早稲田大学審査学位論文
博士（スポーツ科学）

Control of the thigh muscle activity in both legs during sprinting

スプリントにおける両脚の大腿筋活動の制御

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博士学位論文概要

【第 1 章：緒言】

日常生活やスポーツに至るあらゆる場面で、走運動は最も基本的かつ重要な能力である。走運動は両脚の役割(スウィング脚と接地脚)が入れ替わる周期運動であり、陸上競技の短距離走の指導現場でも、両脚を接地の瞬間に素早く挟み込む、“シザース動作”の重要性が広く認知されている。しかし、これまでの走運動に関する研究は、どちらか片脚だけの筋活動を取得するに留まっており、“走運動は両脚の協調運動である”という視点が欠如している。そこで、本学位論文では短距離走の指導現場に筋制御の観点から科学的根拠を提示するため短距離走で特に重要な力発揮を担う股関節筋である大腿直筋(Rectus Femoris: RF)と大腿二頭筋(Biceps Femoris: BF)に着目し様々な条件下の走運動における両脚の RF、BF の筋制御の特徴を解明することを目的とした。

【第 2 章：全力疾走における両脚の大腿直筋と大腿二頭筋の活動のタイミング】

被験者はオリンピック出場者を含む陸上競技短距離選手 18 名であった。全力疾走中の両脚の大腿直筋(RF)および大腿二頭筋(BF)の筋活動を取得した。基準脚側(ipsilateral)の RF(iRF)、BF(iBF)に加え、反対脚側(contralateral)の BF(cBF)の筋活動の onset/offset のタイミング(%ランニングサイクル)を算出した。これらを基に、同側の主動筋と拮抗筋の切換えの指標として “Switch” (iRF-onset[offset]から iBF-offset[onset]までの時間)、両脚の主動筋の協調性を示す “Scissors”(iRF と cBF の onset/offset の時間差)を筋制御の評価指標として定義した。そして、時空間的変数(走速度、ピッチ、ストライド)との相関関係を検討した。その結果、ピッチの高い選手は、① 主動筋(iRF)と拮抗筋(iBF)が同時収縮する現象である共収縮がなく、素早い関節運動に合理的な筋制御(“Switch”)であったこと、② 股関節屈曲のために働くスウィング脚の主動筋(iRF)が、股関節伸展のために働く反対(接地)脚の主動筋(cBF)に対して早いタイミングで活動するという両脚の筋制御の能力(“Scissors”)に優れていたこと、が明らかとなった。

【第 3 章：異なる走速度における両脚の大腿直筋と大腿二頭筋の活動のタイミング】

第 2 章と同一の被験者は、異なる 7 つの主観的努力度(Subjective Effort: SE) [20 % SE (3.77 ± 0.47 $\mathrm{m \cdot s^{-1}}$), 40 % SE (6.44 ± 0.55 $\mathrm{m \cdot s^{-1}}$), 60 % SE (8.00 ± 0.60 $\mathrm{m \cdot s^{-1}}$), 80 % SE(9.09 ± 0.58 $\mathrm{m \cdot s^{-1}}$), 90 % SE (9.48 ± 0.62 $\mathrm{m \cdot s^{-1}}$), 95 % SE (9.70 ± 0.55 $\mathrm{m \cdot s^{-1}}$), 100 % SE (9.82 ± 0.58 $\mathrm{m \cdot s^{-1}}$)]による条件で 50 m 走を実施した。第 2 章と同様の手法で筋活動のタイミング、“Switch”、“Scissors”および時空間的変数を取得した。その結果、SE すなわち走速度はピッチで制御されており、13 名が 100 % SE で最速となった。一方、95 % SE (3 名)、90 % SE (2 名)で最速となる選手も存在し、選手の主観と客観は必ずしも一致しないことが示された。このとき、一部の選手はスウィング期後半の “Switch2”が改善され、共収縮が無い明確な交互収縮が認められた。このことは、SE の変化が“リラックスし

た状態”を誘発し、パフォーマンスに好影響を与えていた可能性を示す。また、高速度($9\ m{\cdot}s^{-1}$: 80-100 % SE)では、RF および BF の筋活動量(RMS)と活動の相対時間の増加が認められたことから、股関節伸展・屈曲を強調する戦略に変化したといえる。また、RF の活動の絶対時間が増加したことから、RF はスウィング(リカバリー)脚の速度を増加させ、ピッチの増加に貢献していたと推察される。しかし、RF-offset の遅れはスウィング期後半の共収縮を生じさせ、ピッチに悪影響を及ぼす可能性があり、筋活動を積極的に終わらせる(弛緩させる)という視点もスプリントで重要であろう。

【第 4 章：100 m 走における両脚の大腿直筋と大腿二頭筋の活動のタイミング】

被験者は陸上競技短距離選手 10 名であった。データロガー筋電図装置を被験者の腰部に装着し 100 m 全力疾走中の RF、BF の筋活動のタイミング、“Switch”、”Scissors” を取得した。10 m ごとの時空間的変数を算出し、最高走速度局面(50-70 m)と減速局面(80-100 m)におけるこれらの変数を比較した。その結果、減速局面では走速度とピッチが減少した。また、減速局面では RF と BF の活動のタイミングがサイクルの後半に遅れ、さらに“Scissors 1”が増加した。つまり、接地脚の cBF の活動に対してスウィング脚の iRF の活動が遅延し、結果的に股関節屈曲のタイミングすなわちスウィング脚のリカバリー動作が遅れたと推察される。これら筋活動のタイミングの変化が 100 m 走の後半のピッチの低下を惹起し、速度逓減の要因である可能性が明らかになった。

【第 5 章：総括論議】

一連の研究より、同側および両脚の大腿筋の制御の指標である “Switch”および“Scissors”は、スプリントにおけるパフォーマンス(ピッチ)に影響し(Chapter 2)、主観的努力度(走速度、ピッチ)の変化に対応し(Chapter 3)、さらに 100 m 走のレース後半の減速(ピッチの低下)の要因である可能性が示唆された(Chapter 4)。走速度の変化はピッチにより制御されているが(Chapter 3)、ピッチの増加はランニングサイクルの短縮を意味する。一方、RF の活動する時間は増加していくことから、高いピッチが要求される高速度のスプリントでは、RF の活動がより重要となる。その際、同側の主動筋と拮抗筋を明確に切り替える能力(“Switch”)は、共収縮が発生しやすくなるため特に高速度では難しくなる。また、両脚の主動筋を時間差なく活動させる能力(“Scissors”)は、特にピッチが増大する高速度で要求される。そしてピッチの高い選手は“Scissors”の能力に優れ(Chapter 2)、ピッチの高い最高速度局面では“Scissors”が有意に短いことから(Chapter 4)、接地脚の BF に対するスウィング脚の RF を早いタイミングで活動させる能力が高いピッチの獲得・維持に貢献していることが明らかになった。これらの知見から、スプリント能力の向上は股関節筋を強く活動(収縮)させるだけでなく、適切なタイミングで活動させること、さらに積極的に抑制(弛緩：リラックス)させるといった“両脚の協調運動”という観点から考慮されるべきであると考えられる。

CHAPTER ABSTRACTS

Chapter 1: General Introduction

Although the running is a cyclic movement (swing leg and contact leg changes alternate), no studies have considered how coordinated the muscle activities in both legs and how it is associated with sprinting performance. Therefore, this doctoral thesis aims to clarify the muscular control of the thigh muscle activity in both legs during sprinting.

Chapter 2: RF and BF activity in both legs at maximal sprinting

I obtained rectus femoris (RF) and biceps femoris (BF) muscle activities in both legs during the maximal running speed (RS) among eighteen male Track & Field athletes. I calculated RF and BF onset/offset timings (% of a running cycle) in both legs (e.g., ipsilateral leg RF [iRF] and contralateral leg BF [cBF]). Based on those timings, I proposed two original muscular control variables as follows: i) "Switch1 (iBF-offset to iRF-onset)" and "Switch2 (iRF-offset to iBF-onset)", that is, switching between RF and BF activities in one leg, and ii) "Scissors1(cBF-onset to iRF-onset)" and "Scissors2 (iRF-offset to cBF-offset)", that is, coordination of muscle activity in both legs. "Switch2", "Scissors1" and "Scissors2" were correlated with step frequency (SF). I demonstrated that smoother switching between iRF and iBF in late swing phase and inter-leg muscular coordination (iRF and cBF) are important to achieve high SF at the maximal RS.

Chapter 3: RF and BF activity in both legs at various running speed

I investigated how RF and BF activities in both legs, especially "Scissors" and "Switch", would change when the subjective effort (SE), that is RS, is varied. Eighteen male Track & Field athletes ran 50 m at 7 different SE [20 % SE (3.77 ± 0.47 $m \cdot s^{-1}$), 40 % SE (6.44 ± 0.55 $m \cdot s^{-1}$), 60 % SE (8.00 ± 0.60 $m \cdot s^{-1}$), 80 % SE (9.09 ± 0.58 $m \cdot s^{-1}$), 90 % SE (9.48 ± 0.62 $m \cdot s^{-1}$), 95 % SE (9.70 ± 0.55 $m \cdot s^{-1}$), 100 % SE (9.82 ± 0.58 $m \cdot s^{-1}$)]. At higher RS (9 > $m \cdot s^{-1}$) stronger muscle activity in both RF and BF were observed which would produce stronger hip extension and flexion. Although the strong activity of RF is required at high RS, too long activation of the RF may induce co-contraction ("Switch2") in the late swing phase, which may inhibit performance. Therefore, it is necessary to achieve appropriate onset and offset timings of the RF and BF in order to attain the high RS (i.e., SF).

Chapter 4: RF and BF activity in both legs at 100-m dash

I examined the differences in the timing of muscle activities of RF and BF in both legs and spatiotemporal variables during the maximal speed (Max) phase (50-70 m) and the deceleration (Dec) phase (80-100 m) of the 100-m dash. I recorded RF and BF activities in both legs with a portable EMG datalogger device from 10 male Track & Field athletes during 100-m dash. I found that RS decreased in Dec phase with decreased SF. Timings of iRF-onset, iRF-offset, iBF-offset, and cBF-offset in the Dec phase shifted to the later in a running cycle than the Max phase. Furthermore, "Scissors1" was longer in the Dec phase. As a result, the delay in the recovery movement of the swing leg is considered to be the cause of the decrease in SF. These results suggest that the limiting factors of the 100-m dash in the Dec phase would be the delayed timing of the RF and BF activity as well as changes in the inter-leg muscular coordination.

Chapter 5: General Discussion

"Switch" and "Scissors" would the determinants of the SF at the maximal RS (Chapter 2), because they corresponded well with the changing SEs (Chapter 3), and it could be one of the deceleration factors in the 100-m dash (Chapter 4). Moreover, while RS is dependent on SF (Chapter 3), SF is determined by the ability to control the switch clearly between agonist and antagonist muscles in one leg ("Switch") and the ability to control the activation timing of agonist muscles of both legs ("Scissors"). In conclusion, sprinting should be considered from the coordination of muscle activities not only in one leg but also on both legs.

ORIGINAL ARTICLE

This doctoral thesis is based on the following paper.

Timing of rectus femoris and biceps femoris muscle activities in both legs at maximal running speed. **G.Kakehata**, Y.Goto, S.Iso, K.Kanosue. *Medicine & Science in Sports & Exercise*: August 18 (2020)-Volume Publish Ahead of Print.

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LIST OF ABBREVIATION

RS	Running Speed
SF	Step Frequency
SL	Step Length
CNS	Central Nerves System
EMG	Electromyography
FT	Flight Time
CT	Contact Time
IAAF	International Association of Athletics Federations
GRF	Ground Reaction Force
GRI	Ground Reaction Impulse
SSC	Stretch-Shortening Cycle
FO	Foot-Off
ATP	Adenosine TriPhosphate
CP	Creatine Phosphate

BF	Biceps Femoris muscle
RF	Rectus Femoris muscle
FS	Foot-Strike
RMS	Root Mean Square
WA	World Athletics
MVC	Maximal Voluntary Contraction
iFS	ipsirateral leg Foot-Strile
iFS2	next ipsirateral leg Foot-Strile
iFO	ipsirateral leg Foot-Off
cFS	contralateral leg Foot-Strile
cFO	contralateral leg Foot-Off
TKEO	Teager-Kaiser Energy Operator
SD	Standard Deviation

iRF	ipsilateral leg RF
iBF	ipsilateral leg RF
cBF	contralateral leg BF
cRF	contralateral leg RF
SE	Subjective Effort
ANOVA	Analysis of Variance
ES	Effect Size
Max	Maximal Speed
Dec	Deceleration

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Preface

Running is one of the most basic and important abilities in daily life and in all aspects of sports. One of the most representative running is “sprinting” which is an important ability in various sports. Previous research on sprinting has examined focused on spatiotemporal variables such as running speed (RS), step frequency (SF), and step length (SL) (Hunter, Marshall, & McNair, 2004a; Salo, Bezodis, Batterham, & Kerwin, 2011), ground reaction force and ground reaction impulse (Clark & Weyand, 2014; Morin, Slawinski, et al., 2015; Weyand, Sternlight, Bellizzi, & Wright, 2000), and lower-limb movements or joint torque (Dorn, Schache, & Pandy, 2012; Ito et al., 1998). However, it is unclear how these variables are achieved by neuro-muscular control. The movements that can be observed are the result of motor commands in the central nervous system (CNS) i.e. brain and spinal cord pathways, and the characteristics of that neural control can be assessed by measuring electromyography (EMG). However, until now it has not always been easy to measure EMG from runners at maximal RS (Howard, Conway, & Harrison, 2018). In recent years, the development of wireless EMG measurement devices has made it possible to measure muscle and nerve activity during dynamic exercises, such as sprinting (Howard et al., 2018). Although several studies have reached maximal RS on the motorized treadmill (Baur, Hirschmüller, Müller, Gollhofer, & Mayer, 2007), muscle activities are different from those in ground running (Van Caekenberghe et al., 2013; Wang, Hong, & Li, 2014). Therefore, the characteristics of neuro-muscular control in maximal RS are still largely unknown.

Moreover, since running is a cyclic movement composed of ground contact phase and flight phase (Hay, 1993), it is necessary to examine the muscle activity of not only one leg but also both legs. To the best of our knowledge, no studies have considered how coordinated EMG activity in both legs and how it is associated with sprinting performance.

Therefore, this present doctoral thesis attempted to comprehensively elucidate the muscular activity of both legs in running in order to provide a scientific basis for the coaching of sprinting.

