Timing of Rectus Femoris and Biceps Femoris Muscle Activities in Both Legs at Maximal Running Speed

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ABSTRACT

KAKEHATA, G., Y. GOTO, S. ISO, and K. KANOSUE. Timing of Rectus Femoris and Biceps Femoris Muscle Activities in Both Legs at Maximal Running Speed. *Med. Sci. Sports Exerc.*, Vol. 53, No. 3, pp. 643–652, 2021. **Purpose:** The purpose of this study was to investigate the relationship between spatiotemporal variables of running and onset/offset timing of rectus femoris (RF) and biceps femoris (BF) muscle activities in both legs. **Methods:** Eighteen male well-trained athletes (age = 20.7 ± 1.8 yr) were asked to run 50 m at maximal speed. The spatiotemporal variables (running speed, step frequency, and step length) over the distance from 30 to 50 m were measured. In addition, RF and BF muscle activities were obtained from both legs using wireless EMG sensors. To quantify the onset and offset timing of muscle activity, the band-pass filtered (20–450 Hz) EMG signal was processed using a Teager–Kaiser energy operator filter. We calculated RF and BF onset/offset timings (%) in both legs (e.g., ipsilateral leg RF [iRF] and contralateral leg BF [cBF]) during running cycle. Based on those timings, we obtained the EMG timing variables (%) as follows: "Switch1 (iBF-offset to iRF-onset)," "Switch2 (iRF-offset to iBF-onset)," "Scissors1 (cBF-onset to iRF-onset)," and "Scissors2 (iRF-offset to cBF-offset). **Results:** We found that "Switch2" had positive ($r = 0.495$, $P = 0.037$), "Scissors1" had negative ($r = -0.469$, $P = 0.049$), and "Scissors2" had positive ($r = 0.574$, $P = 0.013$) correlations with step frequency. However, these variables had no significant correlations with running speed or step length. **Conclusions:** These results indicate that higher step frequency would be achieved by smoother switching of the agonist–antagonist muscle activities and earlier iRF activation relative to the cBF activity. To improve sprint performance, athletes and coaches should consider not only muscle activities in one leg but also coordination of muscle activities in both legs. **Key Words:** ATHLETICS, RUNNING, ELECTROMYOGRAPHY, COORDINATION, COACHING

Sprint running is a fundamental ability in many sports. Because running speed is defined by the product of step length and step frequency, it is necessary to improve one or both of them to increase running speed (1). A gradual increase in running speed is accomplished by an increase in step length in the low speed range. However, the step length eventually plateaus, and an increase in step frequency contributes more in the high-speed range (2,3). At speeds higher than 7 $m \cdot s^{-1}$, hip flexion and extension torques increase sharply (2,3). In addition, the hip flexion torque increases with the speed of leg swing, leading to higher step frequency. Thus, the functions of the hip extensors and flexors are particularly important in achieving high running speed (2,4).

It has been reported that hip extensor muscles play an important role in producing the horizontal component of ground reaction force during sprinting on a treadmill (5). In addition, subjects with a large horizontal component of ground reaction force showed highly EMG activity of the biceps femoris (BF) before ground contact (5). In a sprint cycle, from the moment of a leg's contact with the ground to its next contact, the BF of the leg first achieved hip extension during the ground contact phase (2,6,7). In the latter half of the swing phase, the BF worked to achieve hip extension, showing eccentric activities with knee extension (8,9).

On the other hand, the rectus femoris (RF) muscle, an antagonistic muscle of the BF, first works slightly to support the impact of ground contact (6,10) and then to swing the thigh forward in the swing phase (11). This indicates that the RF, a biarticular muscle, plays a more important role for hip flexion than for knee extension during sprinting (11). Because the activities in these hip joint muscles (BF and RF) increase with an increase in running speed (12), these muscles play an important role, especially in high speed running. Moreover, a previous study has reported that the angular velocity of the hip flexion of the swing leg and maximal velocity of the entire swing leg had significant positive correlation with the running

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speed (13). Therefore, a quick flexion and extension of the hip joint is important to achieve high running speed.

Recently, Howard et al. (14) summarized the timing of onset and offset of lower limb EMG activity in a running cycle. The RF and the BF in a leg cocontract to fix the joints and maintain the posture during the first half of the ground contact phase (6). Furthermore, they show alternate switching activities twice during the swing phase (14). The first is the switch from BF activity, which extends the hip joint at the termination of the ground contact phase, to RF activity, which flexes the joint in the subsequent swing phase ("Switch1"; Fig. 1). The second is the switch from RF activity to BF activity to extend the hip joint in preparation for the next ground contact ("Switch2"; Fig. 1). Although cocontraction is important for maintaining posture during ground contact (6), it would be detrimental for achieving quicker running movements. Therefore, smooth switching between RF and BF ("Switch") would be desirable for achieving a higher step frequency, but this effect has not previously been the subject of analysis.

Moreover, because sprinting is a cyclic movement in which the roles of the left and right legs (contact leg and swing leg) alternate, it is important to consider not only antagonistic muscle activities in one leg but also the coordination of muscle activities in both legs. However, most studies have only examined muscles in one leg without investigating simultaneous of muscle activation in the contralateral leg (14). The research on EMG activities in both legs investigated only the outside (right side) and the inside (left side) legs during sprinting on a curved track (15). However, no studies have investigated the relationship between the timings of muscle activity in both legs and the spatiotemporal variables that affect running speed on a straight track.

