Intramuscular EMG from the hip flexor muscles during human locomotion

E.A. ANDERSSON, J. NILSSON and A. THORSTENSSON

Departments of Neuroscience, Karolinska Institute and Human Biology, University College of Physical Education and Sports, Stockholm, Sweden

ABSTRACT

The purpose was to investigate the activation pattern of five major hip flexor muscles and its adaptation to changing speed and mode of progression. A total of 11 healthy subjects performed walking and running on a motor-driven treadmill at speeds ranging from 1.0 to 6.0 m s⁻¹. Intramuscular fine-wire electrodes were used to record myoelectric signals from the iliacus, psoas, sartorius, rectus femoris and tensor fascia latae muscles. The basic pattern, with respect to number of activation periods, remained the same irrespective of speed and mode of progression. However, differences in the relative duration and timing of onset of activation occurred between individual muscles. Over the speed range in walking, a progressively earlier onset was generally seen for the activation period related to hip flexion. Changes in EMG amplitude were measured in the iliacus and psoas muscles and showed a marked increase and difference between walking and running at speeds above 2.0 m s⁻¹. Thus, the alternating flexion-extension movements at the hip during locomotion appear to be governed by a rather fixed ‘neural program’ which normally only needs minor modulations to accomplish the adjustments accompanying an increase in speed of progression as well as a change from walking to running.

Keywords iliopsoas, locomotion, motor control, muscle coordination.

Received 19 November 1996, accepted 20 May 1997

Human locomotion has a great potential to adapt to different conditions. These include a wide range of speeds, from zero, i.e. in-place locomotion, to short episodes of sprinting at speeds above 10 m s⁻¹. The adaptations over this range of speeds normally involve a transition from one mode of progression to another, namely from walking to running. This transition occurs spontaneously at speeds between 1.5 and 2.0 m s⁻¹ (Thorstensson & Robertsson 1987). However, humans can voluntarily choose either to walk or run at a certain speed within a range of speeds, from zero up to, and even above, 3.0 m s⁻¹. Thus, comparisons can be made between the two modes of progression at the same speed, including the speed where a switch normally occurs. Such comparisons can reveal interesting characteristics of the neural control of the two locomotor ‘programs’ and its adaptability. We have performed such studies previously for the trunk and lower extremity (Thorstensson et al. 1982, 1984, Nilsson et al. 1985b, Nilsson & Thorstensson 1987, 1989; summarized in Nilsson 1990). The present study expands on the previous ones, using a similar paradigm and focusing on the coordination patterns between different hip flexor muscles.

The main movements at the hip during both walking and running consist of a rather stereotyped alternating between flexion and extension, extension occurring primarily during the support phase and flexion mainly during the swing phase of the ipsilateral leg. The control of such a movement appears at first to be rather simple. However, a closer look discloses a fair amount of complexity. Given that the hip joint principally allows movements in all directions, it is evident that to steer the movement primarily into the fore–aft direction requires muscles that can act as both prime movers and stabilizers. Furthermore, there are quite a few individual muscles that can fulfil these requirements at the hip joint.

In order for a muscle to be a potential hip flexor, i.e. having an ability to create a hip flexor torque, it has to
have a lever arm anterior to a transverse axis through the hip joint. Anatomy texts (e.g. Williams & Warwick 1980) generally agree that there are five major muscles that have such a mechanical possibility: the iliacus, psoas, sartorius, rectus femoris and tensor fascia latae. (Additional muscles with a possible hip flexor function are some of the hip adductors.) All these muscle have different geometry, and several of them also have other potential actions at the hip joint as well as at other joints, such as the psoas at the lumbar back and sartorius, and the rectus femoris and tensor fascia latae at the knee.

Electromyographic recordings make it possible to establish whether a muscle is activated and thus really contributing to torque production as assumed from its anatomy. Due to the deep location (psoas and iliacus), relatively small cross-sections, closeness to other muscles and the accompanying risk for ‘cross-talk’ of the EMG (sartorius, and also to some extent rectus femoris and tensor fascia latae), intramuscular recordings are required. Up until now, no study has been performed, using intramuscular recordings with verified electrode locations, of more than four hip flexor muscles simultaneously, covering a large range of velocities including both walking and running, and providing statistics for several subjects.