Chapter 1 General Introduction

1-1 Research history of the sprinting

1-1-1 Spatiotemporal variables

Sprint performance is a complex interaction of numerous factors, including biomechanical factors (Haugen, McGhie, & Ettema, 2019; Hunter et al., 2004a; Mero, Komi, & Gregor, 1992; Novacheck, 1998), the neural factors (Mero et al., 1992; Ross, Leveritt, & Riek, 2001). Previous studies have analyzed split times, and changes in running speed (RS), step frequency (SF), and step length (SL) in 100-m race in Olympic Games and World Championships (Ae, Ito, & Suzuki, 1992; Bae et al., 2011; Bissas, Walker, Tucker, & Paradisis, 2017; Graubner & Nixdorf, 2011; Hommel et al., 2012; Ito, Ishikawa, Isolehto, & Komi, 2006; Mackala, 2007). The main factor determining 100-m times is the maximal RS (Ae et al., 1992; Healy, Kenny, & Harrison, 2019; Slawinski et al., 2017). When Usain Bolt won the 2009 World Championships with a world-record of 9.58 seconds, the maximal RS was 12.34 $m \cdot s^{-1}$, which was higher than those of Tyson Gay (12.20 $m \cdot s^{-1}$) and Asafa Powell (11.90 $m \cdot s^{-1}$) were 2nd and 3rd place (Graubner & Nixdorf, 2011) (Fig. 1-1), indicating that improving the maximal RS is a top priority for sprinters. Since RS is defined by the product of SF and SL, it is necessary to increase both parameters to obtain a high RS, although there is a negative interaction between SF and

SL (Hunter et al., 2004a). According to the deterministic model presented by Hunter et al. (2004a), the flight distance one of the determinants of SL can be improved by increasing the flight time (FT), however, it works against the improvement of SF and vice versa. Since SF is defined by contact time (CT) and FT. In consequence, it is necessary to choose the appropriate combination of SF and SL to improve RS. The finalists of the World Championships Men's 100-m race in 2009 obtained approximately 4.5-5 Hz of SF and of 2.2-2.8 m of SL during the maximal RS phase (Hommel et al., 2012). The SF and SL for the top three athletes were Bolt (SF: 4.49 Hz, SL: 2.77 m), Gay (SF: 4.94 Hz, SL: 2.48 m), and Powel (SF: 4.74 Hz, SL: 2.51 m), respectively (Hommel et al., 2012). The CT and FT gradually decreased from the start to the maximal RS phase, with the CT decreasing less than the FT (Rabita et al., 2015).

Similarly, it has been shown that SF increased with increases the RS, and conversely, the SL decreased (Bosco & Vittori, 1986; Mercer, Vance, Hreljac, & Hamill, 2002; Morin, Samozino, Zameziati, & Belli, 2007; Rabita et al., 2015; Yanai & Hay, 2004).

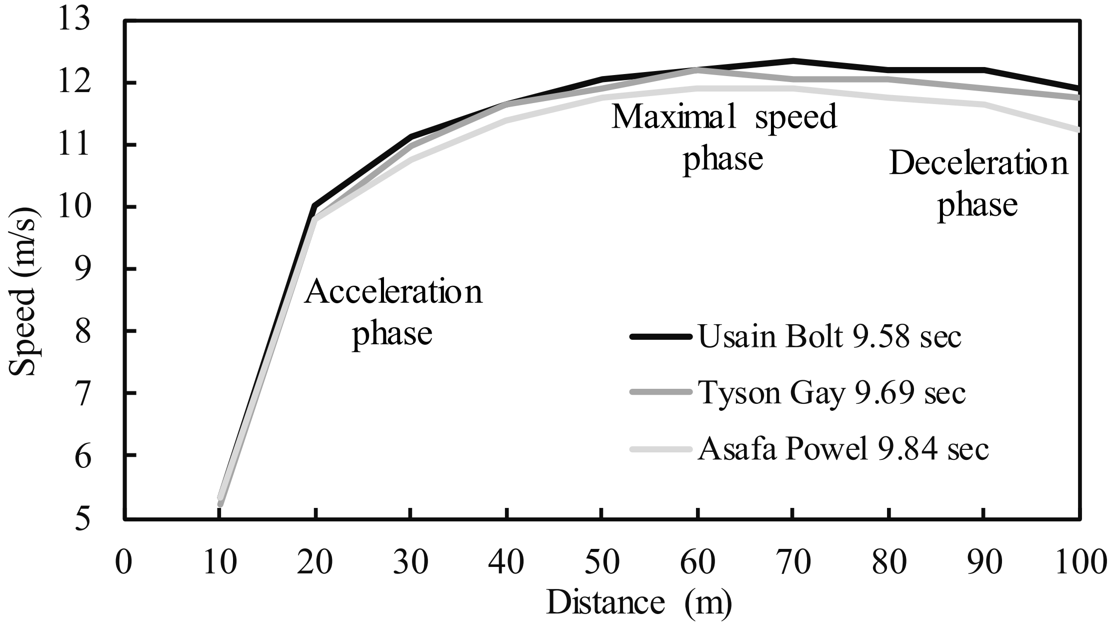

Figure 1-1 Distance-Speed relationship of the Men's 100-m final at the 2009 IAAF (International Association of Athletics Federations) World Championships in Athletics of three fastest athletes (Based on Graubner & Nixdorf, 2011).

1-1-2 Ground Reaction Forces

The running is a cyclic movement composed of the ground contact phase and the flight phase (Hay, 1993). It is only during the ground contact phase that the runner can apply force to the ground by himself. Therefore, the whole body's center of gravity is projected into the air by the reaction of the force applied to the ground during the ground contact phase. The force received by a runner at this time is called ground reaction force (GRF). The integration of GRF in the duration of ground contact time is defined as the ground reaction impulse (GRI), and it is equal to the change in RS in this phase. The GRF is composed of the vertical component and the horizontal component (Fig. 1-2). The vertical component is essential for maintaining the height of the body's center of gravity, and it is necessary for the vertical component to be greater than the body weight (1BW) to support body mass. Previous studies have shown that the maximal vertical component of GRF increases with increasing RS (Nagahara, Mizutani, Matsuo, Kanehisa, & Fukunaga, 2017, 2018) (Fig. 1-2). Moreover, the peak vertical GRF is likely an indicator of achieving a better acceleration of maximal sprinting (Nagahara, Kanehisa, Matsuo, & Fukunaga, 2019). A study comparing the vertical component of GRF between elite sprinters and non-sprinters revealed that the waveforms of the first and latter halves of GRF in elite sprinters were asymmetric (Clark & Weyand, 2014) (Fig. 1-3). Furthermore, elite sprinters have a larger peak GRF in the first half of the ground contact phase (Clark & Weyand, 2014). This is thought to be largely related to the Stretch-Shortening Cycle (SSC) movement during the first half of the ground phase (Ishikawa, Pakaslahti, & Komi, 2007).

The horizontal component of the GRF can be divided into braking and propulsive component. In other words, the running movement is repetitive braking and acceleration in each step cycle. A report on the change in the GRF over during 50 m run from the crouching start showed that the peak braking GRF increased with increasing RS, while the peak propulsive GRF decreased (Nagahara et al., 2019) (Fig. 1-2). Moreover, the net horizontal GRF is highest immediately after the start, having only the propulsive component. In other words, the running acceleration is greatest in the first step after the start. A previous study reported a significant positive correlation of the net horizontal GRF with RS and with SL (Mero & Komi, 1986). Morin, Slawinski, et al. (2015) also reported that the propulsive GRF and the net horizontal GRF were also greater for the world's top-level athletes (100-m best time: 9.95 s) compared to sub-elite athletes (100-m best time: 10.60 s). Other studies have also indicated the importance of increasing both components in order to acquire high RS (Hunter, Marshall, & McNair, 2005). Slawinski et al. (2017) showed in a force-velocity curve that Usain Bolt obtained greater horizontal

GRF even under the same RS than other subjects (Fig. 1-4). It means the ability to keep acquiring the horizontal GRF at very high RS is more important than the capability to produce a high magnitude of GRF at lower speeds during the first meters of the race.

Morin's research group also calculated the ratio of the vertical to the horizontal component of GRF (Morin et al., 2012; Morin, Edouard, & Samozino, 2011; Rabita et al., 2015) (Fig. 1-5). It seems that the direction of the total force applied onto the ground during sprint acceleration is more important to performance than its absolute magnitude. More importantly, sprinters will need to do training not only for increasing the magnitude of GRF but also for adjusting its direction.

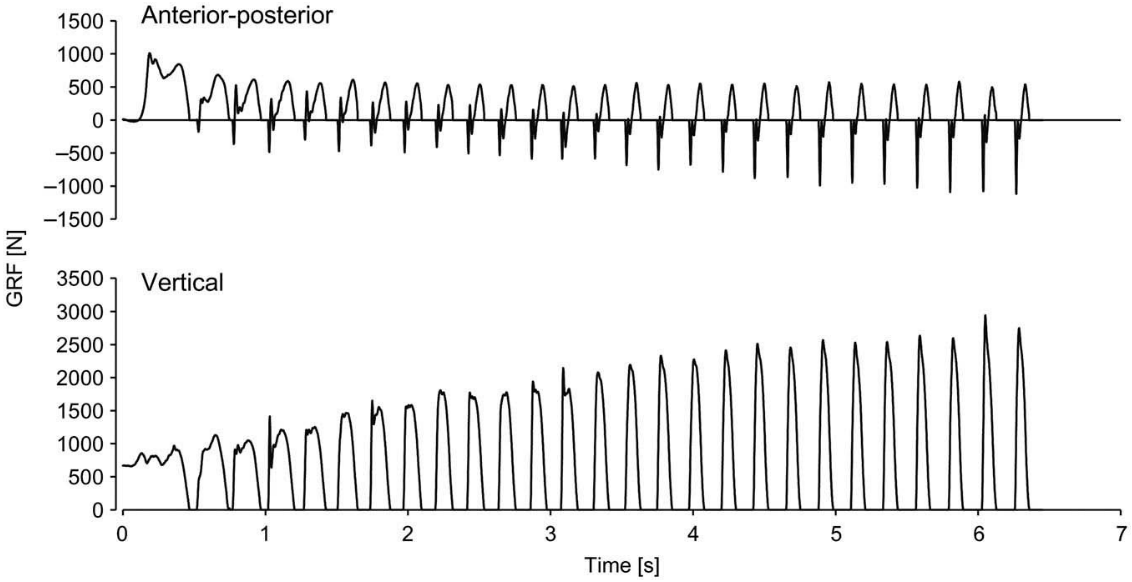

Figure 1-2 Anterior–posterior (propulsive-braking) GRF and vertical GRF signals during accelerated sprinting over the 50-m distance (Nagahara et al., 2018).

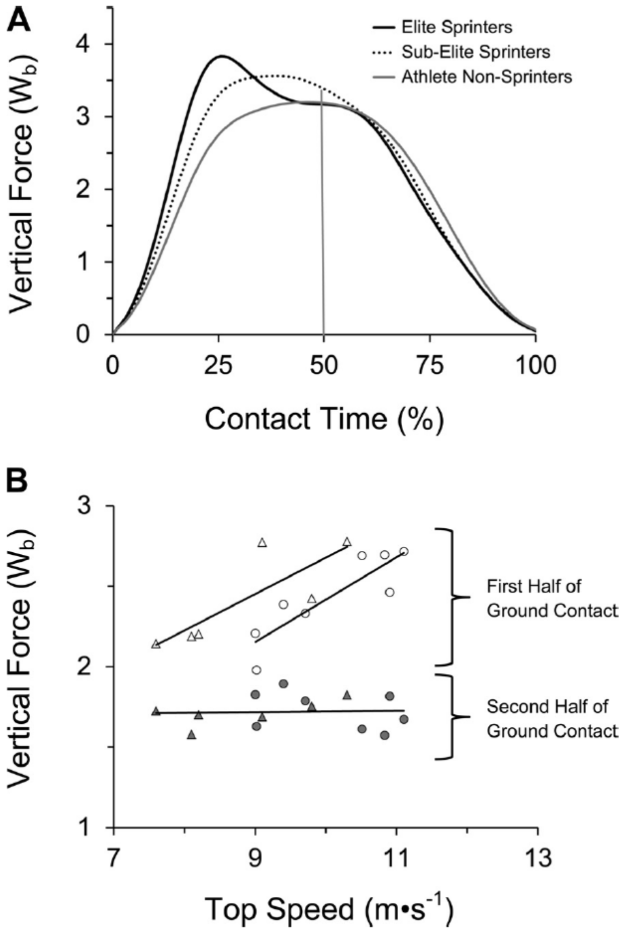

Figure 1-3 Trial-averaged composite vertical ground reaction force-time waveforms vs. top speed for the two male elite sprinters (solid black line), the two male sub-elite sprinters (dotted black line), and four male athlete non-sprinters (solid gray line) (A). Average vertical forces for the first and second half of the ground contact period for subjects in both groups at top speed (B). Circles represent male subjects; triangles represent females subjects; open symbols represent average vertical forces for the first half of the ground contact; shaded symbols represent average vertical forces for the second half of ground contact period. Line fits for the data from the first half of the ground contact period are provided by sex to appropriately account for the leg and contact length differences that influence top speeds. A single line fit for the data from the second half of the ground contact period is plotted for all 14 subjects because the values are similar in magnitude across group and sex. [Linear best-fit regression equations appearing in B that relate ground force to top running speeds are as follows: men first half-stance, force (Wb) = 0.26·Spd-0.22; women first half contact, force (Wb) = 0.23·Spd + 0.41; all subjects second half contact force (Wb) = 0.004·Spd + 1.68] (Clark & Weyand, 2014).

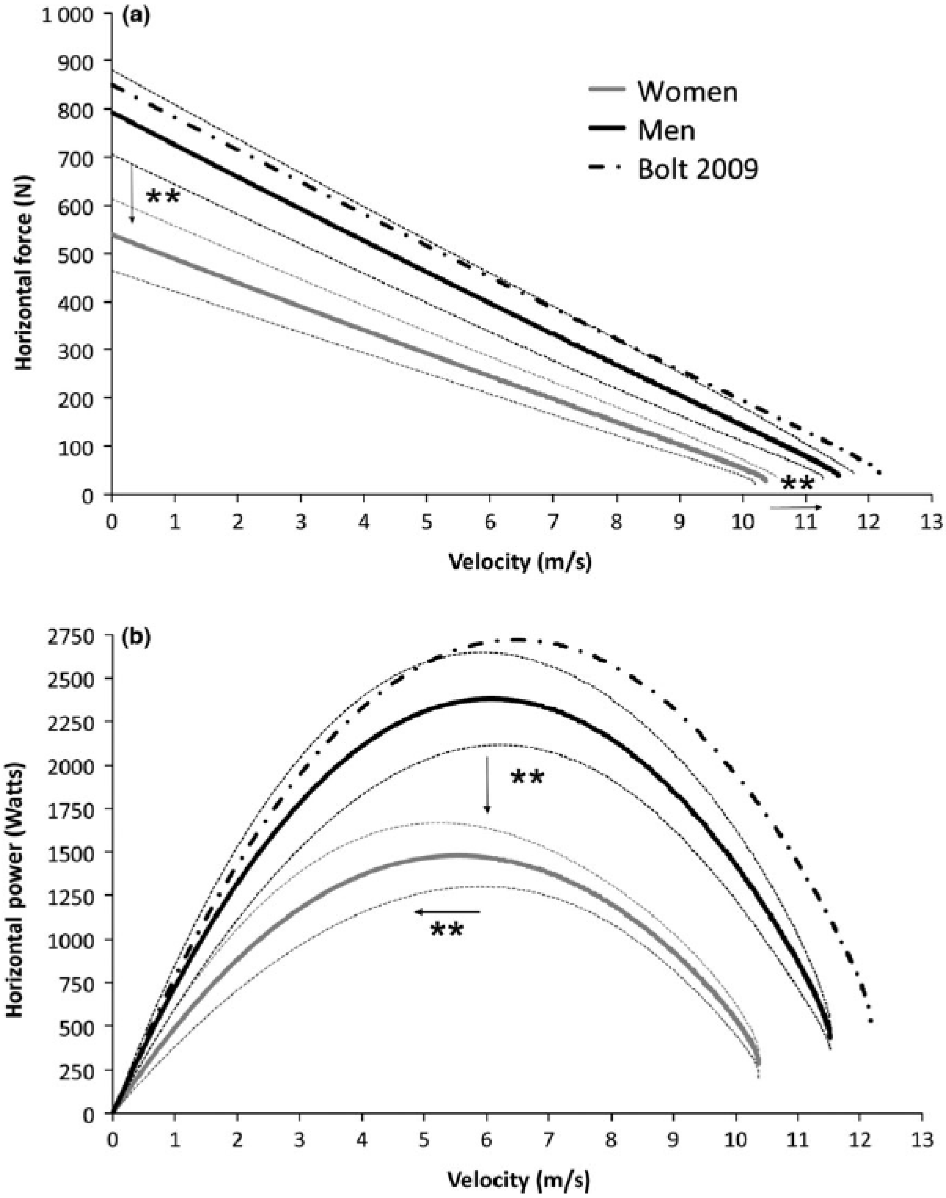

Figure 1-4. Men's (black line) and women's (gray line) force-velocity curve until maximal velocity. Bold lines represent averaged data of the 50 runs collected for women and men sprinters. Thin lines represent the average value plus or minus one standard deviation (P ≤ 0.001). The dotted line represents the actual limit of human sprint performance set by Usain Bolt in 2009 (Slawinski et al., 2017).**