A previous study comparing the running movements of sprinters and distance runners reported that the position of the recovery knee at the foot strike was closer to the contact knee in sprinters than in distance runners (16). In other words, sprinters move the recovery leg in an advanced phase relative to the contact leg. Then moving the swing leg forward more quickly may lead to more rapid preparation for the next ground contact. In other words, earlier timing of swing leg movement relative to contact (contralateral) leg movement would lead to higher step frequency. For this movement, the RF of the recovery leg should begin to be active as early as possible relative to the activation of BF of the contact leg. This can be considered to reflect the forward "scissors movement" of the swing leg relative to the backward movement of the contact leg during the ground contact phase ("Scissors1"; Fig. 1). Examining the timing of muscle activity in both legs would further the understanding of sprint technique for researchers, coaches, and athletes alike.

The purpose of this study is to clarify whether maximal running speed, the most important performance in short-distance sprinting, and its defining factors, step frequency and step length, are related to the onset/offset timing of RF and BF muscle activities in both legs. We especially focus on 1) the switching between RF and BF muscle in the same limb and 2) the muscle activities responsible for the "scissors movement" of both legs. We had two main hypotheses. First, a clear switch between RF and BF in a leg would produce higher step

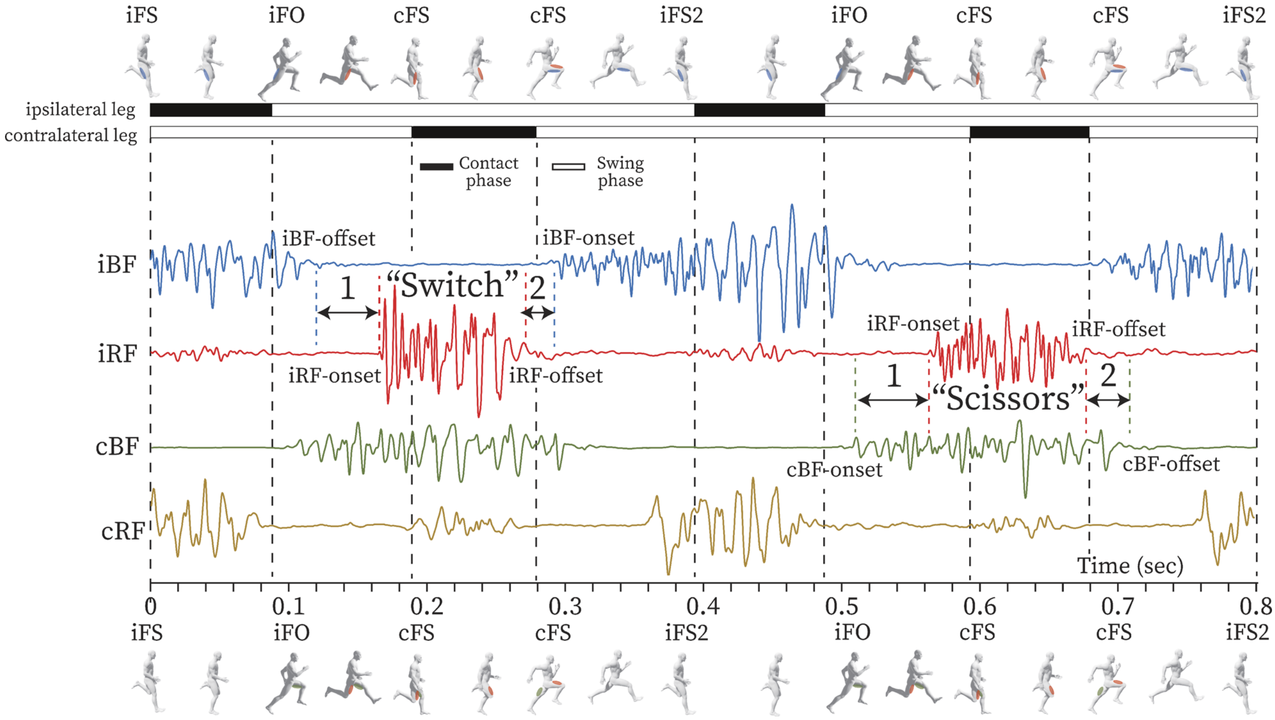

FIGURE 1—Typical example of muscle activities of four muscles in two cycles of running: From the top to the bottom, iBF, iRF, cBF, and cRF (contralateral leg RF) in a subject. The *vertical broken lines* mark the occurrence of iFS (ipsilateral leg FS), iFO (ipsilateral leg FO), cFS, and cFO from left to right. The *black blocks* in the top bars indicate the ground contact phase, and the *white blocks* indicate the swing phase. "Switch" is the timing of switching between iRF and iBF activities in the one leg, and "Scissors" is the as an index showing the coordination between the cBF and the iRF activation in both legs.

frequency. Second, the muscle activity onset timing difference between scissors movement of both legs (swing leg RF activity and contact leg BF activity) would also influence step frequency.

METHODS

Experimental Protocol

Eighteen male well-trained Japanese track and field athletes (World Athletics [WA] score = 1052.5 ± 93.3 points, height = 177.7 ± 6.0 cm, body mass = 69.9 ± 6.9 kg, age = 20.7 ± 1.8 yr) volunteered to participate in the study (Table 1). The WA score refers to the points for each track and field event record. It was referenced from the WA official document (17). Note that the 1052 points are equivalent to a record of 10.46 s in the men's 100 m. The participating athletes specialized in the 100-m, 200-m, 400-m, 110-m hurdles, 400-m hurdles, and long jump events. In addition, six subjects had participated in international competitions (Olympic Games, World Athletics Championships, Universiade).

This study was approved by the Ethics Committees of Waseda University. All subjects were informed of potential risks associated with the experimental procedures. Before the experiments, all subjects gave their written informed consent. All experiments were conducted in accordance with the Declaration of Helsinki.