In the hitherto most comprehensive study on adaptations to speed and mode of progression in human locomotion (Nilsson et al. 1985b, cf. also Nilsson 1990), only rectus femoris among the hip flexors was studied using surface electrodes. An interesting finding was that the amplitude ratio between the two activation periods of rectus femoris during each stride cycle changed gradually with speed, in both walking and running, and providing statistics for corresponding speeds and the activation pattern of the iliacus and psoas muscles.

**MATERIALS AND METHODS**

**Subjects**

In total, 11 habitually active subjects participated, nine men with a mean age, body mass and height of 28 (range 23–35) years, 79 (65–87) kg and 1.85 (1.75–1.95) m, and two women aged 25 and 35 years, of mass 65 and 66 kg, and height 1.73 and 1.78 m, respectively. The experimental procedures were approved by the ethical committee of the Karolinska Institute and all subjects gave their informed consent to participate in the study.

**Protocol, acquisition of movement and temporal data**

The subjects performed level walking (1.0, 1.5, 2.0 and 3.0 m s$^{-1}$) and running (1.5, 2.0, 3.0, 4.0, 5.0 and 6.0 m s$^{-1}$) on a motor-driven treadmill (treadmill belt size: 2.7 × 0.8 m). All subjects were used to treadmill locomotion. The recordings were made during ≈30 s of ‘steady-state’ walking and running at each velocity.

The angular displacement in the sagittal plane at the right hip joint was recorded with an electrogoniometer placed with the pivot point at the trochanter major (Andersson et al. 1996b). The goniometer, with its two levers (10 and 15 cm long) was firmly taped to the skin.
The lower lever was pointing to the lateral midpoint of the knee joint and the upper one was pointing to the midpoint of the crista iliaca.

The instances of foot strike and toe-off were recorded with a pressure-sensitive device mounted to the sole of the right shoe (Nilsson et al. 1985a) and used to calculate temporal aspects of the stride cycle, e.g., durations of the stride cycle, support and swing phases. It consisted of a pressure transducer (National Semiconductor LX-0503 A) connected to a flexible silicone tube which was glued to the outer perimeter of the sole. Deformation of the tubing from foot/belt contact caused a change of pressure inside the tube, which was converted to a voltage change via the transducer. Stride cycle duration \( T_c \) was defined as the time from foot strike (onset of support) of the right foot to the subsequent foot strike of the same foot. The support phase duration \( T_{su} \) was defined as the time from right foot strike to right toe-off. The swing phase duration \( T_{sw} \) was taken as \( T_c - T_{su} \) for the right foot.

Electromyographic recordings

EMG was recorded unilaterally on the right side from the following muscles (Fig. 1): iliacaus (IL), psoas (PS), sartorius (SA), rectus femoris (RF) and tensor fascia latae (TF). For seven subjects, all muscles were investigated, except PS. Simultaneous recordings from PS and IL were performed in four additional subjects (two males and two females), but not at the highest running speed (6 m s\(^{-1}\)).

In all muscles, intramuscular bipolar fine-wire electrodes (multistranded stainless steel with a diameter of 0.22 mm, Teflon-insulated except for 3 mm at each tip) were inserted via a needle (0.7 \( \times \) 50 mm; psoas: 0.9 \( \times \) 200 mm) after hypodermic local anaesthesia. The inter-electrode distance of the tips when hooked onto the needle was \( \approx 5 \) mm. The insertion sites of the electrodes are shown in Figure 1. The tip of the electrodes was placed at an approximate depth from the skin surface of 8.5–12.5 cm for PS, 3–4 cm for IL and 1–1.5 cm for TF, SA and RF. Before and after all experiments, the length of the free ends of the wires outside the skin was controlled and found to be unchanged. The insertion into the PS was made from the back at the L3–L4 level and guided by high-resolution ultrasound. The insertion techniques of the electrodes into psoas and iliacaus have previously been described in more detail (Andersson et al. 1995).

The EMG signals were differentially preamplified (100 times) close to the site of the electrodes using small customized amplifiers attached to the skin. Signals were then bandpass-filtered at 10–1000 Hz, further amplified (10–50 times) and collected together with the signals from the goniometer and the pressure-sensitive foot device on magnetic tape for subsequent analogue-

Figure 1 A schematic picture of the anatomy of the muscles investigated and the approximate insertion sites for the intramuscular electrodes. TF, tensor fascia latae; SA, sartorius; RF, rectus femoris; PS, psoas; IL, iliacaus. The insertion into PS was made from the back at the L3-L4 level.
to-digital conversion and computer analysis. The sampling frequency was 0.5 kHz.