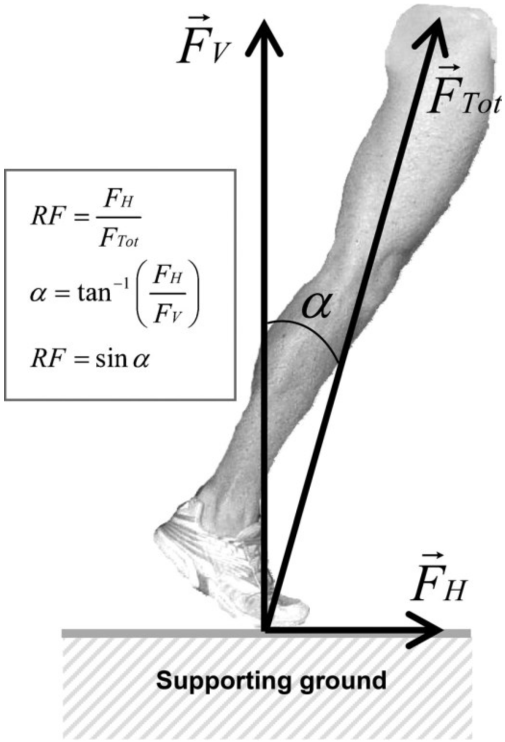

Figure 1-5. Schematic representation of the ratio of forces (RF) and mathematical expression as a function of the total (F_{Tot}) and net positive horizontal (F_H) (i.e., contact-averaged) ground reaction forces. The forward orientation of the total GRF vector is represented by the angle >α. (Morin et al., 2011).

1-1-3 Lower-limb Movements

Numerous biomechanical studies on running movements have focused on the lower limb joints (hip, knee, and ankle), mainly examining joint angles, angular velocity, and joint torque in the sagittal plane (Bezodis, Kerwin, & Salo, 2008; Bushnell & Hunter, 2007; Dorn et al., 2012; Hunter et al., 2004a; Hunter, Marshall, & McNair, 2004b; Ito et al., 1998; Johnson & Buckley, 2001; Kunz & Kaufmann, 1981).

Ralph V. Mann denoted the “Front side Back side sprint mechanics” (Mann, 2011) (Fig. 1-6). He stated that world class sprinters optimize “Front side mechanics (leg motions occurring in front of the extended line through the torso)” and “Back side mechanics (leg motions occurring in the back of the extended line through the torso)” at the maximal RS (Fig. 1-6). He noted two critical reasons why “Front side Back side mechanics” is important for sprint performance (Mann, 2011).

1) *“First, to achieve world class sprint acceleration and velocity, an athlete must be Front Side dominate during ground contact to generate the most effecting ground forces. This simple fact is that, at today’s competition level, a sprinter cannot be competitive at this manner. Thus, achieving this sprint technique coming out of the starting effort is the first performance goal.”* (Mann, 2011).

2) *"Second, it has become painfully evident that, if a sprint athlete fails to achieve Front Side dominance at the beginning of the race, they are unable to shift from that point forward. Thus, if Back Side Mechanics are dominant during the Start, then sprinter will finish the race with Back Side dominance."* (Mann, 2011)

Haugen et al. (2018) found several "Front and Back-side mechanics" variables including thigh and knee angle at foot-off (FO), and maximal thigh extension were correlated with running performance. Therefore, sprinters should get back to the "Front-side mechanics" as soon as possible after FO, without compromising lower-limb extension during ground contact. If "Back side mechanics" become prolonged, hip extension is also prolonged. As a result, recovery movement (hip flexion to swing the thighs forward) would delay. Therefore, Haugen et al. (2018) suggested sprinters should consider the optimal knee and hip extension at the FO.

At speeds higher than 7 $m \cdot s^{-1}$, hip flexion and extension torque sharply increase (Dorn et al., 2012; Schache, Dorn, Williams, Brown, & Pandy, 2014). In addition, the hip flexion torque increases with the speed of leg swing, leading to higher SF. Thus, the functions of the hip extensors and flexors are particularly important in achieving high RS (Dorn et al., 2012; Schache et al., 2011). 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 a significant positive correlation with the RS (Ito et al., 1998). Therefore, a quick flexion and extension of the hip joint are important to achieve high RS. Various studies also pointed out the importance of hip extensor velocity in sprinting (Bezodis et al., 2008; Hunter et al., 2005; Johnson & Buckley, 2001; Kunz & Kaufmann, 1981). Moreover, a previous study comparing the running movements of sprinters and distance runners reported that the position of the recovery knee at the foot strike of the contact leg was closer to the contact knee in sprinters than in distance runners (Bushnell & Hunter, 2007). 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, the earlier timing of the swing leg movement relative to contact (contralateral) leg movement would lead to higher SF. Furthermore, since sprinting is a cyclic movement in which the roles of the left and right legs (contact leg and swing leg) alternate changes (Hay, 1993), sprinter should also consider timings of muscle activity in both legs.

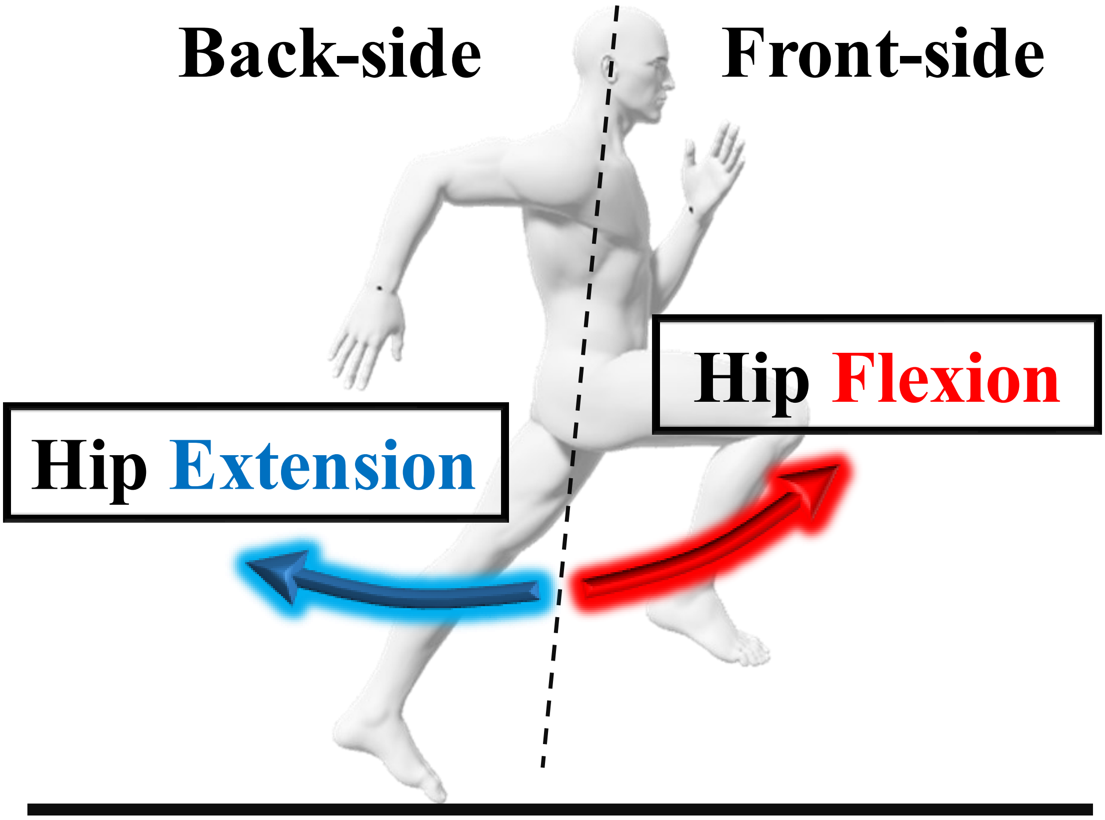

Figure 1-6. Front-side and Back-side mechanics in sprinting (based on Mann (2011); Chapter 12 pp. 134-141).

1-1-4 Neural factors

Sprint performance is influenced by several neural systems (e.g., muscle recruitment, muscle contraction speed, muscle contraction/relaxation rate) or fatigue (e.g., neural decreased firing frequency, decreased adenosine triphosphate (ATP), and creatine phosphate (CP) (Coh, Babic, & Maćkała, 2010; Ross et al., 2001) (Fig. 1-7). The running movements (e.g., joint angle, joint kinematics, or joint mechanical variables) that can be observed are the result of motor commands from the central nervous system (CNS) i.e. the higher brain, the spinal cord, and the control variables of neural origin can be assessed by measuring EMG (Fig. 1-8).

Numerous studies have reported EMG activity during running movements (Andersson, Nilsson, & Thorstensson, 1997; Chumanov, Heiderscheit, & Thelen, 2011; Chumanov, Schache, Heiderscheit, & Thelen, 2012; Dorn et al., 2012; Higashihara, Ono, Kubota, Okuwaki, & Fukubayashi, 2010; Kuitunen, Komi, & Kyrolainen, 2002; Kyrolainen, Avela, & Komi, 2005; Mero & Komi, 1986, 1987; Morin, Gimenez, et al., 2015; Nummela, Rusko, & Mero, 1994; Thelen et al., 2005; Yu et al., 2008). In a sprint cycle, from the moment of a leg's contact with the ground to its next contact, the biceps femoris muscle (BF) of the leg first achieved hip extension during the ground contact phase (Andersson et al., 1997; Dorn et al., 2012; Pinniger, Steele, & Groeller, 2000). In the latter half of the swing phase, the BF worked to achieve hip extension, showing eccentric activities with knee extension (Higashihara et al., 2010; Yu et al., 2008). Moreover, hip extensor muscles play an important role in producing the horizontal component of the GRF during sprinting on a treadmill (Morin, Gimenez, et al., 2015). In addition, subjects with a large horizontal component of the GRF showed strong EMG activity of the BF prior to ground contact (Morin, Gimenez, et al., 2015).

On the other hand, the rectus femoris muscle (RF), an antagonistic muscle of the BF, first works slightly to support the impact of ground contact (Nummela et al., 1994; Pinniger et al., 2000), and then to swing the thigh forward in the swing phase (Mero & Komi, 1987). This indicates that the RF, a bi-articular muscle, plays a more important role in hip flexion than for knee extension during sprinting (Mero & Komi, 1987). Because the activities in these hip joint muscles (BF and RF) increase with an increase in RS (Kuitunen et al., 2002), these muscles should 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 a significant positive correlation with the RS (Ito et al., 1998). Therefore, a quick flexion and extension of the hip joint are important to achieve high RS.

Recently, Howard et al. (2018) summarized the timing of onset and offset of lower limb EMG activity in a running cycle (Fig. 1-9). The RF and BF in a leg co-contract to fix the joints and maintain the posture during the first half of the ground contact phase (Pinniger et al., 2000). Furthermore, they show alternate switching activities twice during the swing phase (Howard et al., 2018). 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. 1-10. A). 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. 1-10. A). While co-contraction is important for maintaining posture during ground contact (Pinniger et al., 2000), it would be detrimental for achieving quicker running movements. Therefore, smooth switching between RF and BF (“Switch”) would be desirable for achieving a higher SF, but so far this effect has not previously been the subject of analysis.

Since sprinting is a cyclic movement in which the roles of the left and right legs (contact leg and swing leg) alternate (Hay, 1993), 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 muscle activity in one leg without the contralateral leg (Howard et al., 2018). The EMG activities in both legs were investigated only for the outside (right side) and inside (left side) legs during sprinting on a curved track (Mastalerz, Gwarek, Sadowski, & Szczepanski, 2012). However, no studies have investigated the relationship between the timings of muscle activity in both legs and the spatiotemporal variables that affect RS 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 (Bushnell & Hunter, 2007). 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, the earlier the timing of swing leg movement relative to contact (contralateral) leg movement, the higher the SF. To accomplish this movement, the RF of the recovery leg should begin to be activated 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. 1-10. B).

However, until now it has not always been easy to measure EMG from runners at especially at their maximal RS (Howard et al., 2018). In recent years, the development of wireless EMG measurement devices has made it possible to measure muscle and nerve activity during dynamic exercises, such as sprint running (Howard et al. 2018).

Nevertheless, previous studies on EMG in running has not been done at RS exceeding 10 m·s^{-1} (12 m·s^{-1} in the world's top sprinters) (Mero & Komi 1987). Although several studies have reached maximal RS on the motorized treadmill (Baur et al., 2007), muscle activities are different from those in ground running (Van Caekenberghe et al., 2013; Wang et al., 2014). Therefore, the characteristics of neural control in maximal speed running are still largely unknown.

