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# Electromyographic Analysis of Hip and Knee Musculature During Running

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## ABSTRACT

The purpose of this study was to describe the firing pattern of 11 hip and knee muscles during running. Thirty recreational runners volunteered to run at 3 different paces with indwelling electromyographic electrodes while being filmed at 100 frames per second. Results demonstrated that medial and lateral vasti muscles acted together for knee extension during terminal swing and loading response, possibly providing a patella stabilizing role. The vastus intermedius muscle functioned with the other vasti, plus eccentrically controlled knee flexion during swing phase. The rectus femoris muscle fired with the vastus intermedius muscle and assisted the iliacus muscle with hip flexion. The hamstrings fired primarily to eccentrically control hip flexion. The adductor magnus, tensor fascia lata, and gluteus maximus muscles afforded pelvic stabilization while assisting with hip flexion and extension. Forward propulsion was provided mainly by hip flexion and knee extension, which is contrary to the view that posterior calf muscles provide propulsion during toe off. Faster running paces lead to increased activity in the muscles. This may lead to more injuries, primarily in the muscles that were contracting eccentrically.

By studying the biomechanics of running, one may develop a better understanding of the pathophysiology of running-related injuries and may offer insights to injury prevention. Other authors have used elite or competitive runners as their subjects or have used treadmills as their running surfaces.<sup>4-7</sup> This study used recreational runners who ran overground, which represents the majority of runners in this country and thus the majority of running-related injuries. Previous authors have used surface electrodes to study muscle function during running.<sup>4-6,10</sup> These studies

are limited by the wide dispersion of the electrical signals through skin and subcutaneous tissues as well as the inability to separate signals from adjacent muscles that may be firing simultaneously. Fine-wire EMG allows accurate measurement of individual muscle activity as well as identifies the firing patterns and intensity of contraction.<sup>3,8</sup>

The purpose of this study was to use fine-wire EMG on recreational runners: 1) to describe the firing pattern of 11 muscles controlling the hip and knee during running, 2) to compare the timing and intensity of contractions among these muscles, and 3) to compare the effect of changing the pace of running on the muscles studied.

## MATERIALS AND METHODS

The subjects in this study were 30 recreational and low-level competitive runners who were running at least 15 miles per week. All runners were injury-free for at least 3 months before the study. There were 21 men and 9 women with an average age of 30.6 years (range, 20 to 53). Both the Centinela Hospital Human Rights Committee and the Centinela Hospital Biomechanics Laboratory Research Review Committee approved this project. The study was conducted at the outdoor track facility of the Centinela Hospital Biomechanics Laboratory in Inglewood, California.

The recording device (Bio-Sentry Telemetry, model 4200-A, Torrance, CA) used in the study allowed a maximum of 8 muscles to be tested in each subject. Sixteen subjects had 8 muscles tested (rectus femoris, vastus medialis, vastus intermedius, vastus lateralis, iliacus, semimembranosus, biceps femoris short head, biceps femoris long head), and 14 subjects had 3 muscles tested (adductor magnus, tensor fascia lata, lower gluteus maximus). Recording of the signal used the Basmajian single-needle technique.<sup>3</sup> After proper skin preparation and isolation of the muscle, dual 50-micron insulated wires with 2 to 3 mm bared tips were inserted into the muscle using a 25-gauge hypodermic needle as a cannula. The wires from each inserted muscle were attached to a ground plate and then taped to the subject's body. The signals were transmitted using an FM-FM telemetry system that was capable of transmitting up to 4 muscles simultaneously. Correct wire electrode placement was confirmed either by electrical stimulation or by a maxi-

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mal muscle test specific to the inserted muscle with the telemetry signal monitored on an oscilloscope (Fig. 1). Each subject wore the battery-operated FM transmitter belt pack oriented to prevent restriction in bodily movements.