Only the data from the additional four subjects who underwent experiments with simultaneous recordings from IL and PS were available for amplitude quantification. Before calculating the average EMG amplitude for IL and PS, bandpass filtering between 50 and 1000 Hz was applied to eliminate movement artifacts from the signals. The EMG signals were then full-wave rectified and the mean amplitude was determined between the onset and termination of the main EMG burst, i.e. over the whole period of activity occurring in the transition from hip extension to flexion. The mean EMG amplitude for each individual muscle was expressed as a percentage of the highest mean EMG value for that particular muscle observed at any of the recorded speeds of walking and running. A mean of three different cycles was calculated for each muscle (IL and PS) and subject ($n = 4$).

Analysis of time of onset and termination of the EMG activity periods was performed by two experienced investigators who together made a decision based on visual inspection. The values are presented both as absolute values and in relation to normalized stride on visual inspection. The values are presented both as absolute values and in relation to normalized stride cycle ($T_c = 100\%$) at each speed of walking and running. A mean of three stride cycles was calculated for each variable and subject. Finally, the mean values for all subjects (±standard error of the mean, SE) were calculated for each muscle and locomotion task.

Statistics

Differences between speeds and muscles with respect to absolute and relative durations, onsets of events as well as relative EMG amplitudes (IL and PS) were tested for significance with a one-way ANOVA followed by a Duncan post hoc test. The level of significance was set at $P < 0.05$.

RESULTS

General pattern

The general pattern of activation of individual muscles is shown schematically in Figure 2 in relation to a normalized stride cycle at each speed of walking and running. One period of activation, occasionally consisting of two peaks, was present for all muscles, except RF and PS, which generally showed two separate bursts of EMG (Figs 2 and 3). The extended period of activation of TF could, particularly at low speeds of locomotion, consist of a number of small bursts, more or less distinguishable. In the analysis, the activation of TF was treated as one continuous activation period. The activation period of IL and SA occurred in conjunction with the transition from hip extension to hip flexion, as did one of the two bursts in PS and RF. These EMG bursts will be referred to below as the main periods of activation. The other activity period of activation for RF occurred in the beginning of the support phase, and for PS at the end of the swing phase (Figs 2 and 3). This second EMG burst for PS was present in all subjects at all speeds above 1.5 m s$^{-1}$ in walking and 2.0 m s$^{-1}$ in running, whereas its occurrence was more erratic at lower speeds. The activity period for TF started in the beginning of the support phase. In general, TF activity did not last as far into the swing phase as that of the other hip flexor muscles (Fig. 2).


durations

Absolute durations (Table 1). The absolute durations of the stride cycle ($T_s$) and support phase ($T_{sw}$) decreased progressively with speed in both walking and running. The absolute durations of the main period of activation, on the other hand, generally did not differ significantly between speeds for any of the muscles, either in walking or in running. The only exceptions occurred at the lowest walking speed, 1.0 m s$^{-1}$, where the EMG burst was significantly different from that in walking at 2.0 m s$^{-1}$ for PS (longer) and SA (shorter) and 3.0 m s$^{-1}$ for PS and TF (both longer), and in running at 4.0–6.0 m s$^{-1}$ for TF (longer). $T_c$ and $T_{sw}$ were significantly shorter in running as compared with walking at 1.5 and 2.0 m s$^{-1}$. However, there were no significant differences in absolute durations of the main EMG burst between walking and running at the same speeds. Over the whole range of speeds, in both walking and running, TF displayed the longest period of activation, whereas the main EMG burst of RF was generally shorter than that of the other muscles. There was no statistical difference in absolute duration of the main burst between IL, PS and SA at any of the speeds.