Experimental Protocol and Data Collection

After 40 min of self-selected warm-up trials (slow jogging to submaximal running effort), subjects ran one 50-m sprint with maximal speed in the straight lane of an official 400-m track. The rest period was about 3–5 min between warm-up trials and the maximal speed trial. From a two-point standing start, subjects were instructed to accelerate from 0 to 30 m and then sprint at their maximal intensity from 30 to 50 m. A timing system (Brower Timing System, Brower, Germany) was set to measure the sprint time of the 30- to 50-m section. All experiments were conducted on clear days and the wind was weak, although wind speed was not measured.

Surface muscle EMG data were sampled at 2000 Hz using wireless EMG sensors (Trigno Wireless Sensor, Delsys Inc., Natick, MA). EMG data were recorded from the RF and BF muscles in both legs. Before the sensors were attached, the involved area of skin was shaved and treated with alcohol to reduce interelectrode impedance. EMG signals for the four muscles were checked after placing the electrodes. To eliminate the influence of motion artifact as much as possible, the EMG sensors were fixed with surgical tape and under wrap tape.

One panning high-speed camera (LUMIX FZ-300, Panasonic, Japan) was used to determine the moments of foot strike (FS) and foot off (FO) from the side of the running track at 240 Hz. At the same time, to synchronize the FS and the FO timing with the EMG data, the flash of the wireless all-around light presenter (Synchronizer, DKH, Tokyo, Japan) was recorded with the same video camera. This optical signal was uploaded into a PC via an A/D converter (Power Lab, ADInstruments, New Zealand). The EMG data and the signal of the synchronization device were fed into a PC via an analog output adapter. After the running trial, a maximum voluntary contraction (MVC) test was performed, in which subjects exerted a 5-s MVC against manual resistance of each muscle.

Data Processing

Spatiotemporal variables. A value obtained by dividing the length of the target section (20 m) with the time in seconds required to run the 30- to 50-m target section was defined as the running speed ($m \cdot s^{-1}$). In addition, the contact time (s) and the flight time (s) for each step were calculated from the number of frames of the high-speed camera, and the step frequency (Hz) was calculated for each step. The step length (m) was calculated by dividing the running speed by the step frequency. Note that all spatiotemporal variables were averaged for the 20-m section (30–50 m).

EMG Data Analysis. The EMG data were imported into the biological signal-processing software (Lab Chart 8 for Windows, AD Instruments) and synchronized with the time

TABLE 1. Individual data and mean and SD values of the running speed, step frequency, step length, contact time, and flight time.

Subject	Event	WA Score (Points)	Age (yr)	Height (m)	Body Mass (kg)	Running Speed ($m \cdot s^{-1}$)	Step Frequency (Hz)	Step Length (m)	Contact Time (s)	Flight Time (s)
A	200 m	1165	23	1.76	65	10.99	4.49	2.45	0.092	0.130
B	110 mH	1136	22	1.85	80	10.87	4.56	2.38	0.089	0.134
C	100 m	1118	23	1.72	71	10.53	4.83	2.18	0.088	0.124
D	LJ	1017	21	1.83	70	10.20	4.82	2.12	0.092	0.116
E	110 mH	1116	20	1.84	81	10.10	4.48	2.25	0.096	0.128
F	100 m	1142	25	1.72	68	10.00	4.69	2.13	0.091	0.122
G	100 m	1040	19	1.77	67	10.00	4.68	2.14	0.090	0.124
H	400 m	1034	19	1.68	66	9.90	4.98	1.99	0.089	0.112
I	100 m	996	20	1.77	68	9.90	4.52	2.19	0.089	0.133
J	400 m	1046	19	1.68	60	9.80	4.51	2.17	0.090	0.131
K	400 m	1014	19	1.80	69	9.80	4.32	2.27	0.102	0.129
L	400 m	1133	22	1.84	76	9.76	3.89	2.51	0.102	0.155
M	400 mH	1156	22	1.88	80	9.48	4.25	2.23	0.110	0.126
N	100 m	783	19	1.70	54	9.43	4.76	1.98	0.089	0.121
O	LJ	983	20	1.75	75	9.39	4.53	2.07	0.093	0.128
P	400 m	973	20	1.78	68	9.30	4.60	2.02	0.098	0.119
Q	100 m	999	19	1.81	71	9.13	4.11	2.22	0.106	0.138
R	110 mH	1094	20	1.83	72	9.05	4.14	2.19	0.108	0.134
	Mean	1052.5	20.7	1.78	69.9	9.87	4.51	2.19	0.095	0.128
	SD	93.3	1.8	0.06	6.9	0.54	0.28	0.14	0.007	0.009

axis of the camera image based on the time when the optical signal of the wireless all-around light presenter was confirmed. In the time information of EMG data, the FS and the FO times read from the captured video were input. In this study, we defined the leg having the first contact with the ground in the analysis section as the "ipsilateral leg" and the leg on the opposite side as the "contralateral leg."

We defined the running cycle as the time from the moment of the ipsilateral leg FS (iFS) until the next ipsilateral leg FS (iFS2) (Fig. 1). The ipsilateral leg contact phase was defined from iFS to ipsilateral FO (iFO). The ipsilateral leg swing phase is divided into early, mid, and late from iFO to the contralateral leg FS (cFS), from cFS to the contralateral leg FO (cFO), and from cFO to iFS2, respectively.

To quantify the onset and offset timing of muscle activity, the EMG signal was processed with a Teager–Kaiser energy operator (TKEO) filter (18). The TKEO filter has been confirmed to be a reliable method of calculating the EMG onset detection (18,19). The discrete TKEO Ψ was defined as follows:

$$\psi[x(n)] = x^2(n) - x(n+1)x(n-1)$$

where x is the EMG value and n is the sample number. The TKEO was applied after the EMG signal was band-pass filtered (20–450 Hz).