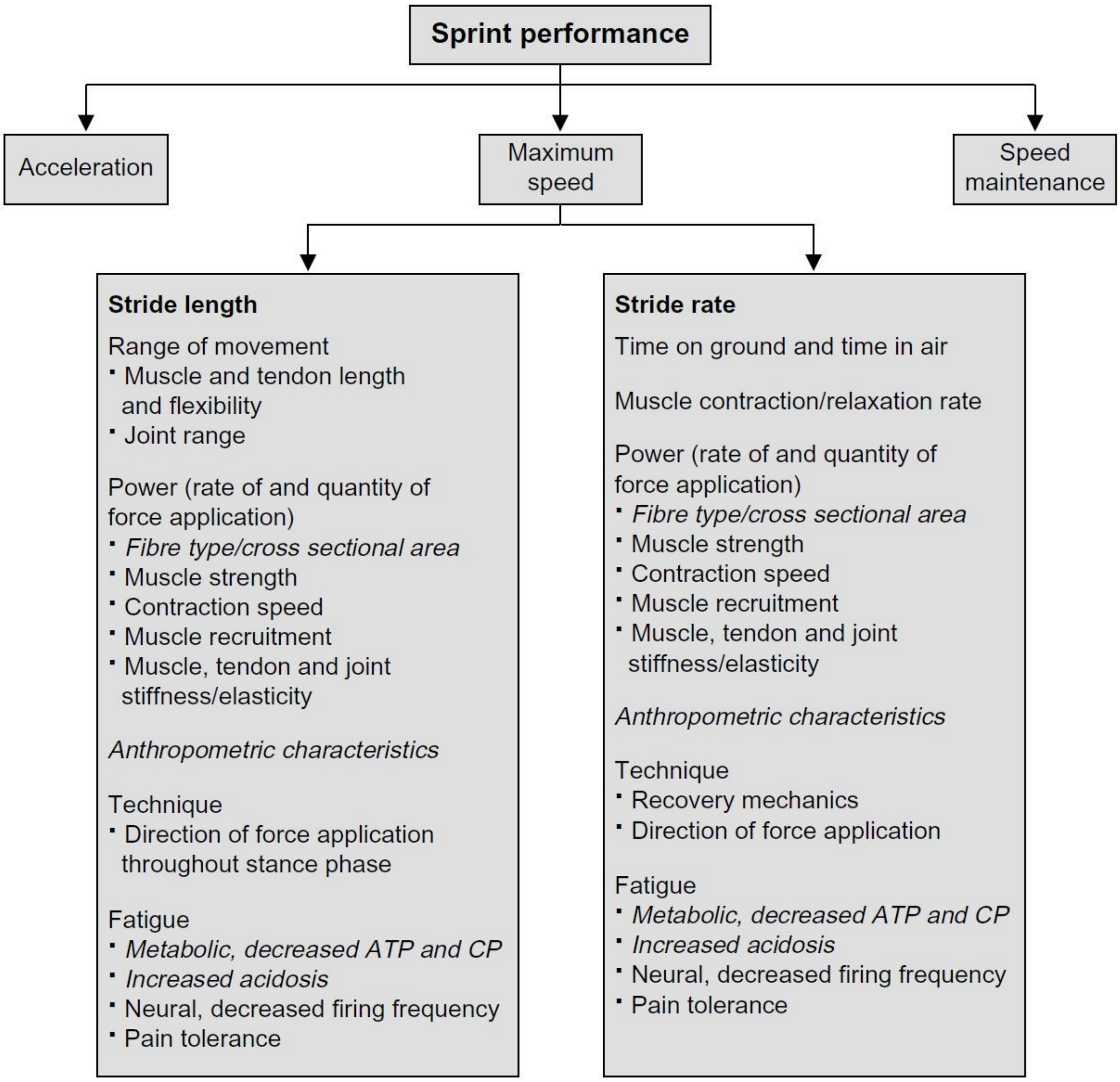

Figure 1-7. Components of sprint performance. Components in italics are not neutrally influenced. ATP = adenosine triphosphate; CP = creatine phosphate (Ross et al., 2001).

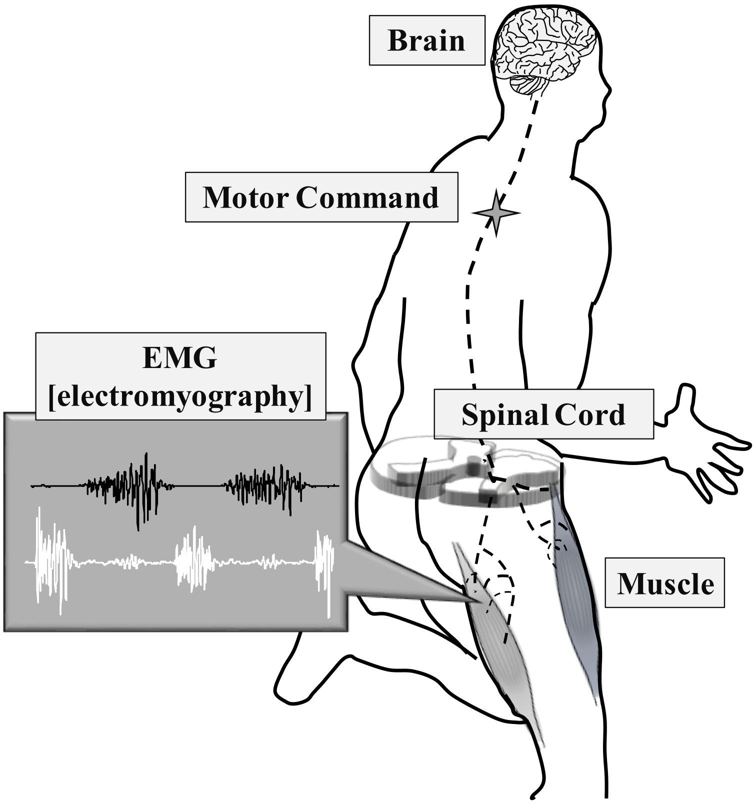

Figure 1-8. The schematic diagram of the neuro-muscular system in humans. Recording the electromyography (EMG) gives us neuro-muscular information.

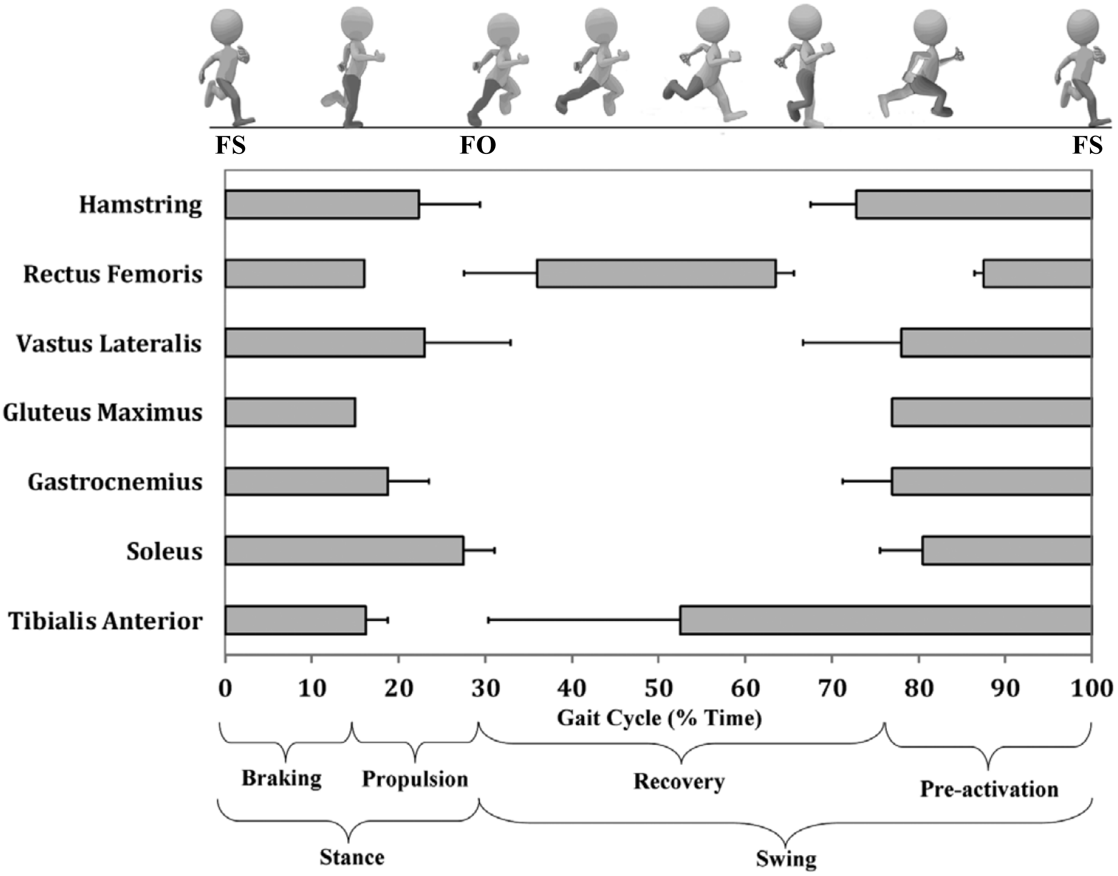

Figure 1-9. The muscle activation timings of the lower limbs during sprinting across the gait cycle as a percentage of time modified from (Howard et al., 2018). (1) The Early Stance (Braking) Phase: This phase begins as the foot-strike (FS) and ends at the mid-stance phase, estimated at 0–15 % of the cycle. (2) The Late Stance (Propulsion) Phase: This phase begins at the mid-stance phase and ends at the foot-off (FO), estimated at 15–30 % of the cycle. (3) The Early and Middle Swing (Recovery) Phase: This phase begins at FO and ends roughly two thirds of the way through the swing phase, estimated at 30–77 % of the cycle. (4) The Late Swing (Pre-activation) Phase: This phase begins roughly two thirds of the way through the swing phase and ends at the FS, estimated at 77–100 % of the cycle. The light grey areas represent periods where there is muscle activity. The error bars in the plot represent the SD of the mean onset and termination times which were gathered.

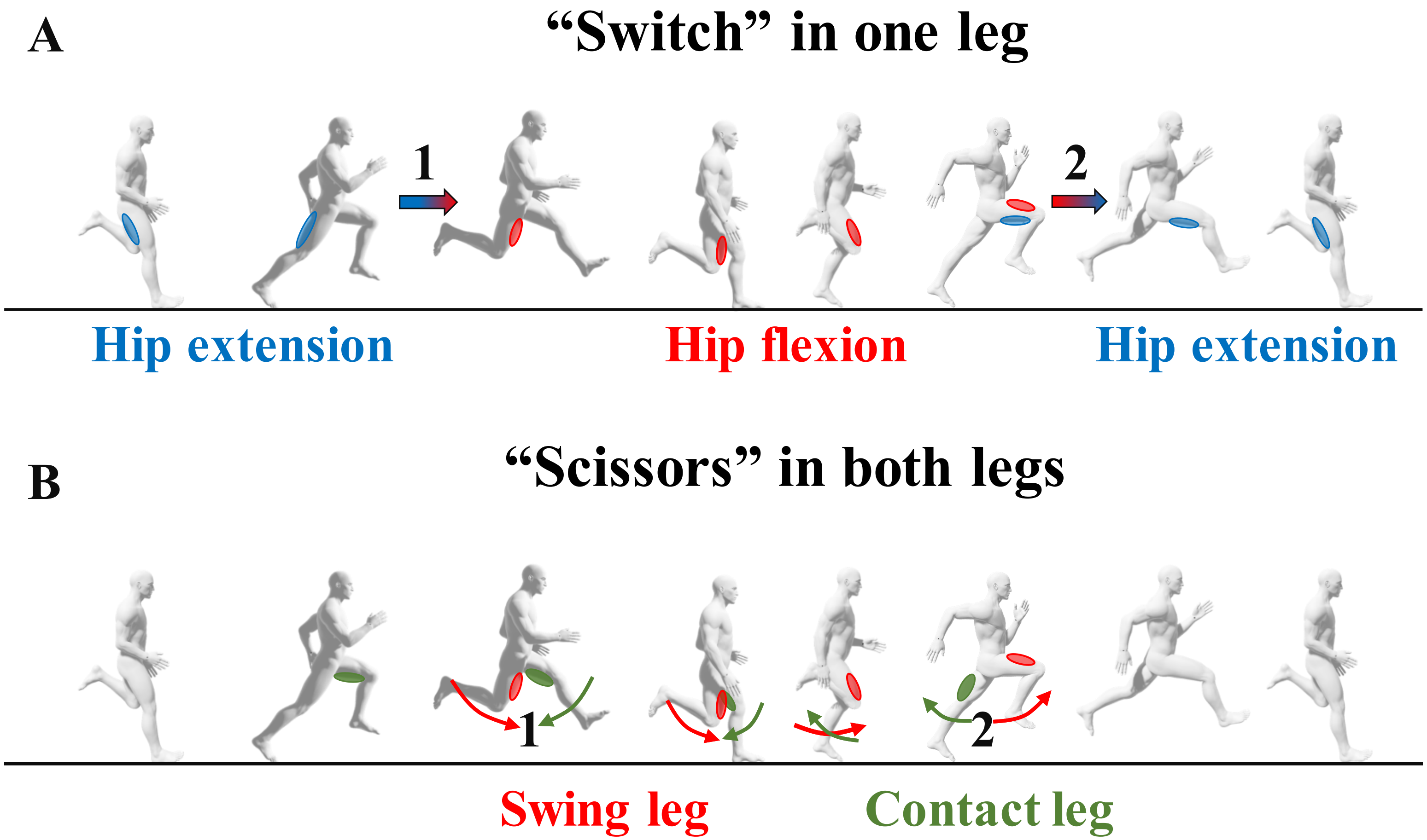

Figure 1-10. The schematic diagram of the (A) “Switch” in one leg and (B) “Scissors” in both legs during one running cycle. Blue indicates BF activity, red indicates RF activity, green indicates contralateral BF activity.

1-2 The purpose of the thesis

Numerous studies analyzed the spatiotemporal variables, GRF, joint movements, and muscle activities of running in one leg. However, running is a cyclic movement in which swing leg and contact leg alternate changing their roles. Therefore, we should consider not only one leg but also both legs during running to provide new insights for running research, coaching, and training.

The purpose of the doctoral thesis is to clarify the control of the thigh muscle (RF and BF) activity in both legs during sprinting.

In **Chapter 2,** I obtained RF and BF muscle activities from both legs using a wireless EMG system during the maximal running speed. I calculated the onset and offset timings (% of a running cycle) in both legs (e.g., ipsilateral leg RF [iRF] and contralateral leg BF [cBF]). Based on those timings, I proposed the two original muscular control variables as follows; "Switch1 (iBF-offset to iRF-onset)", "Switch2 (iRF-offset to iBF-onset)" (Fig. 1-10. A), "Scissors1 (cBF-onset to iRF-onset)" and "Scissors2 (iRF-offset to cBF-offset)" (Fig. 1-10. B). Moreover, I examined how these variables relate to spatiotemporal variables.

In **Chapter 3**, I investigated the muscular control variables in seven different RS conditions which were obtained by controlling the subjective effort of runners.

In **Chapter 4**, I clarified the differences in the muscular control variables and spatiotemporal variables during the maximal speed phase and deceleration phase of the 100-m dash.

In **Chapter 5**, the general discussion was made from the results of Chapters 2, 3, and 4.

Chapter 2

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

(Based on Kakehata et al., (2020) Medicine & Science in Sports & Exercise.)

2-1 Introduction

Recently, Howard et al. (2018) summarized the timing of onset and offset of lower limb EMG activity in a running cycle (Fig. 1-9, in Chapter1). The RF and BF in a leg co-contract to fix the joints and maintain the posture during the first half of the ground contact phase (Pinniger et al., 2000). Furthermore, they show alternate switching activities twice during the swing phase (Howard et al., 2018). 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. 1-10. A, and Fig. 2-4). 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. 1-10. A, and Fig. 2-4). While co-contraction is important for maintaining posture during ground contact (Pinniger et al., 2000), it would be detrimental for achieving quicker running movements. Therefore, smooth switching between RF and BF ("Switch") would be desirable for achieving a higher SF, but this effect has not previously been the subject of analysis.

Moreover, since 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 (Howard et al., 2018). The research on EMG activities in both legs investigated only the outside (right side) and inside (left side) legs during sprinting on a curved track (Mastalerz et al., 2012). However, no studies have investigated the relationship between the timings of muscle activity in both legs and the spatiotemporal variables that affect RS 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 (Bushnell & Hunter, 2007). 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 SF. 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. 1-10. B, and Fig. 2-4). 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 chapter is to clarify whether maximal RS, the most important performance in sprinting, and it determines factors, SF and SL, are related to the onset/offset timing of RF and BF muscle activities in both legs. I especially focused 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 (swing leg RF activity and contact leg BF activity). I had two main hypotheses: First, a clear switch between RF and BF in a leg would produce higher SF. 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 SF.