Relative durations (Fig. 2). The relative duration of $T_{sw}$ tended to decrease with speed, in both walking (67–56% of $T_c$) and running (56–30% of $T_c$) (cf. values for onset $T_{sw}$ in Table 2). Comparing the duration of the main activity period over speeds in the two modes of progression, no significant difference was observed for IL (range of values: 31–39% of $T_c$ in walking and 28–40% of $T_c$ in running), PS (18–29% and 31–42%), TF (38–57% and 43–60%) and SA in running (28–35%). Increasing values with speed were seen in walking for SA (from 13 to 37% of $T_c$) and for RF (from 10 to 26% of $T_c$). RF also showed a significant increase from 12 to 30% of $T_c$ over the range of running speeds investigated. The relative $T_{sw}$ values for running were significantly lower than for walking at 2.0 and 3.0 m s$^{-1}$. There was also a tendency towards a
decrease in relative duration for IL when changing from walking to running at the same speeds (38±28, 35±30 and 39±31% of $T_c$ at 1.5, 2.0 and 3.0 m s$^{-1}$, respectively). Interestingly, the tendency was the opposite for PS (25±31, 18±31 and 29±40% of $T_c$). For the other three muscles, there was no consistent difference between the two modes of locomotion at corresponding speeds. In general, TF had longer (significantly in walking at 2.0 and in running at 1.5, 2.0 and 6.0 m s$^{-1}$) and RF shorter relative durations (significantly in running at 1.5 and 3.0 m s$^{-1}$) than the other muscles. There were no significant differences in relative duration between the main EMG bursts of PS, IL and SA.

**Timing**

Onsets of $T_{sw}$, hip flexion and EMG in relation to the start of $T_c$ (Table 2, Fig. 2). The onset of the swing phase ($T_{sw}$) equal to the end of $T_{su}$ (cf. above) tended to occur earlier in the stride cycle with increasing speed in both walking (67–56% of $T_c$) and running (56–30% of $T_c$). The onset times for hip flexion were similar to onset $T_{sw}$ in walking, whereas the values were generally higher in running, particularly at higher speeds. This means that at higher running speeds, the transition between extension and flexion at the hip occurred well after the completion of the support phase. A switch between...
walking and running also meant a later initiation of hip flexion in relation to start $T_{sw}$ at the speeds of 2.0 and 3.0 $m\ s^{-1}$.

In walking, the onset of the main activity period for IL, PS, SA and RF occurred gradually earlier with increasing speed, differences being significant between the highest and the lowest walking speed applied. In running, no significant differences were found for the EMG onset times with speed, although the mean values were lower (not significant) at the highest than at the lowest speed for all muscles. Comparing EMG onsets between walking and running at corresponding speeds showed no consistent differences, except for an earlier onset for SA in running at 1.5 $m\ s^{-1}$.

TF was always activated significantly earlier than the other muscles. The main activity burst of RF, on the other hand, occurred late in the stride cycle, onset values being significantly higher than for the other muscles at the highest walking speed and the majority of the running speeds. No significant differences were seen in onset times between IL, PS and SA, although IL tended to be activated earlier than PS in walking at all speeds, and earlier than SA in running at the highest speed.

*Onsets of EMG in relation to start of hip flexion* (Table 2, Fig. 2). In walking at the lowest speed, the only muscles, except TF, starting their activation prior to the

### Table 1

<table>
<thead>
<tr>
<th>Speed ($m\ s^{-1}$)</th>
<th>Walking</th>
<th>Running</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.0</td>
<td>1.5</td>
</tr>
<tr>
<td>$T_c$</td>
<td>1.20</td>
<td>1.03</td>
</tr>
<tr>
<td>SE</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>$T_{su}$</td>
<td>0.80</td>
<td>0.65</td>
</tr>
<tr>
<td>SE</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>IL</td>
<td>0.36</td>
<td>0.41</td>
</tr>
<tr>
<td>SE</td>
<td>0.10</td>
<td>0.05</td>
</tr>
<tr>
<td>PS</td>
<td>0.38</td>
<td>0.24</td>
</tr>
<tr>
<td>SE</td>
<td>0.05</td>
<td>0.09</td>
</tr>
<tr>
<td>SA</td>
<td>0.15</td>
<td>0.24</td>
</tr>
<tr>
<td>SE</td>
<td>0.02</td>
<td>0.09</td>
</tr>
<tr>
<td>RF</td>
<td>0.12</td>
<td>0.19</td>
</tr>
<tr>
<td>SE</td>
<td>0.06</td>
<td>0.07</td>
</tr>
<tr>
<td>TF</td>
<td>0.56</td>
<td>0.43</td>
</tr>
<tr>
<td>SE</td>
<td>0.09</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Figure 3  Angular displacement at the hip and ‘raw’ EMG activity from the psoas and iliacus muscles for one subject running at 4.0 $m\ s^{-1}$. The filled horizontal bars at the top denote the periods of ipsilateral (right) support ($T_{su}$). F, flexion; E, extension.
transition from extension to flexion at the hip were IL and PS. At the highest speed of walking, all muscles were activated before the start of hip flexion, the pre-activation being significantly longer for IL (33% of $T_C$) and SA (28% of $T_C$) than at any other speed of walking or running. In running, the average difference between the onset of EMG and hip flexion was in the range 9–22% of $T_C$ for IL, SA and PS. The differences were generally smaller for RF (<10%), even being negative at the lowest running speed, i.e. starting after the initiation of hip flexion.