Before the initiation of testing, a resting recording was done, and a manual muscle strength test was performed to be used later as a normalizing value. The EMG information was bandpass filtered at 100 to 1000 Hz and recorded on a multichannel instrumentation recorder for later retrieval and review. Each runner was allowed to warm up and then was instructed to run at three different, self-selected paces across the field of view of the high-speed camera. Each runner completed at least five passes at every pace of running. The first pace was entitled "jogging" ( $8.45 \pm 0.90$  min/mile), the second pace "training" ( $6.48 \pm 0.70$  min/mile), and the third pace "race" ( $5.44 \pm 0.72$  min/mile).

A 16-mm high-speed camera that was stationary and operated at 100 frames per second was positioned for a lateral view and recorded the subject's performance. Marks were electronically placed on the film and the EMG data to allow synchronization with the EMG signal. The film was viewed on a stop-action projector, and each stride was divided into four phases. Each phase was further divided into intervals based on elapsed time. These intervals were later synchronized with the EMG data. The four phases and number of intervals per phase were as follows (Fig. 2).

1. Stance phase: beginning with right heel strike (RHS) and ending with right toe off (RTO); seven intervals (RHS 1 to 7).

2. Early swing phase: beginning with right toe off (RTO) and ending with left heel strike (LHS); three intervals (RTO 1 to 3).

3. Midswing phase: beginning with LHS and ending with left toe off (LTO); seven intervals (LHS 1 to 7).

4. Late swing phase: beginning with LTO and ending with RHS; three intervals (LTO 1 to 3).

The EMG data were converted from analog to digital signals by computer at a sampling rate of 2500 Hz and were quantified by computer integration. After excluding the noise identified by the resting recording, the peak 1-sec EMG signal during a manual muscle strength test was selected as a normalizing value (100%). Activity patterns



Figure 1. Instrumentation setup of runner.

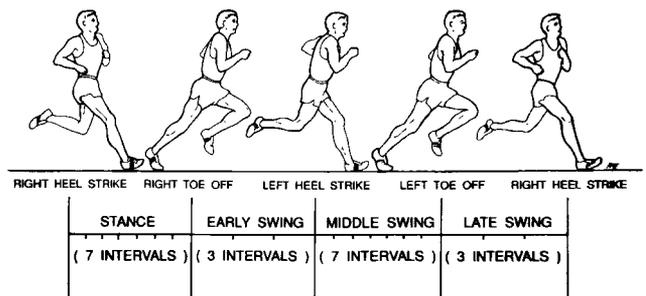


Figure 2. The four phases of the running gait and their intervals.

were assessed every 20 msec and expressed as a percentage of the manual muscle test (MMT) that was the normalization base.

The data were assessed for normality. The percentage of MMT for each phase was then averaged for each muscle, and standard deviations were calculated. An analysis of variance was used to compare a muscle's activity at the three paces, and to compare the firing patterns of the muscles during the training pace ( $P < 0.05$ ). When the analysis of variance revealed statistically significant differences, a post hoc Tukey test ( $P < 0.05$ ) was performed to determine the location of these differences.

## RESULTS

The first part of this section is a description of the EMG activity for each muscle during each phase of gait at a training pace. The second part of this section is a discussion of the results of muscles with similar actions and of the statistically significant differences in their activities. The third part of this section is an examination of the effect of changing the pace on the individual muscle activity.

### INDIVIDUAL MUSCLE ACTIVITY

1. *Vastus medialis muscle.* The vastus medialis exhibited one period of activity in stance (RH2, 99% MMT) (Fig. 3 and Table 1).

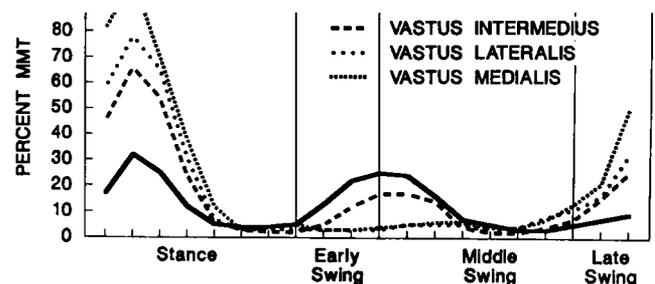


Figure 3. The EMG data of the knee extensors during the training pace.