The EMG onset or offset threshold T was defined as follows:

$$T = \mu + h\sigma$$

where μ is the mean EMG signal during baseline and σ is the SD of the EMG signal during baseline. The baseline was defined as the range of 0.05 s in which the SD of each EMG signal was the smallest in the running cycle. Then h is a preset variable, defining the level of the threshold. The threshold level was set at $h = 15$ (18). The EMG onset or offset timings were normalized for the percent of the running cycle (0%–100%). These timings were averaged over 4–5 cycles to obtain a representative value for each subject. Subsequently, the band-pass filtered rectified EMG was filtered through a low-pass digital filter again at a cutoff frequency of 20 Hz to obtain linear envelope EMG waveforms (9) and normalized as %MVC using the mean amplitude of the MVC (obtained from 3 s out of the 5 s of EMG recorded) (20).

Items calculated to obtain EMG timing. "Switch" and "Scissors" were defined and calculated as follows (Fig. 1):

1. "Switch" of the RF and BF activity in the ipsilateral leg

In this study, to evaluate the timing of switching between ipsilateral leg RF (iRF) and ipsilateral leg BF (iBF) activities, the onset and the offset timings (%) of the iRF and iBF activities in the running cycle were determined.

- iBF-offset: activity offset of iBF
- iRF-onset: activity onset of iRF
- iRF-offset: activity offset of iRF
- iBF-onset: activity onset of iBF

Based on these values, "Switch" was defined as the length of the switching two muscles (iRF to iBF or iBF to iRF) calculated as follows:

- "Switch1" (%) = iRF-onset − iBF-offset
- "Switch2" (%) = iBF-onset − iRF-offset

Note that the calculation produced a negative Switch2 value for some subjects. This indicates cocontraction.

2. "Scissors" in the bilateral leg

To analyze the coordination of contralateral leg BF (cBF) and iRF activities in both legs, the activities of the cBF onset and offset timings (%) were calculated as follows:

- cBF-onset: activity onset of cBF
- cBF-offset: activity offset of cBF

Length of "Scissors" is calculated as an index showing the coordination between the cBF as the hip extensor of the contact leg and the iRF as the hip flexor of the swing leg.

- "Scissors1" (%) = iRF-onset − cBF-onset
- "Scissors2" (%) = cBF-offset − iRF offset

Statistical Analysis

The Pearson's product–moment correlation coefficient was used to determine the correlation between muscle activity timing and spatiotemporal variables (running speed, step frequency, and step length). Similarly, the correlations between running speed and step frequency, step length, contact time, and flight time were also tested. All statistical analyses were performed using statistical processing software (SPSS version 25, IBM, Armonk, NY). We set a significance level of 0.05.

RESULTS

Spatiotemporal variables. Table 1 shows the individual data and mean values and SD of the running speed, step frequency, step length, contact time, and flight time. Figure 2A shows the relationship between step frequency and step length, with isovelocity curves. Figures 2B–2E show the relationship between running speed and the other four spatiotemporal variables. There was a significant negative correlation between running speed and contact time ($P = 0.007$, $r = -0.592$). However, there was no correlation between running speed and step frequency ($P = 0.112$, $r = 0.387$), step length ($P = 0.056$, $r = 0.459$), and flight time ($P = -0.075$, $r = 0.769$).

Timing of foot contact and EMG activities. Figure 3 shows the onset and offset timing of three muscles in a running cycle (100%). Figure 3A shows "Switch" of the iRF and iBF, and Figure 3B shows "Scissors" of the iRF and cBF. The top figures Figures 3A and 3B show the timings of FS and FO of the ipsilateral (iFS and iFO) and contralateral (cFS and cFO) legs in one running cycle as 100%. The ipsilateral leg touched