### Activity levels

There were no significant changes in the EMG levels in IL or PS, expressed in relation to the highest observed EMG level for either muscle, in the speed range 1.0–2.0 m s$^{-1}$ (Fig. 4). At higher speeds, the mean EMG increased significantly, reaching values four to five times as high as at the lower speeds (Fig. 4). Switching from walking to running at the same speeds resulted in an increased EMG amplitude at 3.0 m s$^{-1}$ only (Fig. 4). No significant differences in activity levels relative to the highest observed for each muscle were present between PS and IL at any of the corresponding walking and running speeds.

### DISCUSSION

The main purpose of this study was to provide a comprehensive view of the activation patterns, pri-

---

**Table 2** Onsets of the swing phase ($T_{sw}$), hip flexion (HF) and EMG for IL, PS, SA, RF and TF in relation to the start of the stride cycle ($T_C$) during locomotion at different speeds (m s$^{-1}$) expressed as a percentage of $T_C$. Values are means and standard errors (SE). $n = 7$ for all variables, except PS for which $n = 4$.

<table>
<thead>
<tr>
<th>Speed (m s$^{-1}$)</th>
<th>Walking</th>
<th></th>
<th>Running</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_{sw}$</td>
<td>67</td>
<td>63</td>
<td>61</td>
<td>56</td>
<td>56</td>
</tr>
<tr>
<td>SE</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>HF</td>
<td>59</td>
<td>56</td>
<td>54</td>
<td>57</td>
<td>52</td>
</tr>
<tr>
<td>SE</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>IL</td>
<td>44</td>
<td>37</td>
<td>33</td>
<td>25</td>
<td>36</td>
</tr>
<tr>
<td>SE</td>
<td>8</td>
<td>6</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>PS</td>
<td>55</td>
<td>50</td>
<td>48</td>
<td>33</td>
<td>35</td>
</tr>
<tr>
<td>SE</td>
<td>4</td>
<td>8</td>
<td>9</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>SA</td>
<td>71</td>
<td>58</td>
<td>43</td>
<td>29</td>
<td>43</td>
</tr>
<tr>
<td>SE</td>
<td>1</td>
<td>7</td>
<td>8</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>RF</td>
<td>60</td>
<td>48</td>
<td>48</td>
<td>44</td>
<td>54</td>
</tr>
<tr>
<td>SE</td>
<td>3</td>
<td>8</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>TF</td>
<td>4</td>
<td>6</td>
<td>3</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>SE</td>
<td>6</td>
<td>5</td>
<td>6</td>
<td>6</td>
<td>1</td>
</tr>
</tbody>
</table>

---

**Figure 4** Mean EMG amplitudes (±SE, $n = 4$) for the iliacus (squares) and psoas (circles) muscles at different velocities of walking (filled symbols) and running (open symbols). Values are expressed as a percentage of the highest value observed for each muscle.
marily with respect to durations and timing, for five major muscles which, from an anatomical point of view, are expected to contribute to hip flexion torque during locomotion.