**TABLE 1**  
Muscle activity of hip and knee throughout the running cycle at training pace (expressed as a percent of manual muscle test)

Muscle	Stance						Early swing				Middle swing						Late swing			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Rectus femoris Mean	17	32	25	12	5	4	4	5	13	22	25	24	16	7	5	3	3	5	7	9
Vastus intermedius Mean	45	66	54	24	6	3	2	2	5	12	17	17	14	4	2	2	4	7	15	25
Vastus lateralis Mean	58	78	65	31	7	3	3	3	3	3	3	5	5	5	3	4	8	11	16	32
Vastus medialis Mean	81	99	70	38	12	3	4	5	3	3	4	5	6	6	4	4	7	13	21	50
Biceps femoris (short head) Mean	10	13	18	27	35	27	13	9	14	25	35	35	21	12	11	17	25	35	33	18
Iliacus Mean	12	15	15	10	9	11	14	21	31	37	41	32	22	15	11	7	9	9	11	10
Lower gluteus maximus Mean	41	39	28	14	11	10	10	8	10	10	11	16	15	12	11	9	9	13	15	30
Biceps femoris (long head) Mean	35	38	49	52	44	28	12	5	5	6	9	15	18	18	23	36	49	62	63	44
Semimembranosus Mean	25	30	28	21	19	18	15	9	7	6	6	8	11	15	23	40	54	65	64	41
Adductor magnus Mean	39	58	50	29	18	11	13	22	21	16	22	30	27	17	16	21	27	28	28	42
Tensor fascia lata Mean	26	38	36	27	19	17	18	30	33	29	20	26	31	27	25	19	17	22	26	27

2. *Vastus lateralis* muscle. Similar to the vastus medialis muscle, the vastus lateralis muscle demonstrated one period of activity in stance (RH2, 78% MMT) (Fig. 3 and Table 1).

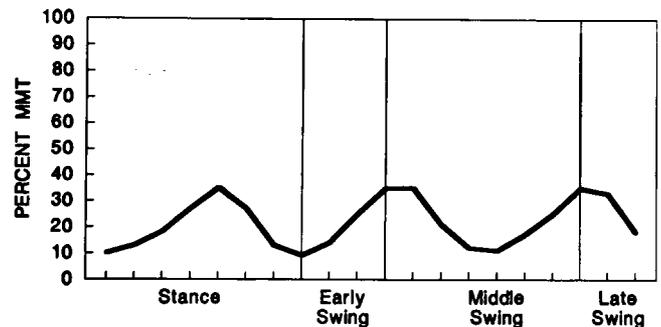
3. *Vastus intermedius* muscle. The vastus intermedius muscle revealed two periods of activity. One was similar to the vastus lateralis and vastus medialis muscles in stance (RH2, 66% MMT). The second area of activity was in middle swing (LH1, 17% MMT) (Fig. 3 and Table 1).

4. *Rectus femoris* muscle. The rectus femoris muscle functioned similarly to the vastus intermedius muscle with two periods of activity. One peak was during stance (RH2, 32% MMT), and the second area of activity was in middle swing (LH1, 22% MMT) (Fig. 3 and Table 1).

5. *Biceps femoris short head*. The short head of the biceps femoris muscle had three periods of activity. The first peak was during stance (RH5, 35% MMT), the second peak was during middle swing (LH1, 35% MMT), and the third peak was during late swing (LT1, 35% MMT) (Fig. 4 and Table 1).

6. *Semimembranosus* muscle. The semimembranosus muscle had two periods of activity. The first peak was during stance (RH2, 30% MMT) and the second peak was during late swing (LT1, 65% MMT) (Fig. 5 and Table 1).

7. *Biceps femoris long head*. The long head of the biceps femoris muscle was similar to the semimembranosus muscle with two periods of activity. The first peak was in stance (RH4, 52% MMT), and the second peak was during late swing (LT1, 62% MMT) (Fig. 5 and Table 1).