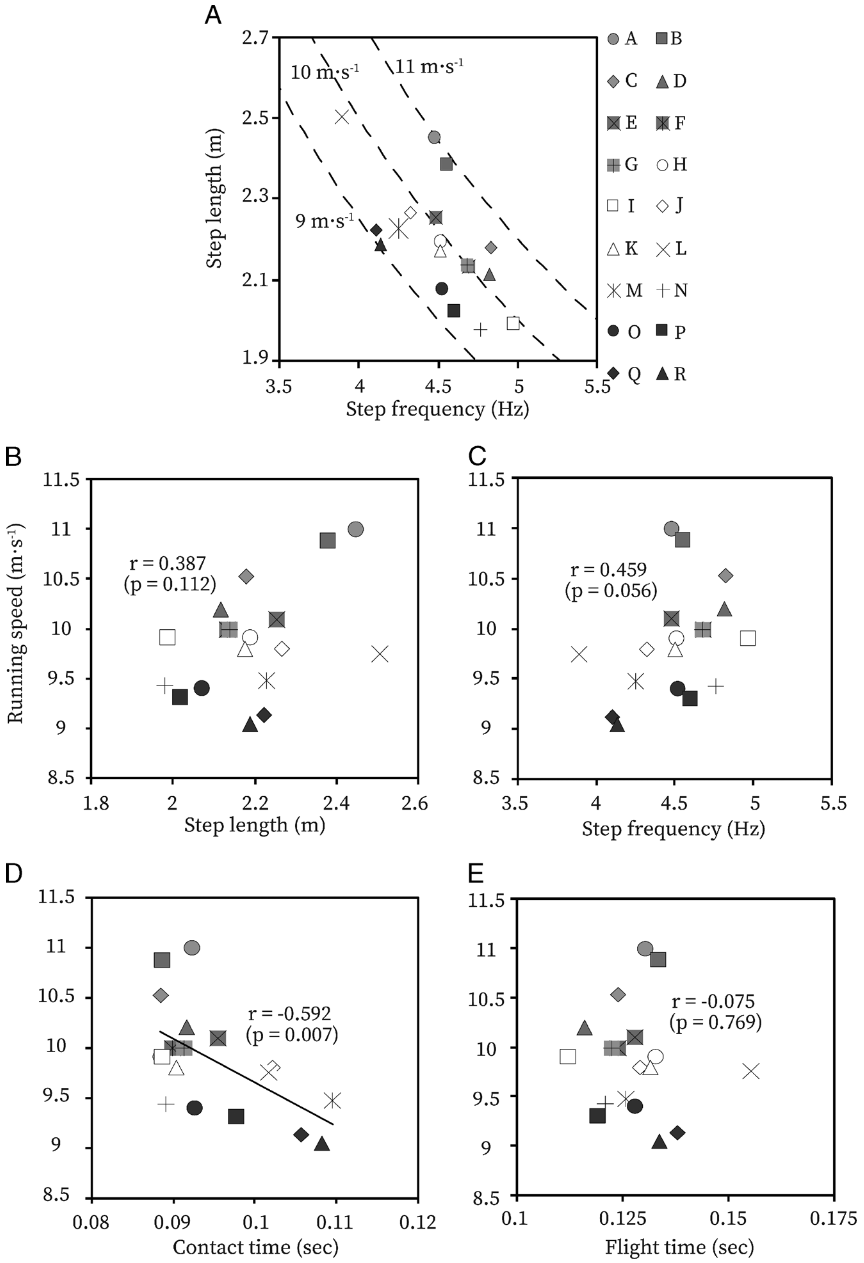

FIGURE 2—Relationship between running speed, step frequency, and step length (A); running speed and step frequency (B); running speed and step length (C); running speed and contact time (D); and running speed and flight time (E). There was a significant negative correlation between running speed and contact time. Different symbols labeled A through R represent the 18 subjects.

the ground from 0% (iFS) to 21.2% ± 1.1%, and the contralateral leg from 50.1% ± 1.2% (cFS) to 71.3% ± 1.4% (cFO). The middle figures show averaged activation timings (%) and actual averaged EMG waveforms (%MVC) of all subjects. As for the "Switch" of the ipsilateral leg (Fig. 3A), the iBF continued to be active even after contact phase (21.2% ± 1.1%) until 31.1% ± 4.0%. There followed a phase in which neither iBF nor iRF was active in all subjects; that is, iRF began to be active after iBF terminated its activity. iRF became active from early swing phase (39.5% ± 4.4%) to late swing phase (72.3% ± 6.2%). Then toward the iFS2 (100%), iBF began to become active again at late swing phase (73.8% ± 4.2%). Note that in 8 of 18 subjects, iRF and iBF showed cocontraction (negative "Switch2" values), meaning the iBF became active before the iRF finished its activity, whereas the remaining subjects showed clear switching from the iRF to the iBF (positive "Switch2" values).

Regarding "Scissors" of the two legs (Fig. 3B), the contralateral contacting leg BF (cBF) was active during a wider phase (22.3% ± 4.0% to 77.6% ± 5.3%) than the ipsilateral swinging iRF (39.5% ± 4.4% to 72.3% ± 6.2%) in all subjects. That is, the cBF always activated before the iRF and continued activation until after iRF termination.

Relationship between EMG activity and spatiotemporal variables. The relationship between onset and offset timing of iRF, iBF, and cBF activities and spatiotemporal