**Qualitative analysis – comparison with literature**

A qualitative analysis of the general activation pattern showed that two of the five muscles, iliacus and sartorius, displayed one main EMG burst, occurring in conjunction with the transition from hip extension to flexion. For sartorius, these results are similar to those reported for walking by Greenlaw (1973) also using intramuscular recordings. Winters & Yack (1987), on the other hand, reported a biphasic sartorius pattern in walking, with an EMG period also early in the support phase. It cannot be excluded, however, that the activity picked up by their surface electrodes placed rather widely on the thin sartorius muscle might also have contained ‘cross-talk’ from nearby situated parts of quadriceps femoris. For iliacus, our results are in general agreement with earlier studies on walking (Greenlaw 1973, Lindén & Delhez 1986) and running (Lindén & Delhez 1986, Mann et al. 1986, Jönhagen et al. 1996). A tendency towards a splitting of the main EMG burst into two during walking, as reported by Lindén & Delhez (1986), occurred occasionally in three of our seven subjects at lower walking speeds. In running, we found that the activation of iliacus started about 20% earlier in the stride than that found by Lindén & Delhez (1986) and generally before toe-off (except at 5.0 m s\(^{-1}\)), in contrast to Mann et al. (1986) who found onset of iliacus activation after onset of the swing phase.

In two muscles, psoas and rectus femoris, two bursts of EMG were generally present in both walking and running. In psoas, one EMG burst was related to the onset of hip flexion, as also reported for walking by previous authors (Keagy 1966, Greenlaw 1973). The other occurred during the latter part of the swing phase, and was more marked during higher speeds of both walking (cf. Greenlaw 1973) and running. It can be assumed that this second period of psoas activation contributes to control and stabilize the movements of the trunk in the frontal plane (Thorstensson et al. 1982, 1984). Involvement of psoas, and not iliacus, in lateral trunk stabilization has been shown in standing (Andersson et al. 1995). Other examples of a selective activation of either of the two portions of the iliopsoas muscle have been demonstrated in certain standing, sitting and lying positions (Andersson et al. 1995, 1996). Here, the presence of an additional burst of EMG selectively in psoas during the swing phase provides more evidence of this phenomenon. Otherwise, there was a general coherence in the activation pattern between iliacus and psoas (see below). The existence of two EMG bursts in the rectus femoris muscle is well established in both walking (e.g. Nilsson et al. 1985b, Ericson et al. 1986, Shiavi et al. 1992) and running (e.g. Nilsson et al. 1985b, Jönhagen et al. 1996). Since rectus femoris is a two-joint muscle, selective actions at either the hip or the knee joints are difficult to deduce. However, it appears as if the burst occurring mainly during the swing phase primarily provides a hip flexor action. The other period of activation starting initially in the support phase coincides with a general activation of the vastii muscles, i.e. single joint knee extensor muscles. Thus, rectus femoris could in this case contribute knee extensor torque to control flexion of the knee and induce a subsequent knee extension. Of the five muscles investigated, the tensor fascia latae appears to be least involved in controlling hip flexion. It was active with varying magnitude during most of the support phase and its duration rarely lasted into the hip flexion phase. Instead, the prolonged activation during support is most likely related to an abductor stabilizing function at the hip and possibly also to controlling knee flexion–extension (cf. Carlsöö & Fohlin 1969, Mann et al. 1986).

A comparison of the onset times of the activation periods in relation to the start of hip flexion, in both relative and absolute terms, allows an assessment of the possible role of each muscle for the control of the hip movements during locomotion. At low walking speeds, the sartorius and rectus femoris muscles could not be involved to brake and reverse the hip extension since they were generally activated after the initiation of hip flexion. Iliacus appears to be the main switch muscle in walking at low speeds, and iliacus and psoas in slow running, beginning their activation usually more than 100 ms before the switch from hip extension to flexion. At higher speeds, such a pre-activation was common for all muscles, allowing for a utilization of the mechanically efficient coupling between eccentric (lengthening) and concentric (shortening) muscle actions (cf. Cavagna 1977). In walking, there was a tendency for iliacus to be activated before psoas, and over the whole range of velocities iliacus and psoas tended to be activated earlier than sartorius and rectus femoris.

**Adaptations to speed**

With an increase in speed, the durations of the stride cycle and the support phase decreased in both walking and running. Simultaneously, there is an increase in net hip movement amplitude (Nilsson et al. 1985b). This increase in net amplitude is mainly accomplished by an increase in hip flexion angle, i.e. a more flexed hip at start of extension, and only to a smaller extent via an increase in extension angle at start of flexion. Consequently, there is a larger angular movement at the hip occurring during a shorter time, i.e. a higher angular
acceleration, which in turn means a higher demand for hip flexor torque. However, at the same time an increased flexion at the knee with speed causes a lowering of the moment of inertia and of the need for flexor torque. Lacking the necessary kinetic data, we can only conclude from the present data what the outcome actually is with respect to changes in the pattern of EMG with speed in the various muscles.