**Figure 4.** The EMG data of the biceps femoris short head during training pace.

8. *Lower gluteus maximus* muscle. The gluteus maximus muscle had one period of activity that peaked during stance (RH1, 41% MMT) (Fig. 5 and Table 1).

9. *Iliacus* muscle. The iliacus muscle had one period of activity that peaked during middle swing (LH1, 41% MMT) (Fig. 6 and Table 1).

10. *Adductor magnus* muscle. The adductor magnus muscle had three areas of activity. The first peak was in stance (RH2, 58% MMT), the second peak was during early swing (RT1, 22% MMT), and the third peak was in middle swing (LH2, 30% MMT) (Fig. 7 and Table 1).

11. *Tensor fascia lata* muscle. The tensor fascia lata muscle demonstrated three periods of activity. The first

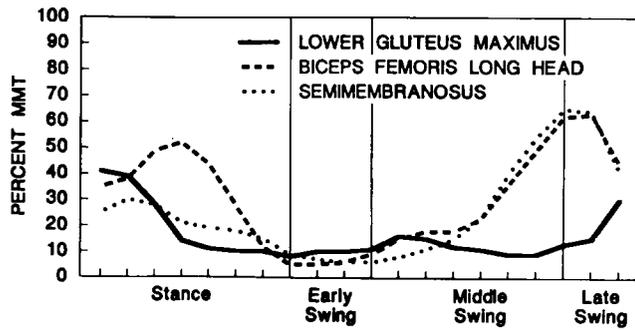


Figure 5. The EMG data of the hip extensor muscles during training pace.

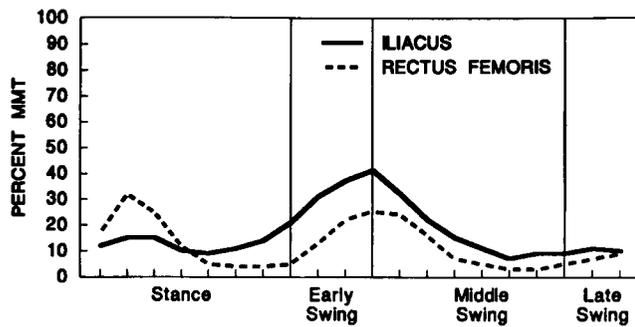


Figure 6. The EMG data of the hip flexor muscles during training pace.

peak was in stance (RH2, 38% MMT), the second peak was in early swing (RT2, 33% MMT), and the third peak was in middle swing (LH3, 31% MMT) (Fig. 7 and Table 1).

COMPARISONS OF MUSCLE ACTIVITY

Knee extensors

The knee extensors consisted of the quadriceps muscles. The major period of activity was during early stance. During peak activity, the three vasti had significantly greater activity than the rectus femoris muscle ( $P < 0.05$ ), and the vastus medialis was significantly greater than the vastus intermedius muscle ( $P < 0.05$ ). There was no significant difference between the vastus lateralis and vastus medialis muscles (Fig. 3). The second period of activity was during early and middle swing. Only the rectus femoris and vastus intermedius muscles had activity during this period, and there was no significant difference between the activities of these two muscles (Fig. 3).

Knee flexors

The knee flexors consisted of the semimembranosus muscle, long head, and short head of the biceps muscle. The short head of the biceps muscle had three periods of activity, while the semimembranosus and long head of the

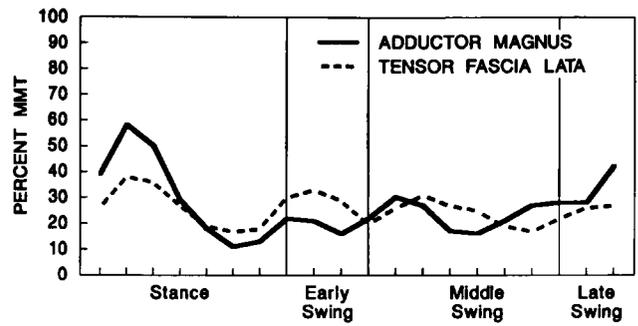


Figure 7. The EMG data of the adductor magnus and tensor fascia lata muscles during training pace.