2-2 Methods

Subjects

Eighteen male well-trained Japanese Track & Field athletes (World Athletics [WA] Score: 1052.5 ± 93.3 pts, height: 177.7 ± 6.0 cm, body mass: 69.9 ± 6.9 kg, age:

20.7 ± 1.8 years) volunteered to participate in the study (Table 2-1). The WA Score refers to the points for each Track & Field event record. It was referenced from the WA official document (Spiriev, 2017). Note that the 1052 points are equivalent to a record of 10.46 sec in the men's 100 meters. The participating athletes specialized in the 100 meters, 200 meters, 400 meters, 110 meters hurdles, 400 meters 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.

Procedure

After 40 min of self-selected warm-up trials (slow jogging to sub-maximal running effort), subjects ran one 50 m sprint with the maximal RS in the straight lane of an official 400 m track. From a 2-point standing start, subjects were instructed to accelerate from 0-30 m, and then sprint at their maximal intensity from 30-50 m.

Data collection

A timing system (Brower Timing System, Brower, Germany) was set to measure the sprint time of the 30-50 m section (Fig. 2-1). Surface muscle EMG data were sampled at 2000 Hz using wireless EMG sensors (Trigno Wireless Sensor, Delsys, USA). EMG data were recorded from the RF and BF muscles in both legs. Before the sensors were attached, the involved area of the skin was shaved and treated with alcohol to reduce inter-electrode impedance. EMG signals for the four muscles were checked after placing the electrodes. In order to eliminate the influence of motion artifact as much as possible, the EMG sensors were fixed with surgical tape and under wrap tape (Fig. 2-2). A panning high-speed camera (LUMIX DMC FZ-300, Panasonic, Japan) was used to determine the moments of FS (Foot-Strike) and FO (Foot-Off) from the side of the running track at 240 Hz. At the same time, in order to synchronize the FS and FO timing with the EMG data, the flash of the wireless all-around light presenter (Synchronizer, DKH, 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 maximal voluntary contraction (MVC) test was performed, in which subjects exerted a 5 s MVC against manual resistance of each muscle.

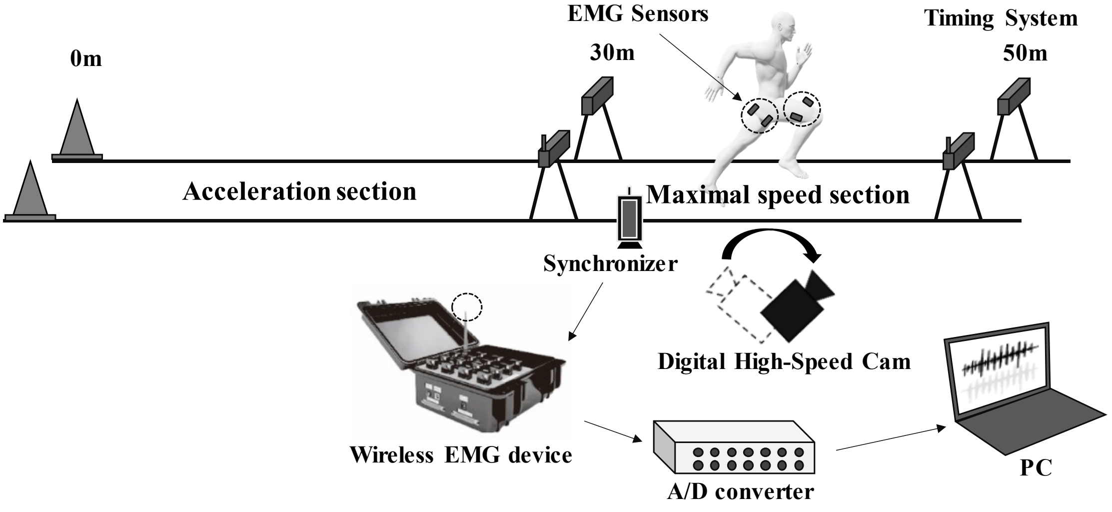

Figure 2-1. Schematic diagram of the experimental set up in chapter 2.

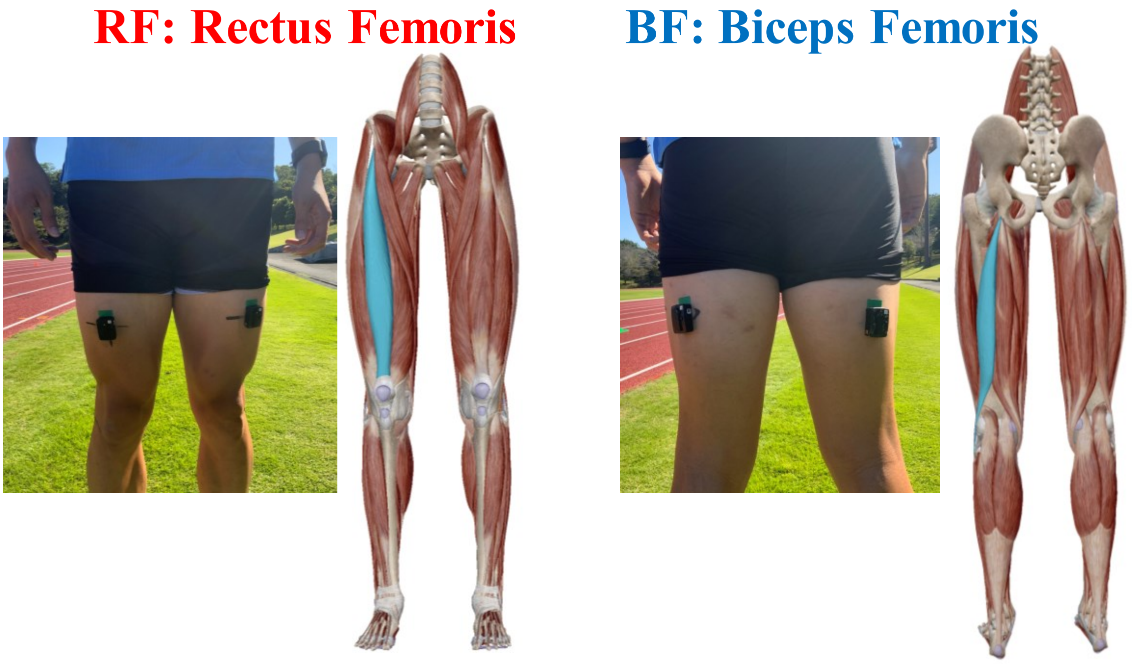

Figure 2-2. Rectus Femoris and Biceps Femoris muscles.

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 30-50 m target section was defined as the RS ($m \cdot s^{-1}$). In addition, the CT (sec) and FT (sec) for each step were calculated from the number of frames of the high-speed camera, and the SF (Hz) was calculated for each step. The SL (m) was calculated by dividing the RS by the SF. 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 (LabChart 8, ADInstruments, New Zealand) and synchronized with the time 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 FO times read from the captured video were input. In this study, I 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”.

I defined the running cycle as the time from the moment of the ipsilateral leg FS (iFS) until the next ipsilateral leg FS (iFS2). The ipsilateral leg contact phase was defined from iFS to ipsilateral FO (iFO). The ipsilateral leg swing phase is divided into early, mid, late from iFO to the contralateral leg FS (cFS), from cFS to the contralateral leg FO (cFO) from cFO to iFS2, respectively (Fig. 2-3).

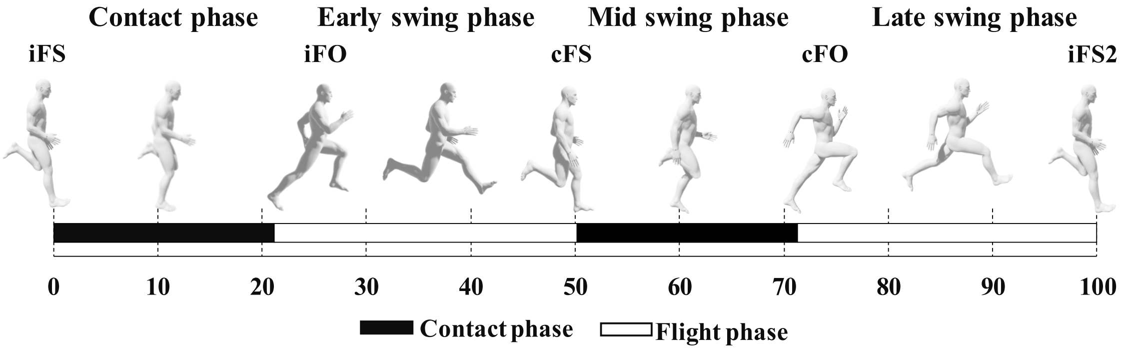

Figure 2-3. Defining the phase of running cycle.

In order to quantify the onset and offset timing of muscle activity, the EMG signal was processed with a TKEO (Teager-Kaiser Energy Operator) filter (Solnik, Rider, Steinweg, DeVita, & Hortobagyi, 2010). The TKEO filter has been confirmed to be a reliable method of calculating the EMG onset detection (Li, Zhou, & Aruin, 2007; Solnik et al., 2010). The discrete TKEO Ψ was defined as:

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

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:

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

where μ is the mean EMG signal during baseline and σ is the standard deviation (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 (Solnik et al., 2010). The EMG onset or offset timings were normalized for the % 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 cut-off frequency of 20 Hz to obtain linear envelope EMG waveforms (Yu et al., 2008) and normalized as % MVC using the mean amplitude of the MVC (obtained from 3 s out of the 5 s of EMG recorded) (Albertus-Kajee, Tucker, Derman, Lamberts, & Lambert, 2011).

Items calculated to obtain EMG timing

“Switch” and “Scissors” were defined and calculated as follows (Fig. 2-4).

1. “Switch” of the RF & BF activity in the ipsilateral leg

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

- iBF-offset: activity offset of ipsilateral leg BF.
- iRF-onset: activity onset of ipsilateral leg RF.
- iRF-offset: activity offset of ipsilateral leg RF.
- iBF-onset: activity onset of ipsilateral leg BF.

Based on these values, “Switch” was defined as the length of the switching time two muscles (iRF to iBF or iBF to iRF) activity were calculated as follows.

- “Switch1” (%) = iRF-onset – iBF-offset
- “Switch2” (%) = iBF-onset – iRF-offset

* The calculation produced a negative Switch2 value for several subjects. This indicates co-contraction.

2. “Scissors” in the bilateral leg.

In order to analyze the coordination or synchronization 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 contralateral leg BF.
- cBF-offset: activity offset of contralateral leg BF.

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

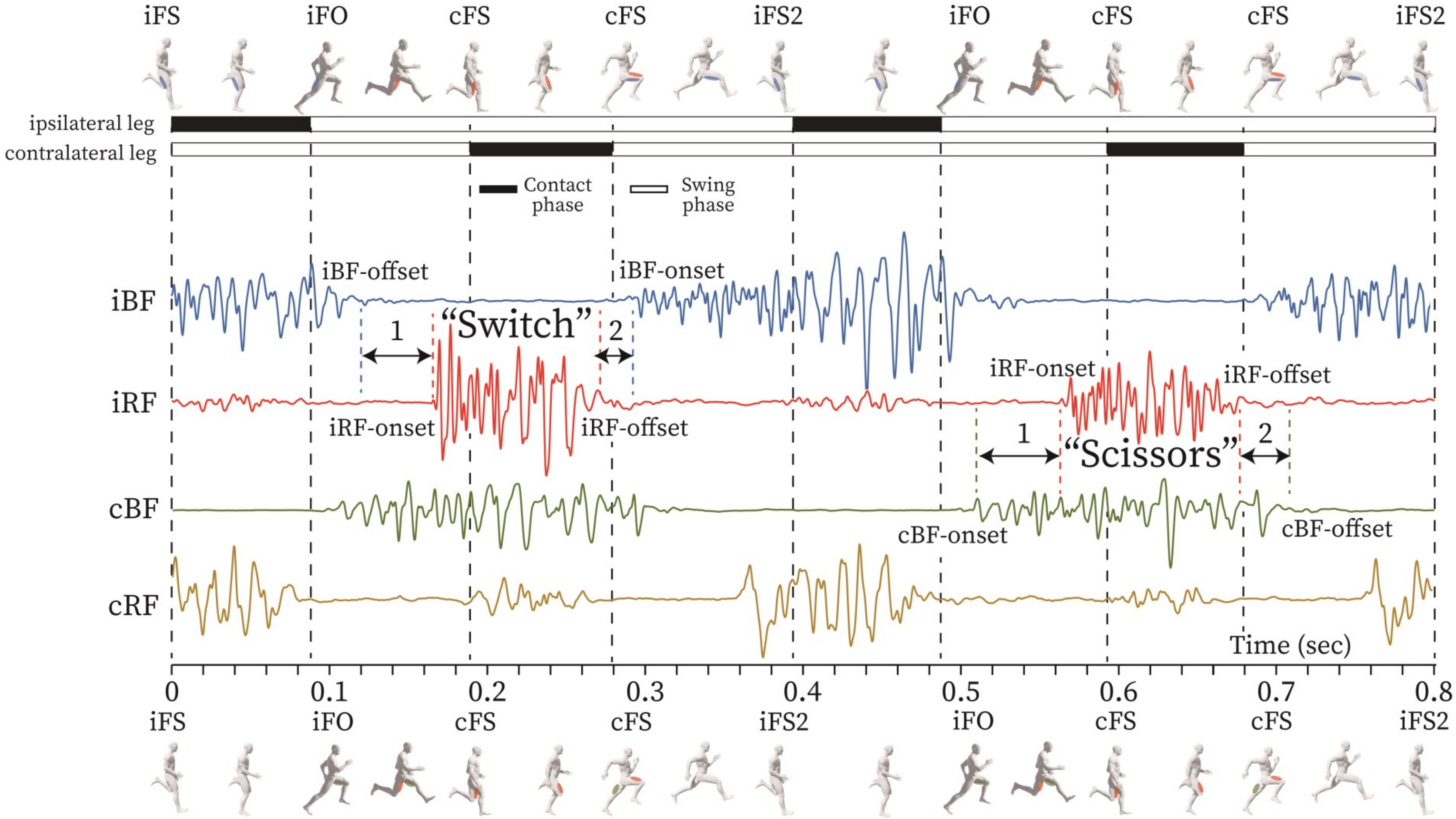

Figure 2-4. Typical example of muscle activities of four muscles in two cycles of running: From the top to the bottom, iBF (ipsilateral leg BF), iRF (ipsilateral leg RF), cBF (contralateral leg BF), and cRF (contralateral leg RF) in a subject. The vertical broken lines mark the occurrence of iFS (ipsilateral leg foot-strike), iFO (ipsilateral leg foot-off), cFS (contralateral leg foot-strike), and cFO (contralateral leg foot-off), 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.

Statistical analysis

The Pearson's product moment correlation coefficient was used to determine the correlation between muscle activity timing and spatiotemporal variables (RS, SF, and SL). Similarly, the correlation between RS and SF, SL, CT, and FT were also tested. All statistical analyses were performed using statistical processing software (SPSS ver.25, IBM, USA). I set a significance level of 0.05.

2-3 Results

Spatiotemporal variables

Table 2-1 shows the individual data, and mean values and SD of the RS, SF, SL, CT, and FT. Figure 2-5 A shows the relationship between SF and SL, with iso-velocity curves. Figures 2-5 B-E show the relationship between RS and the other four spatiotemporal variables. There was a significant negative correlation between RS and CT (p = 0.007, r = -0.592). However, there was no correlation between RS and SF (p = 0.112, r = 0.387), SL (p = 0.056, r = 0.459), and FT (p = -0.075, r = 0.769).