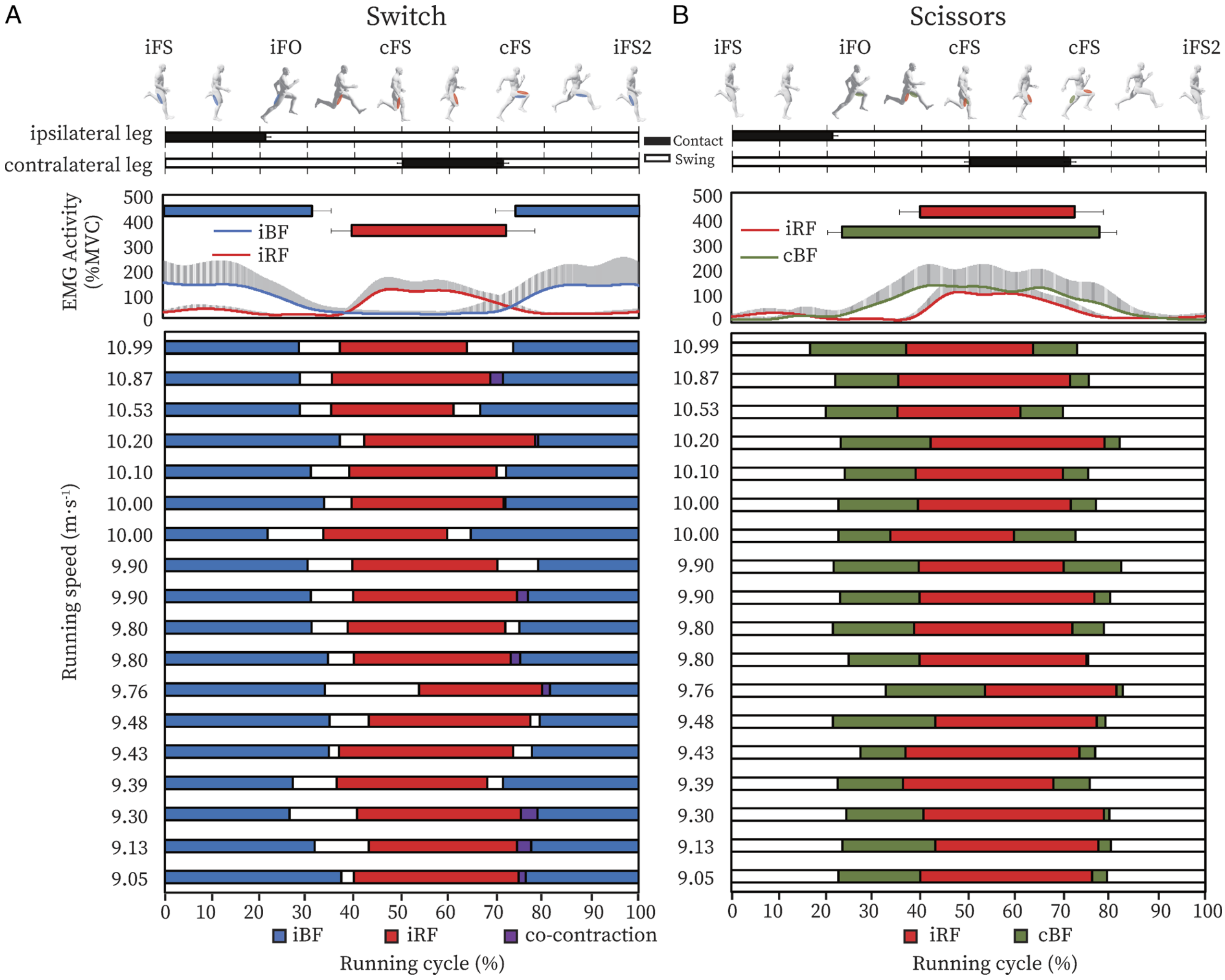

FIGURE 3—Relative activation phases: "Switch: iRF and iBF" (A) and "Scissors: iRF and cBF" (B) in one running cycle. The top figures show the timings of FS and FO of the ipsilateral (iFS and iFO) and contralateral (cFS and cFO) legs. The middle figures show the averaged EMG waveforms (%MVC) and averaged activation timings of all subjects. A, *Blue and red* indicate iBF and iRF activities, respectively. *White* indicates the time when both muscles are inactive. *Purple* indicates cocontraction. B, *Green* indicates cBF activity. *White* indicates the time when both muscles are inactive. Note that iRF and cBF activation overlap.

variables was examined using Pearson's product–moment correlation coefficient (Figs. 4A and 4B). There was a significant negative correlation with running speed and iRF-offset ($r = -0.527$, $P = 0.025$). The higher the step frequency, the earlier the iRF became active ($r = -0.652$, $P = 0.003$), and iRF activity finished in the mid swing phase or late swing phase ($r = -0.498$, $P = 0.035$; Fig. 4B). However, step length did not correlate with the timing of any muscle activity. As for the length of the "Switch" (Figs. 4C and 4D), "Switch2" had a significant positive correlation with step frequency ($r = 0.495$, $P = 0.037$), whereas "Switch1" had no significant correlation with any variables.

As for the length of the "Scissors" (Figs. 4E and 4F), there was no significant correlation between "Scissors" and neither running speed nor step length. On the other hand, the higher the step frequency, the shorter the "Scissors1" ($r = -0.469$, $P = 0.049$), and the higher the step frequency, the longer the "Scissors2" ($r = 0.574$, $P = 0.013$).

Step length was not significantly correlated with any of the muscle activity variables ($P > 0.05$), not shown in Fig. 4.

DISCUSSION

The overall goal of the present study was to clarify the relationship between spatiotemporal variables (maximal running speed, step frequency, or step length) and onset/offset timing of RF and BF muscles in both legs during maximal running speed. Our main findings were as follows: 1) RF onset and offset timings were significantly correlated with running speed and step frequency; 2) the length of "Switch2," "Scissors1," and "Scissors2" had significant correlations with step frequency; and 3) these variables had no significant correlations with running speed nor step length. Thus, clear switching between agonist–antagonist muscle (iRF and iBF) in the late swing phase ("Switch2") would be advantageous for achieving higher step frequency. Furthermore, the length of onset