biceps muscle had only two. During stance, the peak activity of the long head of the biceps muscle was significantly higher than the semimembranosus and short head of the biceps muscles ( $P < 0.05$ ) (Figs. 4 and 5). During early and middle swing, only the short head of the biceps muscle demonstrated activity while the long head and semimembranosus muscles were essentially inactive (Figs. 4 and 5). During middle and late swing, the semimembranosus and long head of the biceps muscles had significantly greater activity than the short head of the biceps muscle ( $P < 0.05$ ) (Figs. 4 and 5).

Hip flexors

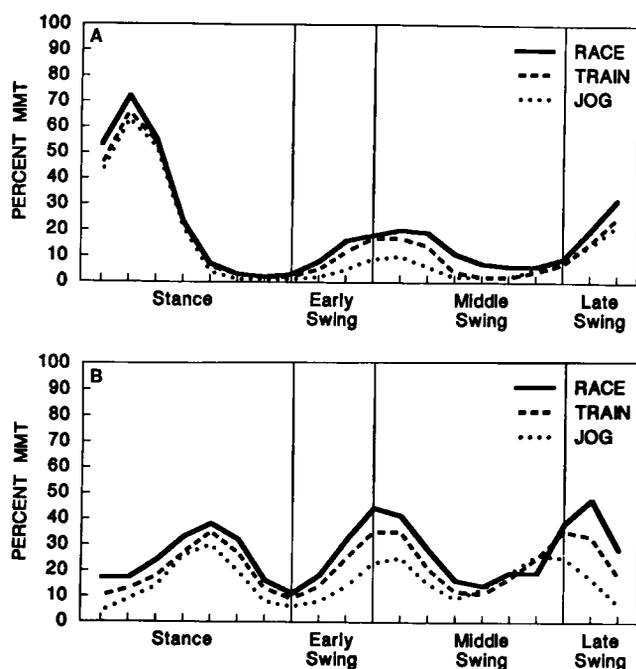
The two major hip flexors studied were the rectus femoris and iliacus muscles. The rectus femoris muscle demonstrated significantly greater activity than the iliacus muscle during stance ( $P < 0.05$ ). The iliacus muscle had a significantly higher peak activity ( $P < 0.05$ ) than the rectus femoris muscle during early and middle swings (Fig. 6).

Hip extensors

The three major hip extensors studied were the gluteus maximus, semimembranosus, and long head of the biceps muscles. The gluteus maximus muscle only had one period of activity during late swing and stance, which deviated from the two periods of activity of the semimembranosus and long head of the biceps muscles during late swing and stance. During stance, the peak activity of the long head of the biceps muscle was significantly greater than the semimembranosus and the gluteus maximus muscles ( $P < 0.05$ ) (Fig. 4). During late swing, there was no significant difference between the semimembranosus and the long head of the biceps muscles.

COMPARISONS OF DIFFERENT PACES

All of the muscles demonstrated a general trend of increased activity with similar patterns. The vastus intermedius and short head of the biceps muscles have been selected as examples to illustrate this trend (Fig. 8).



**Figure 8.** The EMG data of the vastus intermedius (A) and the biceps femoris short head (B) muscles during the three paces of running.

## DISCUSSION

The EMG data discern the pattern and amplitude of electrical firing of a particular muscle. The function of the contracting muscle is determined by the motion of the joint over which the muscle crosses and the other forces that are being applied to the same joint during muscle contraction. The function of the studied muscles can be most easily described by discussing their functions during each phase of the running gait.

## PHASES OF RUNNING

### Stance

The stance phase began at heel strike with the knee at  $13^\circ$  of flexion and the hip at  $18^\circ$  of flexion.<sup>12</sup> The knee flexion increased as the lower extremity absorbed the weight of the body (loading response) until the center of gravity moved in front of the knee, at which time, the knee began to extend. The hip moved into slightly more flexion during loading response, after which, it began to extend.