Only the psoas and iliacus were analysed with respect to EMG amplitude. A considerable increase in EMG amplitude with increased speed above 2 m s\(^{-1}\) was noticed for the two muscles in both modes of progression. The absolute durations of the EMG periods were, on the other hand, maintained even though the cycle duration decreased. Thus, there seems to be no adaptation in the control of the duration of the activation, which is in contrast to the shortening earlier shown for the ankle extensors (Nilsson et al. 1985b). As a result, the relative duration of the EMG bursts tended to increase with speed, particularly for the psoas, sartorius and rectus femoris muscles. In this context, it should be remembered that the swing phase, during which most of the hip flexor activity occurs, also becomes longer relative to the stride cycle with increasing speed.

The start of the main activity period relative to onset of hip flexion generally did not present any significant differences for individual hip flexor muscles, with a few exceptions. However, there was a general tendency towards a more synchronous activation of all muscles at higher speeds.

Comparison between walking and running

Normally the subjects would have spontaneously switched from walking to running at a speed between 1.5 and 2.0 m s\(^{-1}\) (Thorstensson & Robertson 1987). In earlier studies, certain distinct differences between the two modes have been documented (Nilsson 1990), one being the shortening of the durations of the stride cycle and the support phase, which was also observed here. Interestingly, the support phase was longer than 50% in running at the slowest speed, which means that there was a double support phase, usually present only in walking (cf., however, Nilsson et al. 1985b). Another difference coupled to the higher stride cycle frequency was the clearly smaller propulsive reaction forces during each support phase in running at the same speed (Nilsson & Thorstensson 1987). Nilsson et al. (1985b) have also shown that the net hip angular displacement amplitude was somewhat smaller in running than in walking at the same speeds in the range 1.0–2.0 m s\(^{-1}\). The only hip flexor muscle studied by Nilsson et al. (1985b) was the rectus femoris. This muscle demonstrated a conspicuous difference between walking and running at corresponding speeds, the hip flexion burst being significantly larger than that related to knee extension in walking, whereas the reverse pattern was present in running.

Walking at 3.0 m s\(^{-1}\) does not represent a normal condition since all subjects would normally have run at this speed. However, a comparison between walking and running at this speed is of particular interest because the mean stride cycle duration, and thus the stride frequency, was similar in the two modes of progression. Furthermore, the net angular displacement at the hip as well as the extreme angles of hip flexion and extension have been shown to be of similar magnitude in walking and running at this speed (Nilsson et al. 1985b). Thus, the angular acceleration ought to be similar, whereas the moment of inertia of the straighter leg in walking should be higher and therefore also the demand for a muscular flexor moment of force (torque) at the hip (cf. Nilsson 1990). To accomplish this higher torque, several strategies appear possible, e.g. increasing the magnitude and/or the duration of the activation, starting the activation earlier in relation to the start of hip flexion, and/or recruiting additional or other synergistic muscles, changing the recruitment pattern towards more synchronization, etc.

From the present data, it is evident that the strategy of increasing amplitude was applicable on the iliacus and psoas muscle activation. For both muscles the values for walking were about twice as high in walking than in running at 3.0 m s\(^{-1}\). In contrast, there was no amplitude difference at 1.5 or 2.0 m s\(^{-1}\). The other muscles were, for technical reasons, not available for amplitude quantification and no comparable data appear in the literature. There was no marked difference in absolute duration of activation for any of the muscles. In terms of onsets of activation in relation to the initiation of hip flexion, all examined muscles, except tensor fascia latae, started earlier in walking (84–231 ms) than in running (22–126 ms). Thus, the strategies used to accomplish an increased hip flexor torque in walking as compared with running at 3.0 m s\(^{-1}\) appeared primarily to involve an increase in activation levels and a shift of activation onsets, whereas modulation of durations of the activation periods seemed to play a minor role.

This study was supported by grants from the Swedish Work Environment Fund (90–0798) and the Research Council of the Swedish Sports Federation (27/91). The authors gratefully acknowledge Dr Helen Grundström, Department of Radiology, Danderyds Hospital, for providing the ultrasound expertise.

REFERENCES


Andersson, E., Oddsson, L., Grundström, H. & Thorstensson, A. 1995. The role of the psoas and iliacus