance it is compressed by the weight and downward velocity of the trunk and in the second half it extends again, so the major energy exchange is a storage and release of elastic energy [20,21]. Due to active muscle work the energy increases in the course of the process [22].

The activation bursts are not completely simultaneous. Quadriceps is first, followed by the calf muscles. This is probably related to the kinematics: maximum knee flexion is earlier than maximum ankle dorsiflexion, which can be explained by the combination of leg shortening–lengthening and forward progression movement. The activations all start before foot contact, to achieve a landing with a stiff leg. This part of the extensor activation goes along with a co-contraction of the hamstrings for the knee, FF(4) and of TA for the ankle, FF(10). The burst of hip flexor psoas from 80% to 100% may serve the same purpose. All extensor bursts end before toe-off, but muscle force continues for sufficient time after the end of activation to cover the complete stance phase, see Appendix B in Ref. [23]. The EMG amplitudes in calf and quadriceps muscles are high, but increase only little with speed, in GX somewhat more.

The major difference between walking and running profiles was present in the calf group. In running the activation bursts of quadriceps and calf are more or less simultaneous, in walking the major calf muscle burst is at the end of stance. The quadriceps action is more or less the same, both in walking as in running there is a knee flexion–extension movement together with quadriceps activity at initial stance. In walking the activation is less, however, so that no aerial phase results, cf. Fig. 2c. This is reflected in much lower knee extension moments, 30 N m–40 N m–80 N m in slow–normal–fast walking [24], compared to running [25], 210 N m at 2.72 m s^{-1}. The ankle moment is also low at that time, because the ground reaction force is close to the ankle. After midstance the knee remains straight, so knee moment can be low, but now the ankle moment increases to a maximum at push-off. Shortly, in running quadriceps and calf work together in absorbing and generating energy, by way of a single elastic bounce, while in walking impact absorption and push-off are wider separated in time and done separately by quadriceps and calf. A consequence is that in running quadriceps and calf both produce upward force to the trunk. In walking calf muscle force is directed more horizontally, contributing power not only to the trunk but also to the swing leg.

The other major muscle action is the alternate hip flexion by psoas, iliacus and RF, around the instant of maximal hip flexion at 50%, and extension by the glutei, which starts at maximal hip extension, around 80%. The glutei participates both in this action and in the stance action. In contrast to the stance actions of quadriceps and calf, the amplitudes of the hip flexors and GX show a major increase with speed:

two-fold in GX and four-fold in psoas and iliacus between speeds of 2.25 and 4.5 m s^{-1} [14]. This suggests that speed increase in running is mainly accomplished by a larger leg swing due to increased hip flexor and extensor action.

Next to these major actions, there are the actions of hamstrings and TA. Hamstrings act late in swing, and probably their action in running is the same as in walking, viz. the arrest of leg swing. TA activity is needed to keep the foot in the neutral position against gravity and passive triceps surae elasticity. The final peak at terminal swing (90%) is a co-contraction against triceps surae. Similarly, final hamstring activity is simultaneous with the onset of quadriceps activation.

For the whole stance duration the extensors must be active to prevent collapse of the leg. In fast running, the stance burst is sufficiently long to achieve this effect. In walking and jogging the stance period is considerably longer. In these cases we see a continuous activity over stance of the calf muscles, especially SO, Fig. 5b. In jogging this holds also of quadriceps, Fig. 2b. In walking the latter activity is less needed, because the knee is almost straight. The stance activity of hamstrings (FF5) serves possibly hip extension, but this has to be investigated in more detail. The same holds for the low TA activity in stance.

4.6. Central pattern generator

The finding of invariant EMG profiles is in agreement with current ideas on a central pattern generator (CPG) for human locomotion [26]. Supportive findings are a.o. the pre-activations in FF(1, 2, 6) before foot contact. Next, there is the remarkable finding that the timing of the EMG profiles is constant, while toe-off goes from 37% at 2.25 m s^{-1} down to 27% at 4.5 m s^{-1}. The same effect was found in walking, but the change in relative stance duration is less in that case. Exceptions are TA and RF (FF(3)), the onsets of which are clearly linked to the start of swing. The deviant patterns in jogging, compared to running, are an other exception. In jogging stance is so much prolonged, that a prolonged activity in quadriceps and calf muscles is needed to ensure sufficient support.

On the other hand, several muscle activities are thought to originate from reflexes, e.g. TA during swing and the continuous activity in the calf muscles during early (walking) or late (jogging) stance, which can be ascribed to a reflex in response to foot loading (extensor reinforcing reflex) [26]. The start of swing seems to be initiated by hip extension [27]. Some coupling between motion and a CPG is needed anyway to ensure that the CPG remains in pace with the movement [28]. To determine which actions are reflexes and which are fully programmed is a research program in itself, for which the present data can only give very indirect support. The major outcome of the present research so may just be to provide an accessible database for EMG data in running.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gaitpost.2006.06.013.

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