The three heads of the vasti and the rectus femoris muscle all contracted to stabilize the knee during the loading response. Without this contraction, the knee undoubtedly would have buckled as it accepted the body weight. The three heads of the vasti had significantly greater activity than did the rectus femoris muscle as they played a greater role in knee stabilization. Of the three vasti, the medialis and lateralis muscles exhibited greater activity than did the intermedius muscle. The oblique line of pull from the medial and lateral vasti was apparently more vi-

tal in stabilizing the patella in the trochlear groove than was the straight line of pull from the intermedius muscle. The adductor magnus, lower gluteus maximus, and tensor fascia lata muscles were also active during the loading response when there was a forward momentum; they functioned to stabilize the hip medially, laterally, and posteriorly. Thus, as the lower extremity accepted the body's weight and the momentum was moving forward, muscles from both the hip and knee were active for stabilization. These findings are similar to those of Mann et al.<sup>6</sup> that used surface electrodes.

As the center of gravity moved in front of the knee, the long head of the biceps femoris muscle initiated hip extension. Immediately after the hip extension, the short head of the biceps femoris muscle demonstrated a peak as it contracted eccentrically to control knee extension.

### Early swing

The early swing phase began at toe off with the knee in  $18^\circ$  of flexion and the hip in  $5^\circ$  of extension.<sup>12</sup> The knee moved into more flexion, and the hip remained in extension as the center of gravity remained in front of the knee.

The short head of the biceps muscle demonstrated an increase of activity as it initiated knee flexion. The semimembranosus and long head of the biceps muscles were silent, not appearing to be important in knee flexion during early swing, and they no longer were needed for hip extension as the hip was preparing to move into flexion.

The vastus intermedius muscle demonstrated increasing activity as it contracted eccentrically, controlling knee flexion. It is interesting that even with an increase in pace, the vastus intermedius muscle was the only vastus muscle that was active during early and middle swing. This may be because of its direct line of pull on the patella when the knee is flexed, while the vastus lateralis and vastus medialis muscles have more oblique orientations. It is possible that during flexion when the patella is well seated in the trochlear groove, the vastus medialis and lateralis muscles are not needed for patellar control as in stance. Unlike studies using surface electrodes, it appears that the three vasti do not necessarily act as a single unit.<sup>6,10</sup>

The rectus femoris, iliacus, tensor fascia lata, and adductor magnus muscles all demonstrated activity in controlling the hip extension and in preparing to initiate hip flexion. The rectus femoris muscle also assisted the vastus intermedius muscle in controlling knee flexion.

### Middle swing

The middle swing phase began at contralateral heel strike with the ipsilateral knee at  $50^\circ$  of flexion and the ipsilateral hip at  $4^\circ$  of extension.<sup>12</sup> The knee continued to flex both actively and passively as the hip came into flexion. At the end of the phase, the hip and knee extended.

The iliacus and rectus femoris muscles demonstrated peak activity as the hip flexed. The tensor fascia lata and adductor magnus muscles demonstrated activity as they assisted hip flexion from an extended position and stabilized the pelvis. The semimembranosus and long head of

the biceps muscles contracted eccentrically, controlling the hip flexion. The lower gluteus maximus muscle assisted the hamstrings only during the race pace.

After initiating knee flexion in early swing, the short head of the biceps muscle continued to flex the knee in middle swing. The knee flexion was assisted also by the momentum provided by active hip flexion. The vastus intermedius muscle continued to control knee flexion along with the rectus femoris.

### Late swing

The late swing phase began at contralateral toe off with the knee in 33° of flexion and the hip in 20° of flexion.<sup>12</sup> The hip and knee continued to extend as the lower extremity prepared for heel strike.