Table 2-1. Individual data, and mean values and SD of the RS, SF, SL, CT, and FT.

Subject	Event	WA Score (points)	Age (years)	Height (m)	Body mass (kg)	Running speed $(\mathrm{m \cdot s^{-1}})$	Step Frequency (Hz)	Step Length (m)	Contact time (sec)	Flight time (sec)
A	200m	1165	23	1.76	65	10.99	4.49	2.45	0.092	0.130
B	110mH	1136	22	1.85	80	10.87	4.56	2.38	0.089	0.134
C	100m	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	110mH	1116	20	1.84	81	10.10	4.48	2.25	0.096	0.128
F	100m	1142	25	1.72	68	10.00	4.69	2.13	0.091	0.122
G	100m	1040	19	1.77	67	10.00	4.68	2.14	0.090	0.124
H	400m	1034	19	1.68	66	9.90	4.98	1.99	0.089	0.112
I	100m	996	20	1.77	68	9.90	4.52	2.19	0.089	0.133
J	400m	1046	19	1.68	60	9.80	4.51	2.17	0.090	0.131
K	400m	1014	19	1.80	69	9.80	4.32	2.27	0.102	0.129
L	400m	1133	22	1.84	76	9.76	3.89	2.51	0.102	0.155
M	400mH	1156	22	1.88	80	9.48	4.25	2.23	0.110	0.126
N	100m	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	400m	973	20	1.78	68	9.30	4.60	2.02	0.098	0.119
Q	100m	999	19	1.81	71	9.13	4.11	2.22	0.106	0.138
R	110mH	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
	S.D.	93.3	1.8	0.06	6.9	0.54	0.28	0.14	0.007	0.009

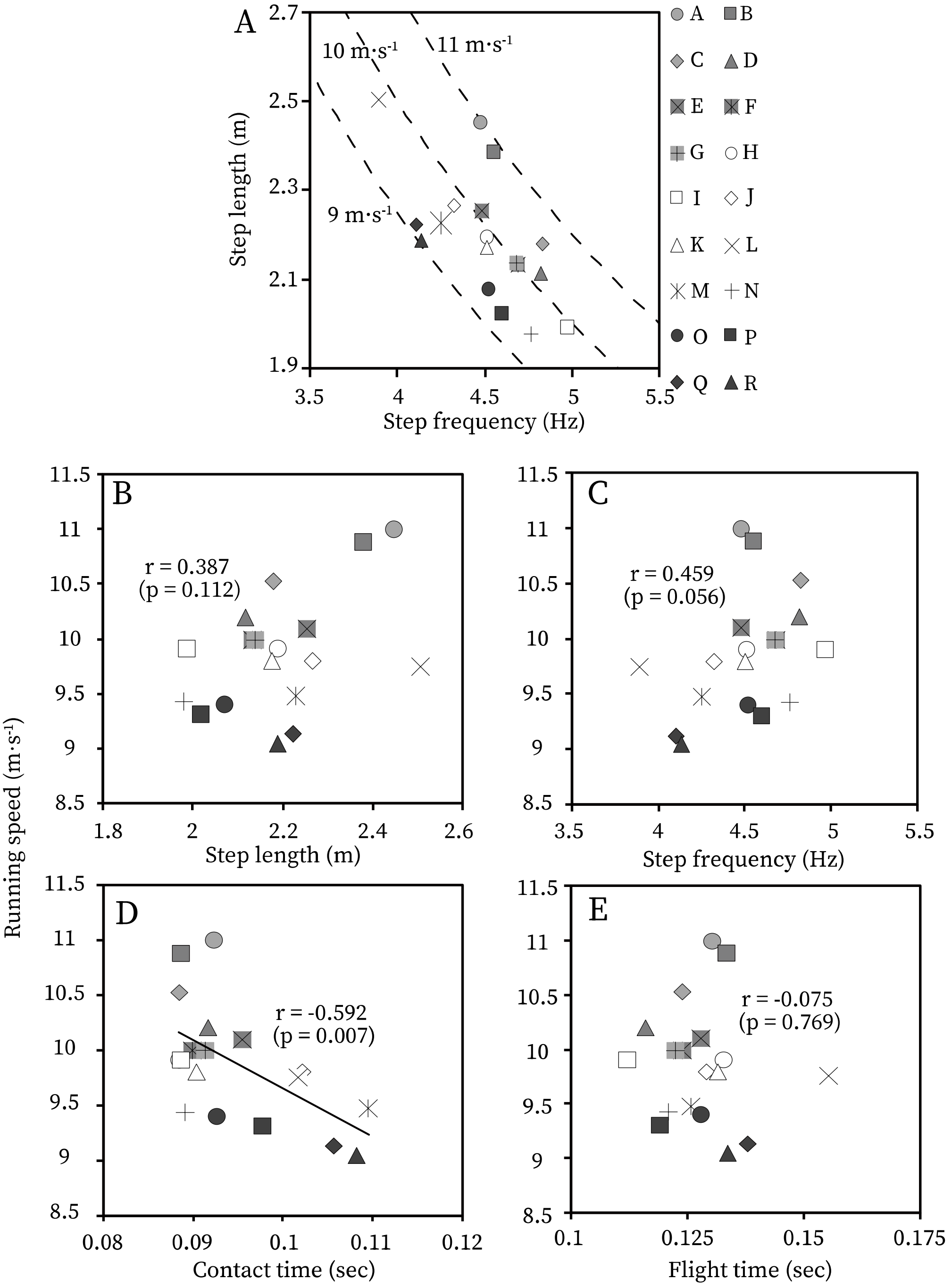

Figure 2-5. Relationship between RS, SF and SL (A), RS and SF (B), RS and SL (C), RS and CT (D), and RS and FT (E). There was a significant negative correlation between RS and CT. Different symbols labeled A through R represent the 18 subjects.

Timing of foot contact and EMG activities

Figure 2-6 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 Figure 3A and B 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 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 the 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 the early swing phase (39.5 ± 4.4 %) to the late swing phase (72.3 ± 6.2 %). Then, toward the iFS2 (100 %), iBF began to become active again at the late swing phase (73.8 ± 4.2 %). Note that in eight out of 18 subjects iRF and iBF showed co-contraction (negative “Switch2” values), meaning the iBF became active before the iRF finished its activity, while the remaining subjects showed clear switching from the iRF to the iBF (positive “Switch2” values).

Regarding “Scissors” of the two legs (Fig. 2-6 B), 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.

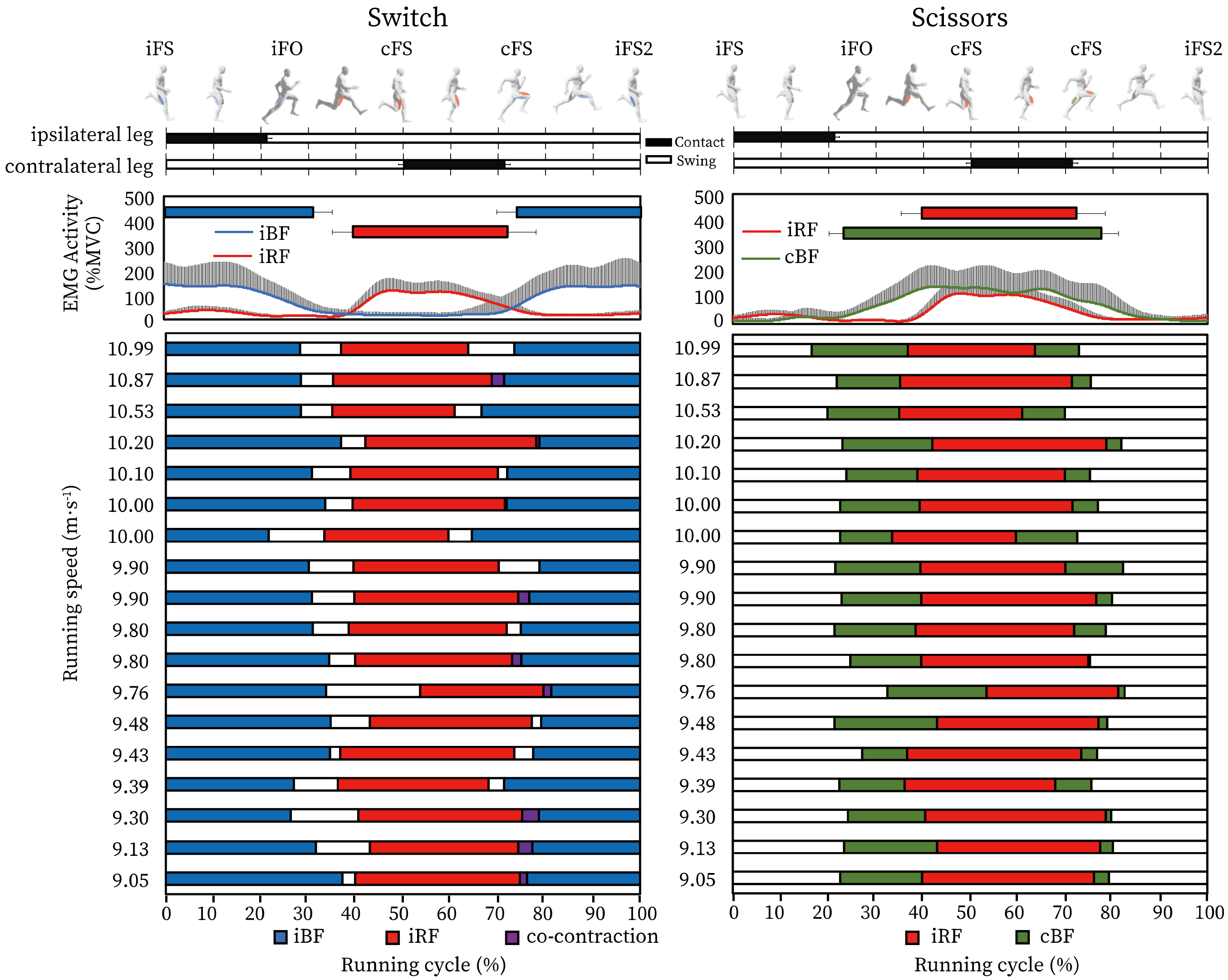

Figure 2-6. Relative activation phases: (A) "Switch: iRF and iBF", and (B) "Scissors: iRF and cBF" in one running cycle. The top figures show the timings of foot-strike (FS) and foot-off (FO) of the ipsilateral (iFS and iFO) and contralateral (cFS and cFO) legs. The middle figures show the averaged EMG 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 co-contraction. (B) Green indicates cBF activity. White indicates the time when both muscles are inactive. Note that iRF and cBF activation overlap.

Relationship between EMG activity and spatiotemporal variables

The relationship between onset and offset timing of iRF, iBF, and cBF activities and spatiotemporal variables were examined using Pearson's product moment correlation coefficient (Fig. 2-7 A and B). There was a significant negative correlation with RS and iRF-offset (r = -0.527, p = 0.025). The higher the SF 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. 2-7 B). However, SL did not correlate with the timing of any muscle activity. As for the length of the “Switch” (Fig. 2-7 C and D), “Switch2” had a significant positive correlation with SF (r = 0.495, p = 0.037), while “Switch1” had no significant correlation with any variables.

As for the length of the “Scissors” (Fig. 2-7 E and F), there was no significant correlation between “Scissors” and neither RS nor SL. On the other hand, the higher the SF, the shorter the “Scissors1” (r = -0.469, p = 0.049), and the higher the SF, the longer the “Scissors2” (r = 0.574, p = 0.013).

SL was not significantly correlated with any of the muscle activity variables ($p > 0.05$), not shown in Fig. 2-7.

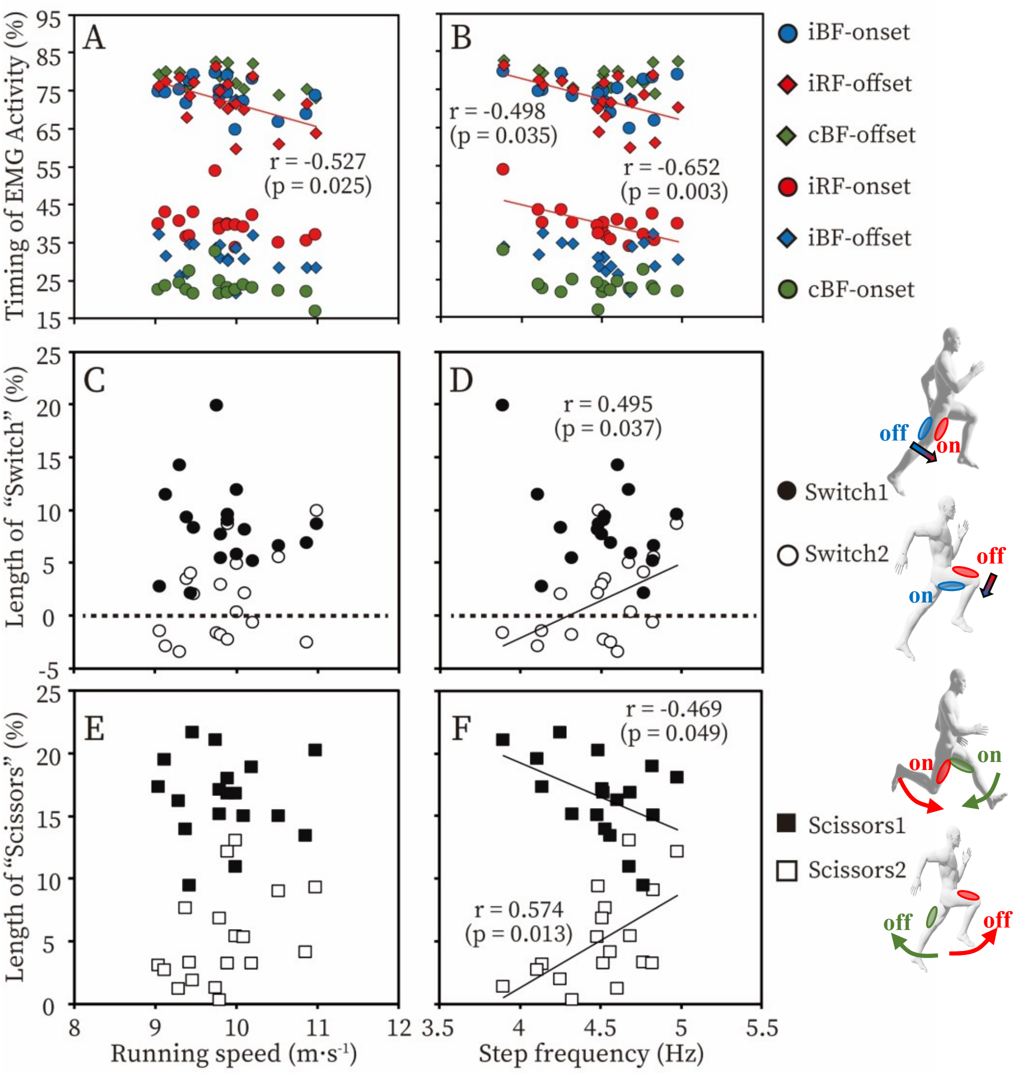

Figure 2-7. Muscle activity timing (A, B), length of "Switch" (C, D), and "Scissors" (E, F) in relation to RS (left) and SF (right).