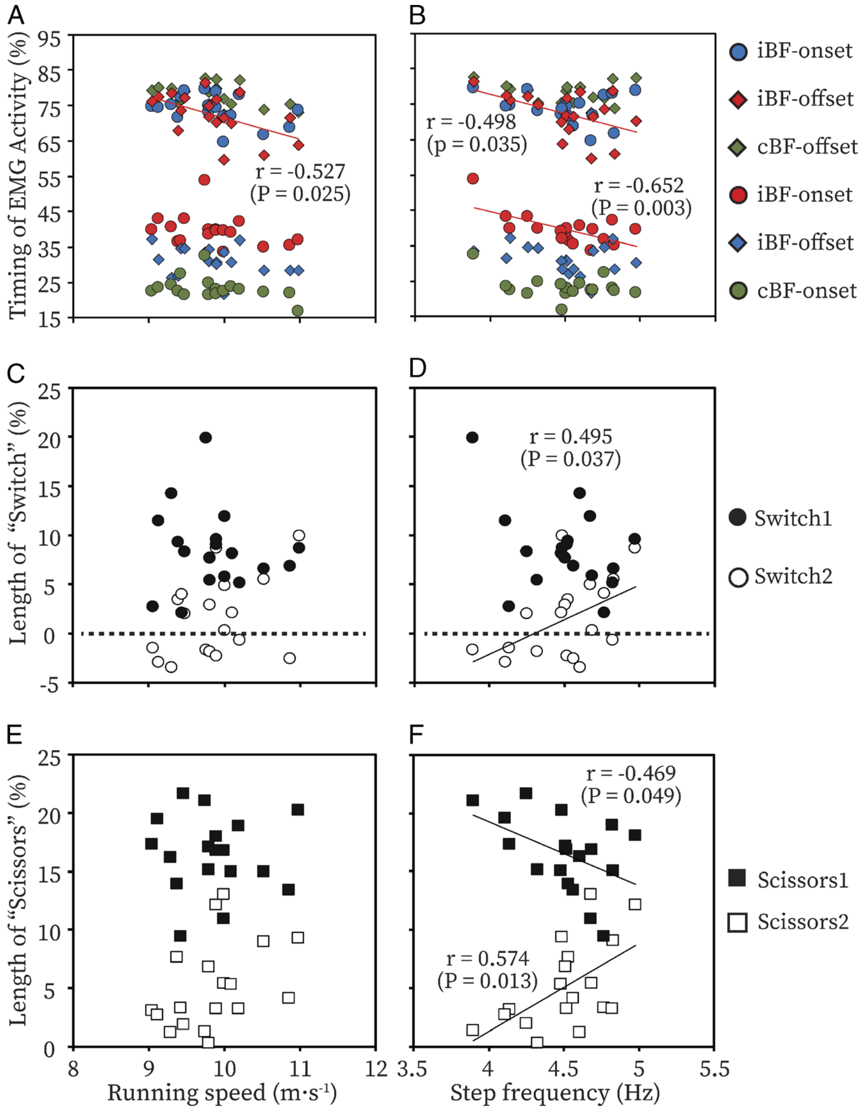

FIGURE 4—Muscle activity timing (A, B), length of "Switch" (C, D), and "Scissors" (E, F) in relation to running speed (*left*) and step frequency (*right*).

or offset time difference of agonist muscles in both legs (iRF and cBF) would also affect step frequency ("Scissors1" and "Scissors2").

Before discussing the correlation between timing of muscle activity and the spatiotemporal variables that affect running speed, the running speed of the subjects in the present study will be compared with previous studies. The mean running speed of all subjects in the present study was 9.87 ± 0.54 $m \cdot s^{-1}$, ranging from 9.30 to 10.99 $m \cdot s^{-1}$ (Table 1). In previous studies examining muscle activity during sprinting, running speed was slower than the present study: 7.5 ~ 10.20 $m \cdot s^{-1}$ for track running and 6.63 ~ 9.36 $m \cdot s^{-1}$ for treadmill running (11). Moreover, seven subjects ran at speeds over 10.00 $m \cdot s^{-1}$ in this study. Therefore, the subjects in this study could run faster than those in previous studies (14). Besides, there was a significant negative correlation between running speed and contact time ($r = -0.592$, $P = 0.010$; Fig. 2D), which is similar to Weyand et al. (21). However, in the current study, there was no significant correlation between running speed and step frequency, step length, or flight time. Previous studies demonstrated that the combination of step frequency and step length to get higher running speed differs among individuals (22,23). Our experiments also showed various combinations of step frequency and step length (Fig. 2A). The subjects in the present study were a group of well-trained athletes. For athletes at this level, improved running speed could not be attributed just to an improvement in one or the other.

Relationship between "Switch" and the spatiotemporal variables. This study first tried to clarify whether a clear "Switch" in one leg would optimize the spatiotemporal variables, resulting in an increased running speed. Therefore, we focused on the switching of RF and BF in the same leg, between the flexor and the extensor muscles of the hip joint. The "Switch1," the switch from BF activation for the hip extension to RF activation for hip flexion, could be accomplished without cocontraction in all subjects, and clear alternating contractions were observed (Fig. 3A). However, there was no correlation between "Switch1" and running speed and step frequency (Fig. 4C). Meanwhile, "Switch2," from RF activation to BF activation, showed individual differences; some subjects showed cocontraction of the RF and BF while some did not (Fig. 3A). Interestingly, "Switch2" had positive correlation with step frequency ($r = 0.495$, $P = 0.037$) (Fig. 4D). Regarding the switching between agonist and antagonist muscles, Fujii and Moritani (24) did an interesting study on the world's fastest drummer and showed clear alternating activities of the wrist flexor and extensor muscles without cocontraction during drumming at the maximum rate. The offset timing of activity in the world's fastest drummer was earlier than that in nondrummers or ordinary drummers. Our study similarly found that the earlier the RF onset and offset, the higher the step frequency (Fig. 4B). Moreover, there was a significant positive correlation between "Switch2" and step frequency (Fig. 4D). This could be because if RF for hip flexion is kept active unnecessarily for a long time in the late swing phase, it resists the subsequent BF activity for hip extension, slowing the downward swing of the thigh. However, the BF is a biarticular muscle that acts on hip extension and knee flexion (25). In the late swing phase, it works to absorb the forward movement of the thigh and to extend the hip joint in preparation for the next ground contact (26). Therefore, switching between RF and BF activity is more complicated than the simple switching between the extensor and the flexor in the drumming task. In "Switch2," some subjects showed a cocontraction (Figs. 4C and 4D). In the late swing phase, switching should be accomplished without cocontraction to increase step frequency. Hamstring injuries are common in high-speed sprints (27), especially to the BF (27–29). It has been pointed out that the risk of injury increases as the load on the muscle–tendon complex, muscle activity (EMG amplitude), negative work, and peak muscle length increase in the late swing phase (29). Present results also show that the iBF activity peaks at late swing phase, and it was greater than the MVC value (Fig. 3). Moreover, previous studies reported that a poor balance of the quadriceps–hamstrings strength ratio increases the risk of hamstring injury (30). In addition, subjects with a history of hamstring injuries have a large peak torque of the quadriceps (31). Thus, the subjects showing antagonistic RF activity might have a higher risk of BF injury occurring in the late swing phase.