The three vasti demonstrated activity in extending the knee. The rectus femoris muscle was silent as the hip was extending. The short head of the biceps was active controlling the knee extension. The semimembranosus, long head of the biceps, and the lower gluteus maximus muscles were active for hip extension with assistance from the adductor magnus muscle, which could extend the hip from the flexed position. The tensor fascia lata muscle was active in controlling the hip extension.

The use of fine wire instead of surface electrodes has enabled a more exact determination of a specific muscle's activity. These findings showed that the quadriceps muscle has three functional muscle units during running. The vastus medialis and vastus lateralis muscles act together as one unit. There may be a patella stabilizing role in having these two muscles contracting simultaneously. This would be most necessary in the stance phase when the limb is weightbearing, the knee is in extension, and the patella is most unstable in the trochlear groove. The vastus intermedius muscle was found to have the additional role of eccentric contraction during swing. The rectus femoris muscle assisted with the eccentric control of knee extension, and it had the additional function of concentric hip flexion during swing. The semimembranosus and long head of the biceps muscles were found to act primarily at the hip; they did not assist the short head of the biceps muscle during pure knee flexion.

There has been some disagreement in the literature as to the main source of forward propulsion in running. Ounpuu<sup>10</sup> and Winter<sup>19</sup> state that through plantar flexion the ankle is the major power generator in running. Results from an earlier study at this laboratory demonstrated that the posterior muscles of the lower leg contracted eccentrically to stabilize the ankle as the center of gravity passes over the foot (stance phase), and they did not supply the power for "pushoff" at terminal stance.<sup>13</sup> The posterior calf muscles appear to stabilize the stance limb while the trunk moves forward. In this study, it was found that the concentric contractions with the greatest amplitude contributing to forward motion were those of hip flexion (iliacus and rectus femoris muscles) during early and midswing, and of knee extension (vastus intermedius, medialis, and lateralis muscles) during late swing. The powerful flexion of the hip and extension of the knee in the swing limb propel

the body forward. We, therefore, agree with Mann et al.<sup>6</sup> that hip flexors and, secondarily, knee extensors are the most important muscle groups producing forward propulsion during running.

Eccentric contractions are frequently implicated in muscle strains and delayed muscle soreness.<sup>1,2,9,14,15,17,18</sup> In this study, the muscles with the highest level of eccentric action were the rectus femoris (which simultaneously was functioning concentrically at the hip) and the vastus intermedius muscles, both functioning at the knee during early and middle swing, the short head of the biceps femoris muscle functioning at the knee during late swing and the semimembranosus and long head of the biceps femoris muscle during middle swing.

With an increase in pace, the muscles not only increase their eccentric activity but also must withstand more rapid and severe lengthening of the muscles.<sup>11</sup> This may be a factor in delayed muscle soreness and muscle strain with an increased running pace or with bursts of speed, as in sprinting to first base. Therefore, for the recreational runner, it is important to follow a graduated training schedule to allow muscles to accommodate to increases in the eccentric loading. Strength training for the recreational runner should concentrate on eccentric strengthening of the hip and knee flexors and extensors.

This study serves as a baseline of normative data for the recreational runner. Future studies focusing on dysfunctions related to running will now be able to be developed and interpreted relative to normal function.

### SUMMARY

The important findings of this study include the following.

1. The quadriceps muscles have three functional units. The vastus lateralis and vastus medialis muscles acted synchronously in late swing for knee extension and in stance for patellar and knee stabilization. The vastus intermedius muscle functioned with the other two vasti, plus had a role of deceleration of knee flexion during early and middle swing. The rectus femoris muscle functioned with the vastus intermedius muscle. The contraction of the rectus femoris muscle during early and middle swing was for hip flexion as well as to control knee flexion.

2. Forward propulsion in running is provided by hip flexion during early and middle swing and knee extension during late swing. The major hip flexors were the iliacus and the rectus femoris muscles, and the vasti were the major knee extensors.

3. The eccentrically contracting muscles during running have been identified (i.e., the rectus femoris, vastus intermedius, and short head of the biceps, long head of the biceps, semimembranosus muscles) and may have an increased risk of injury with an increase in running pace.

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