2-4 Discussion

The overall goal of the present study was to clarify the relationship between spatiotemporal variables (RS, SF, and SL) and onset/offset timing of RF and BF muscles in both legs during maximal RS. Our main findings were, 1) RF onset and offset timings were significantly correlated with RS and SF, 2) the length of “Switch2”, “Scissors1” and “Scissors2” had significant correlations with SF, and 3) these variables had no significant correlations with RS nor SL. Thus, clear switching between agonist-antagonist muscle (iRF and iBF) in the late swing phase (“Switch2”) would be advantageous for achieving higher SF. Furthermore, the length of onset or offset time difference of agonist muscles in both legs (iRF and cBF) would also affect SF (“Scissors1” and “Scissors2”).

Before discussing the correlation between the timing of muscle activity and the spatiotemporal variables that affect RS, the RS of the subjects in the present study will be compared with previous studies. The mean RS of all subjects in the present study was 9.87 ± 0.54 $m \cdot s^{-1}$, ranging from 9.30 to 10.99 $m \cdot s^{-1}$ (Table1). In previous studies examining muscle activity during sprinting, RS 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 (Howard et al., 2018). 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 (Howard et al., 2018). Besides, there was a significant negative correlation between RS and CT (r = -0.592, *p* = 0.010, Fig. 2-5 D), which is similar to Weyand et al. (2000). However, in the current study, there was no significant correlation between RS and SF, SL, or FT. Previous studies demonstrated that the combination of SF and SL to get higher RS differs among individuals (Kakehata, Kobayashi, Matsuo, Kanosue, & Iso, 2020; Kunz & Kaufmann, 1981; Salo et al., 2011). Our experiments also showed various combinations of SF and SL (Fig. 2-5 A). The subjects in the present study were a group of well-trained athletes. For athletes at this level, improved RS 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 RS. Therefore, I 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 co-contraction in all subjects, and clear alternating contractions were observed (Fig. 2-6 A). However, there was no correlation between “Switch1” and RS and SF (Fig. 2-7 C). Meanwhile “Switch2”, from

RF activation to BF activation, showed individual differences; several subjects showed co-contraction of the RF and BF while several did not (Fig. 2-6 A). Interestingly, "Switch2" had negative correlation with SF ($r = 0.495$, $p = 0.037$) (Fig. 2-7 D). Regarding the switching between agonist and antagonist muscles, Fujii and Moritani (2012) did an interesting study on the world's fastest drummer, and showed clear alternating activities of the wrist flexor and extensor muscles without co-contraction during drumming at the maximal rate. The offset timing of activity in the world's fastest drummer was earlier than in non-drummers or ordinary drummers. Our study similarly found that the earlier the RF onset and offset, the higher the SF (Fig. 2-7 B). Moreover, there was a significant negative correlation between "Switch2" and SF (Fig. 2-7 D). 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 bi-articular muscle that acts on hip extension and knee flexion (Battermann, Appell, Dargel, & Koebke, 2011). 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 (Chumanov, Schache, et al., 2012). Therefore, switching between RF and BF activity is more complicated than the simple switching between the extensor and flexor in the drumming task. In "Switch 2", several subjects showed a co-contraction (Fig.

2-7 C and D). In the late swing phase, switching should be accomplished without co-contraction in order to increase SF. Hamstring injuries are common in high-speed sprints (Duhig et al., 2016), especially to the BF (Askling, Tengvar, & Thorstensson, 2013; Duhig et al., 2016; Ekstrand et al., 2012), most likely occur during the late swing phase (Schache, Wrigley, Baker, & Pandy, 2009). 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 (Ekstrand et al., 2012). Present results also show that the iBF activity peaks at the late swing phase, and it was greater than the MVC value (Fig. 2-6). Moreover, previous studies reported that a poor balance of the Q-H (quadriceps-hamstrings) strength ratio increases the risk of hamstring injury (Croisier, Ganteaume, Binet, Genty, & Ferret, 2008). In addition, subjects with a history of hamstring injuries have a large peak torque of the quadriceps (Freckleton & Pizzari, 2013). 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 the “scissors movement” affect the spatiotemporal variables and therefore RS. To investigate this, I 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. 2-6 B). Neither “Scissors1” nor “Scissors2” had any correlation with RS. 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 SF (Fig. 2-7 F). Therefore, in order to achieve high SF, it is important that the onset and offset of iRF occur at early timing relative to cBF activity. Previous research has demonstrated the distance of the swing leg knee relative to the contact leg knee at FS is significantly shorter in sprinters than in distance runners (Bushnell & Hunter, 2007). Therefore, it would be important to quickly recover the swing leg relative to the contact leg to obtain a higher RS. 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 (Mero & Komi, 1987). Moreover, the onset timing of hip flexion activity was earlier at a speed of 6.0 m·s^{-1} than at lower speeds of 1.5 to 5.0 m·s^{-1} (Andersson et al., 1997). Similarly, the RF onset timing comes earlier in the running cycle as the RS increases to 9.0 m·s^{-1} (Dorn et al., 2012). When running at less than 7.0 m·s^{-1}, the RS is achieved by increasing the SL, mainly by activating the ankle plantar flexor muscles. However, sprinting at high speeds higher than 7.0 m·s^{-1} requires a shift to a strategy of increasing the swing leg velocity by increasing the hip mechanical work (Dorn et al., 2012; Schache et al., 2011; Schache et al., 2014). In other words, the hip joint muscle during the swing phase demonstrated the most dramatic increase in activity at the faster RS (Schache et al., 2011; Schache, Brown, & Pandy, 2015). Indeed, the iRF-onset and iRF-offset timing both exhibited a negative correlation with SF (Fig. 2-7 B). Most importantly, “Scissors” was significantly correlated with SF (Fig. 2-7 F). 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 SF.

2-5 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 RS.

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 co-contraction in several subjects. Thus, I believe that the smooth switching between RF and BF activity in the same leg seems to be important to obtain a high SF.

Regarding the “Scissors”, the subjects with higher SF 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 SF.

In conclusion, smoother switching and coordinated inter-leg muscle activity are important to achieve high SF. Coaches and athletes should not only consider muscle activity timing in one leg, but also the coordination between both legs to improve sprint technique during maximal RS.

Chapter 3

Timing of Rectus Femoris and Biceps Femoris Muscle Activities in Both Legs at various speed running.

3-1 Introduction

"The fundamental goal in all running events is to maximize average running speed over the course of the race" (IAAF, 2009). Sprinting is described in the Oxford Dictionary of Sports Studies as *"intense running at speed over a short distance"* (Tomlinson, 2010). In other words, sprinting is the running at speed over a short distance at maximal speed, and most of the sprinting is considered to be achieved with maximal effort. For this reason, sprint training in track and field for improving maximal RS or acceleration ability tends to be done at maximal effort or near the maximal speed intensity (Haugen, Seiler, Sandbakk, & Tonnessen, 2019; IAAF, 2009) (Table3-1).

On the other hand, in addition to maximal speed intensity, training at a lower speed intensities are also often performed to improve speed endurance ability or improve running techniques (Haugen, Seiler, et al., 2019) (Table 3-1). Athletes rely on their own subjective feeling when controlling their RS. In this case, coaches often express running intensity with "subjective effort (SE)" scaled relative to the maximal sprint effort (100 %)

to make runners control the RS (Kakehata et al., 2020).

Kakehata et al., (2020) reported that SE (i.e., RS) is mainly controlled by SF. In Chapter 2, the SF at maximal RS was shown to be related to the two muscular control 1) “Scissors”; the coordination or synchronization of RF and BF muscle activity in both legs, and 2) “Switch”; the smoother switching between agonist and antagonist muscles. However, it is unclear how those muscular control would change when the subjective effort (SE), that is, RS is varied.

Furthermore, it has also been shown that 100 % SE is not necessarily the SE with the fastest speed (Kakehata et al., 2020). This study showed that several subjects ran 50 m fastest at a sub-maximal SE. Thus, the optimal combination of SF & SL for obtaining maximal speed does not necessarily occur at the maximal SE. This result suggests that the timing of muscle contraction and relaxation, in other words, the coordination of muscular control, would also change with changing subjective effort, thus influencing performance.

Therefore, in this Chapter, it is aimed to clarify the relationship between “Scissors” and “Switch” features and spatiotemporal variables in various RS (i.e., subjective effort [SE]) conditions.

Table 3-1. Summary of best practice sprint training recommendations (adapted from Haugen et al., 2019)

Training method	Distance (m)	Intensity (%)	Recoveries (min)	Total session volume (m)	Initiation	Time to next HIS (hours)	Footwear and surface
Acceleration	10–50	> 98	2–7	100-300	Block/3-point/crouched	48	Spikes on track
Maximal velocity	10–30[a]	> 98	4–15	50-150[a]	20–40-m flying start	48–72	Spikes on track
Sprint-specific endurance	80–150	> 95	8–30	300–900	Standing start	48–72	Spikes on track
Speed endurance	60–80	90–95	2–4 (8–15)	600–2000	Standing start	48–72	Spikes on track
Resisted sprints	10–30	80-95[b]	3–6	50-200	3-point/crouched	48–72	Optional
Assisted sprints	10–30[a]	≤ 105	5–15	≤ 100[a]	20–40-m flying start	48	Spikes on track
Tempo	100–300	60–70	1–3	1000–2000	Standing start	24	Trainers on grass

Intensity is expressed in percent of maximal velocity. Recovery = time between repetitions (sets). HIS = high-intensive session

aFlying start distance excluded

bThe perceived effort is maximal, so the velocity decline is caused by resistance loading

Haugen et al.(2019) Sports Medicine-Open

3-2 Methods

Subjects

Subjects were identical to Chapter 2.

Procedure

Subjects performed 7 different "Subjective Efforts (SE)" running (20 % SE, 40 % SE, 60 % SE, 80 % SE, 90 % SE, 95 % SE, and 100 % SE) in the straight lane of an official 400 m track. "Subjective Effort (SE)" scaled relative to the maximal sprint effort (100 %) (Kakehata et al., 2020), such as: "Run at 90 % SE". The rest period was about 3-5 minutes between trials. From a 2-point standing start, subjects were instructed to accelerate in the zone of 0-30 m, and then sprint at the given SE in the zone of 30-50 m.

Data collection, Data processing, and EMG data analysis

These processes were basically the identical to Chapter 2.

Items calculated to obtain EMG variables

I obtained onset/offset of EMG timing (%), "Switch" (%), "Scissors" (%), and EMG waveforms (% MVC) with identical methods as Chapter 2. In addition, I also calculated the root mean square (RMS) values of EMG (% MVC) in the 4 phases, contact phase, early swing phase, mid swing phase, and late swing phase of a running cycle (Fig. 2-3).

Statistical analysis

One-way factor analysis of variance (ANOVA) with a Greenhouse-Geisser was performed to test the difference in spatiotemporal variables (RS, SF, SL, CT, and FT) and EMG variables of "Switch", "Scissors", onset/offset timings, and RMS at seven different SEs. All statistical analyses were performed using statistical processing software (SPSS ver.25, IBM, USA). I set a significance level of 0.05.

3-3 Results

Spatiotemporal variables

Table 3-1, 3-2, and 3-3 show that individual data, and mean ± SD of the RS, SF, and SL at seven different SEs. In addition, Table 3-4 shows the statistical data of the spatiotemporal variables at seven different SEs. The significant main effect of SE was observed in all spatiotemporal variables as described below (Table 3-4).

The significant main effect of SE was observed in RS ($F = 457.4$, $p < 0.001$, effect size (*ES*) $\eta^2 = 0.964$). RS significantly increased at all SE as compared to the SE one level below except that there was no significant difference between 95 % SE and 100 % SE. Note that several subjects obtained the maximal RS at sub-maximal SE sprinting. That is, 3 out of 18 subjects obtained the maximal RS at 95 % SE (Subject F, J, p), similarly, 2 out of 18 subjects 90 % SE (Subject D, I).

The significant main effect of SE was observed in SF ($F = 274.0$, $p < 0.001$, $ES = 0.942$). Just as the RS, the SF significantly increased with each SE increment except for that from 95 % SE to 100 % SE. There were significant increases of 17.2 % between 20-40 % SEs, 12.5 % between 40-60 % SEs, and 8.8 % between 60-80 % SEs, with a slight increase between 80 % SE and 100 % SE (80-90 % SE: 4.94 % increase, 90-95 % SE:

3.60 % increase, 95-100 % SE: 1.32 % increase, Fig. 3-1 B and Table 3-2).

The significant main effect of SE was observed in SL (*F* = 142.0, *p* < 0.001, *ES* = 0.893). SL differed significantly between adjacent SEs up to 80 %SE, with an increase of 29.3 % between 20-40 % SEs, 8.2 % increase in the 40-60 % SEs and 3.5 % increase in the 60-80 % SEs. SL reached its maximal value at 80 % SE, and then the rate of increase turned negative with no significant difference between adjacent SE in the range of 80-100 % SEs (80-90 % SEs: 0.8 % decrease, 90-95 % SEs: 1.3 % decrease, 95-100 % SEs: 0.2 % decrease, Fig. 3-1 B and Table 3-3).

The significant main effect of SE was observed in CT (*F* = 328.4, *p* < 0.001, *ES* = 0.951). There was a significant difference in CT between 20-60 % SE and 80 % SE. There were also significant differences between 80 % SE and 95-100 % SEs. However, there was no significant difference between 90-100 % SEs (Fig. 3-1 C).

The significant main effect of SE was observed in FT (*F* = 49.9, *p* < 0.001, *ES* = 0.746) (Table 3-4). Significant differences were found between 20 % SE and 60-100 % SEs, also 40 % SE and 80-100 % SEs, and 60 % SE and 80-90 % SEs. In addition, a significant difference was also found between 90 % SE and 100 % SE. However, no significant difference was found between 95 % SE and 100 % SE (Fig. 3-1 D).

Table 3-1. Individual data, and mean values ± SD of the RS and relative values at seven different SEs.

Subject	Running speed ($m \cdot s^{-1}$)						
	20%SE	40%SE	60%SE	80%SE	90%SE	95%SE	100%SE
A	3.10	5.81	7.58	8.55	10.20	10.75	10.99
B	3.63	6.35	7.91	10.00	10.25	10.31	10.87
C	4.02	6.67	8.47	9.80	10.53	10.64	10.75
D	4.25	7.43	8.81	9.66	10.20	10.15	10.05
E	3.18	7.07	8.89	9.26	9.52	10.00	10.00
F	4.22	5.97	7.75	9.85	9.90	10.00	9.95
G	4.30	6.56	7.14	8.66	9.13	9.71	9.90
H	4.18	6.62	8.40	9.30	9.39	9.66	9.90
I	4.02	6.29	8.51	9.22	10.10	10.05	9.85
J	3.75	6.76	7.19	9.52	9.66	9.80	9.39
K	4.21	6.99	8.55	9.22	9.39	9.39	9.80
L	3.51	5.76	8.51	9.26	9.43	9.43	9.76
M	4.02	6.54	8.20	8.26	8.73	9.17	9.48
N	3.41	5.33	7.72	8.03	8.47	9.05	9.39
O	2.91	5.88	6.67	8.58	9.17	8.93	9.30
P	4.39	6.94	7.94	9.09	9.01	9.43	9.22
Q	3.26	6.94	7.97	8.37	8.47	9.13	9.13
R	3.57	6.02	7.87	8.97	9.01	9.05	9.05
Mean	3.77	6.44	8.00	9.09	9.48	9.70	9.82
SD	0.47	0.55	0.60	0.58	0.62	0.55	0.58
Relative value (%)	38.5	65.8	81.7	92.7	96.5	98.8	100
SD	5.1	6.7	6.7	5.7	3.8	2.6	-

Table 3-2. Individual data, and mean values ± SD of the SF and relative values at seven different SEs.