Relationship between "Scissors" and the spatiotemporal variables in both legs. This study also focused on whether EMG activities related to "scissors movement" affect the spatiotemporal variables and therefore running speed. To investigate this, we analyzed not only the activity of RF and BF in the ipsilateral leg but also the relative timing of iRF activity with respect to the activity of cBF (Fig. 3B). Neither "Scissors1" nor "Scissors2" had any correlation with running speed. On the other hand, "Scissors2" was positively ($r = 0.574$, $P = 0.013$) and "Scissors1" was negatively ($r = -0.469$, $P = 0.049$) correlated with step frequency (Fig. 4F). Therefore, to achieve high step frequency, it is important that the onset and offset of iRF occur at early timing relative to cBF activity. Previous research has demonstrated that the distance of the swing leg knee relative to the contact leg knee at FS is significantly shorter in sprinters than in distance runners (16). Therefore, it would be important to quickly recover the swing leg relative to the contact leg to obtain a higher running speed. In addition, with reference to RF activity during sprinting, RF plays a more important role in hip flexion than in knee extension during the swing phase (11). Moreover, the onset timing of hip flexion activity was earlier at a speed of 6.0 $\mathrm{m \cdot s^{-1}}$ than at lower speeds of 1.5 to 5.0 $\mathrm{m \cdot s^{-1}}$ (7). Similarly, the RF onset timing comes earlier in the running cycle as the running speed increases to 9.0 $\mathrm{m \cdot s^{-1}}$ (2). When running at less than 7.0 $\mathrm{m \cdot s^{-1}}$, the running speed is achieved by increasing the step length, mainly by activating the ankle plantar flexor muscles. However, sprinting at high speeds higher than 7.0 $\mathrm{m \cdot s^{-1}}$ requires a shift to a strategy of increasing the swing leg velocity by increasing the hip mechanical work (2–4). In other words, the hip joint muscle during swing phase demonstrated the most dramatic increase in activity at the faster running speed (4,32). Indeed, the iRF-onset and iRF-offset timing both exhibited a negative correlation with step frequency (Fig. 4B). Most importantly, "Scissors" was significantly correlated with step frequency (Fig. 4F). These results indicate that athletes should consider not only ipsilateral leg activity but also the coordination of ipsilateral and contralateral muscle activity, that is, to extend the hip joint in one leg and to flex the hip joint in the other as quickly as possible to obtain a higher step frequency.

Limitations and implications. The present study found significant correlations between the timing of some muscle activities and step frequency. The EMG activities during the "Scissors," the timing of agonist muscle activities in both legs, and the "Switch," an activity change between RF and BF in one leg, were correlated with step frequency. However, the correlation coefficients of "Scissors" and "Switch" were not overly strong (<0.65). Therefore, several questions arise.

First, to what degree do "Scissors" and "Switch" determine sprint performance? Running speed is the product of step frequency and step length (1), and the combination of the step frequency and step length is different among subjects of this study (Fig. 2A). This difference may be attributed to the difference in running movements among individuals. Therefore, it is necessary to consider not only the timing of muscle activity but also the factors of ground reaction forces that define the step length (33) or running kinematics (e.g., lower limb movement) (1,16,32). However, we did not measure the ground reaction forces or lower limb joint movements. In the present study, step length was not significantly correlated with the timing of any muscle activity. In other words, it should be noted that the timing of muscle activity alone does not explain everything about running performance. In future studies, "Scissors" and "Switch" should be considered, not only in terms of muscle activity but also in relation to the actual running movement and its relationship to ground reaction force.

Second, are the characteristics of "Scissors" and "Switch" specific only to the relatively high-level sprinters participating in this study, or are they common to nonathletes as well? In the present study, we recruited only competitive athletes who trained specifically in athletics. Their competition levels were equivalent to a record of 10.46 s in the men's 100 m. Based on previous studies of muscle activity patterns during running (14), one would expect that the "Scissors" and "Switch" themselves would be commonly observed in nonathletes. However, further research would be required to answer this question.

The present results obtained in high-level competitive athletes would have important implications for the application to several sprint training programs. For example, drill training that attempts to minimize the time difference between the onset of muscle activity in the support and swing legs might be possible. This would lead to a faster recovery leg and consequently improve step frequency during sprint. Performing mini-hurdle drills placed at narrow intervals with a primary focus on switching between RF and BF activities more smoothly may lead to increasing step frequency during sprint. In addition, acquiring the proper timing of contraction and relaxation of RF and BF may help prevent BF injuries, especially those occurring in the late swing phase.

CONCLUSION

This study examined how "Switch" (switching between RF and BF activities in one leg) and "Scissors" (timing of agonist muscle activity in both legs) correlate with running performances at maximal running speed.

Regarding the "Switch," although switching from the iBF-offset to the iRF-onset in the early swing phase ("Switch1") showed clear alternating contraction in all subjects, switching from the iRF-offset to the iBF-onset in the late swing phase ("Switch2") included a cocontraction in some subjects. "Switch2" was correlated with step frequency. Thus, we believe that the smooth switching between RF and BF activity in the same leg seems to be important to obtain a high step frequency.

Regarding the "Scissors," the subjects with higher step frequency had shorter "Scissors1" (time difference between cBF-onset and iRF-onset) and longer "Scissors2" (time difference between cBF-offset and iRF-offset). In other words, the timing of the iRF activity should be earlier in relation to the activity of the cBF to obtain high step frequency.

We conclude that smoother switching and coordinated interleg muscle activity are important to achieve high step frequency. Coaches and athletes should consider not only muscle activity timing in one leg but also the coordination between both legs to improve sprint technique during maximal running speed.

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