Subject	Step frequency (Hz)						
	20%SE	40%SE	60%SE	80%SE	90%SE	95%SE	100%SE
A	2.51	2.93	3.33	3.63	4.09	4.38	4.49
B	2.67	3.22	3.71	4.15	4.24	4.57	4.56
C	2.68	3.30	3.81	4.29	4.65	4.92	4.98
D	2.72	3.65	4.13	4.46	4.75	4.72	4.71
E	2.81	3.44	4.19	4.26	4.47	4.65	4.68
F	2.69	3.05	3.57	4.48	4.59	4.69	4.78
G	2.92	3.43	4.23	4.49	4.60	4.87	4.98
H	2.66	3.18	3.38	3.94	4.22	4.49	4.52
I	2.82	3.22	3.92	4.15	4.48	4.48	4.38
J	2.65	3.50	3.90	4.13	4.23	4.23	4.36
K	2.48	3.24	3.52	3.67	3.70	3.70	3.89
L	2.79	3.30	3.68	3.70	3.94	4.09	4.25
M	2.81	3.05	3.81	3.86	4.16	4.60	4.53
N	2.68	3.32	3.35	4.26	4.47	4.51	4.74
O	2.63	3.18	3.62	4.25	4.51	4.63	4.59
P	2.88	3.70	3.95	4.41	4.59	4.77	4.73
Q	2.75	3.23	3.56	3.70	3.79	4.08	4.25
R	2.72	3.05	3.71	4.09	4.25	4.27	4.32
Mean	2.71	3.28	3.74	4.11	4.32	4.48	4.54
SD	0.11	0.21	0.28	0.29	0.30	0.31	0.27
Relative value (%)	59.9	72.4	82.6	90.5	95.1	98.6	100
SD	3.4	5.5	6.2	4.1	3.4	2.2	-

Table 3-3. Individual data, and mean values ± SD of the SL and relative values at seven different SEs.

Subject	Step length (m)						
	20%SE	40%SE	60%SE	80%SE	90%SE	95%SE	100%SE
A	1.23	1.99	2.28	2.36	2.49	2.46	2.45
B	1.36	1.97	2.13	2.41	2.42	2.26	2.38
C	1.50	2.02	2.22	2.28	2.26	2.16	2.16
D	1.56	2.04	2.13	2.17	2.15	2.15	2.13
E	1.13	2.05	2.12	2.17	2.13	2.15	2.14
F	1.57	1.96	2.17	2.20	2.16	2.13	2.08
G	1.62	2.06	2.11	2.20	2.16	2.16	2.19
H	1.43	1.93	1.99	2.07	2.04	1.98	1.99
I	1.43	1.95	2.17	2.22	2.25	2.24	2.25
J	1.40	2.03	2.15	2.24	2.16	2.17	1.98
K	1.59	2.00	2.19	2.23	2.22	2.22	2.25
L	1.41	1.78	2.42	2.53	2.55	2.55	2.51
M	1.44	1.98	2.23	2.24	2.22	2.24	2.23
N	1.21	1.75	2.02	2.08	2.04	1.97	2.07
O	1.11	1.85	1.84	2.02	2.03	1.93	2.03
P	1.53	1.88	2.01	2.06	1.96	1.98	1.95
Q	1.18	2.15	2.24	2.26	2.24	2.24	2.15
R	1.31	1.98	2.12	2.19	2.12	2.12	2.10
Mean	1.39	1.96	2.14	2.22	2.20	2.17	2.17
SD	0.16	0.10	0.13	0.13	0.16	0.16	0.16
Relative value (%)	64.4	91.0	98.9	102.4	101.5	100.3	100
SD	8.8	7.7	4.9	3.8	2.6	3.5	-

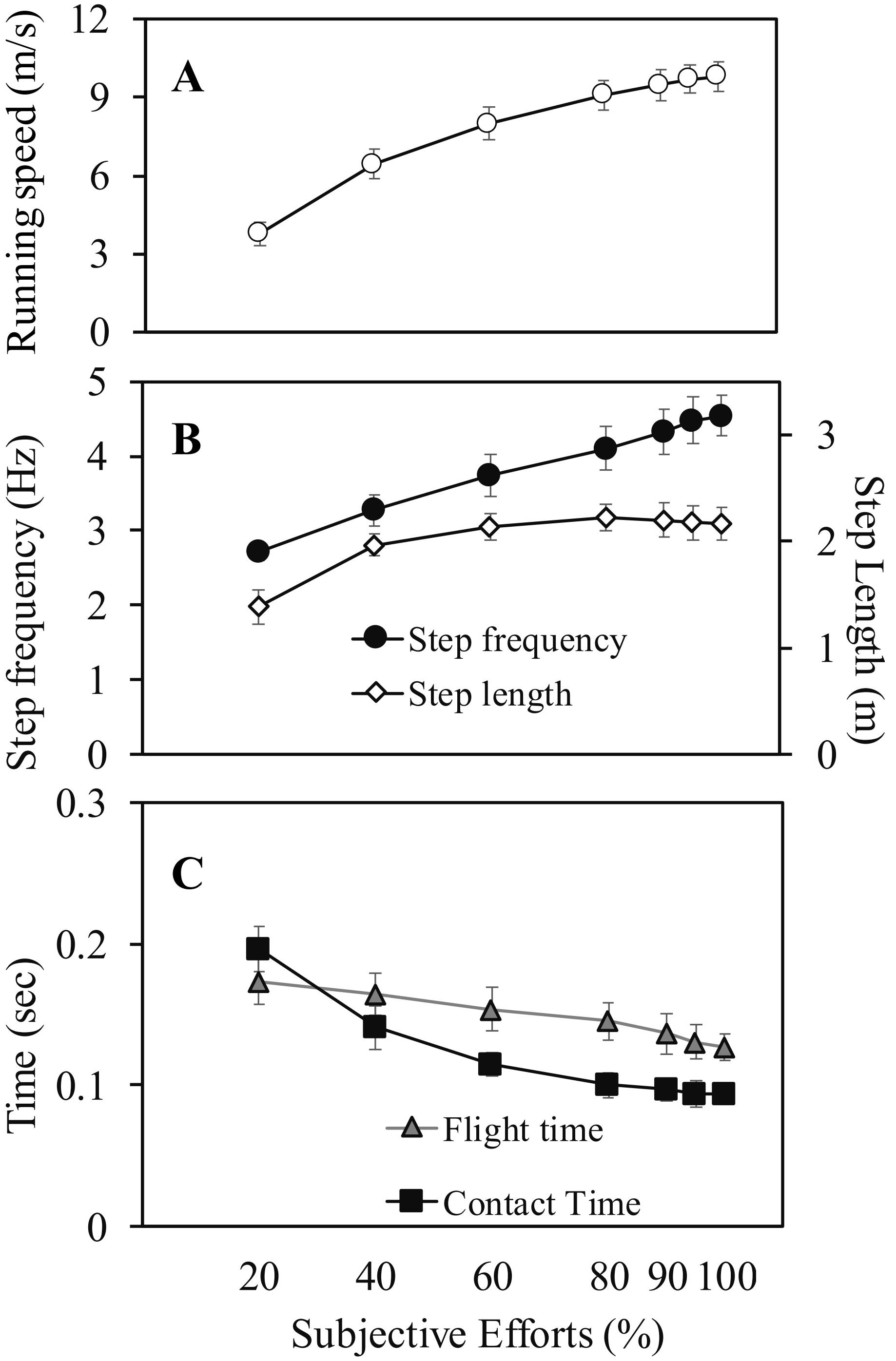

Figure 3-1. Spatiotemporal variables RS (A), SF, SL (B), FT, and CT (C) at seven different SEs.

EMG amplitudes (RMS)

Figure 3-2 shows the EMG waveforms (% MVC) at seven different SEs. I found that activity amplitudes (RMS) of three muscles were increased with SE. First, iRF was almost inactive at 20 % SE and slightly active at 40 % SE during the swing phase. After 60 % SE, iRF increased sharply and it was higher than 100 % MVC value after 80 % SE (9 $m \cdot s^{-1}$ >). Second, iBF showed two specific activities during the contact phase and late swing phase. On the other hand, cBF activated before the iRF and continued to be activated until after the iRF offset.

Figure 3-3 shows the RMS of three muscles at seven different SE levels. The horizontal axis indicates the contact phase, early swing phase, mid swing phase, and late swing phase, in this order.

Significant main effect of SE was observed in iRF ($F = 29.4$, $p < 0.001$, $ES = 0.634$). There was a significant difference in iRF between 20 % SE and more than 60 % SE in the early swing phase and mid swing phase. There was also a significant difference between 40 % SE and 60 % SE and more than 80 % SE in the early swing phase and mid swing phase. There was a significant difference between the late swing phase of 20 % SE and 40 % SE and more than 80 % SE. In addition, there were significant differences between 60 % SE and 95 % and 100 % SE.

Significant main effect of SE was observed in iBF ($F = 30.2$, $p < 0.001$, $ES = 0.640$). iBF was significantly different between 20 % SE and more than 40 % SE in the contact phase. There were significant differences between 20 % SE and higher SEs in the early swing phase, between 40 % SEs and 80 % SEs or higher, and between 60 % SEs and 90 % SE or higher SEs in the early swing phase. Furthermore, there was a significant difference between 20 % SE and 40 % SE in the late swing phase; 20 % SE and 40 % SE were significantly different from 60 % SE, respectively. However, there was no significant difference in the mid swing phase.

Significant main effect of SE was observed in cBF (*F* = 21.3, *p* < 0.001, *ES* = 0.556). cBF was significantly different 20 % SE and more than 40 % SE, and 40 % SE and more than 90 % SE in the early swing phase, mid swing phase, and late swing phase.

EMG onset and offset timings

Figure 3-4 shows the mean ± SD and statistics data of onset/offset timing in relative time (% running cycle) and absolute time (running cycle) of iRF, iBF, and cBF at seven different SE.

As regards the onset and offset timing in relative time, significant main effect of SE was observed in iRF-onset (*F* = 23.6, *p* < 0.001, *ES* = 0.581), iRF-offset (*F* = 33.2, *p* < 0.001, *ES* = 0.662), iBF-offset (*F* = 23.8, *p* < 0.001, *ES* = 0.584), iBF-onset (*F* = 7.2, *p* < 0.001, *ES* = 0.297), cBF-onset (*F* = 10.5, *p* < 0.001, *ES* = 0.382), and cBF-offset (*F* = 18.7, *p* < 0.001, *ES* = 0.524) (Table 3-4). Because twelve subjects had inactive for iRF in 20 % SE, I excepted iRF-onset/offset timings from statistics analysis.

Now for the absolute time for length of EMG activity (sec), significant main effect of SE was observed in iBF (Contact phase) (*F* = 5.4, *p* < 0.001, *ES* = 0.240), cBF (*F* = 3.0, *p* = 0.028, *ES* = 0.152), and iRF (*F* = 28.9, *p* < 0.001, *ES* = 0.629). In contrast, there was no significant main effect of SE in iBF (Swing phase) (*F* = 1.1, *p* = 0.361, *ES* = 0.060) (Table 3-4).

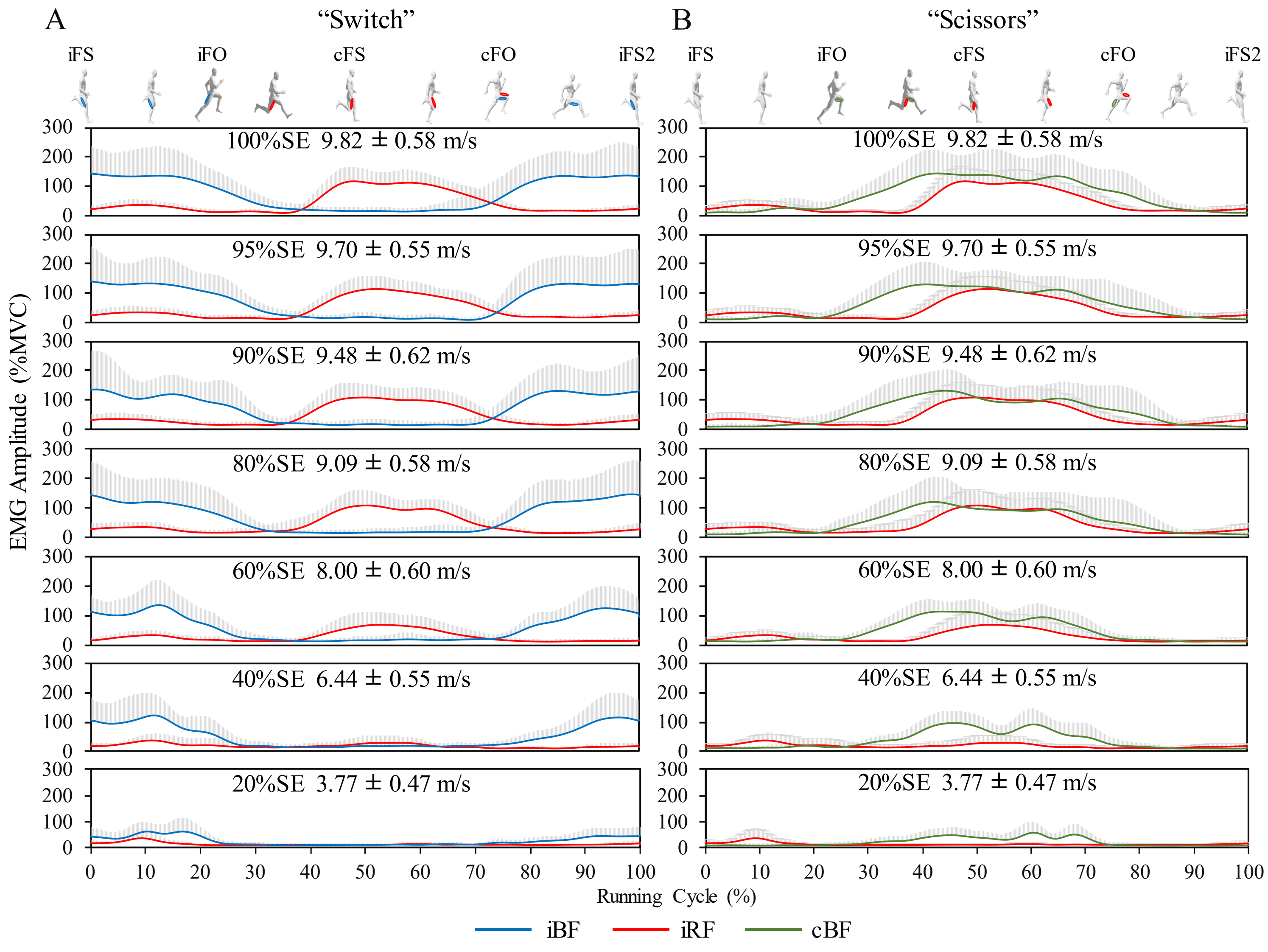

Figure 3-2. Mean EMG waveforms (% MVC) at seven different SEs in all subjects. Blue, red, and green lines indicate iBF, iRF, and cBF activities respectively.

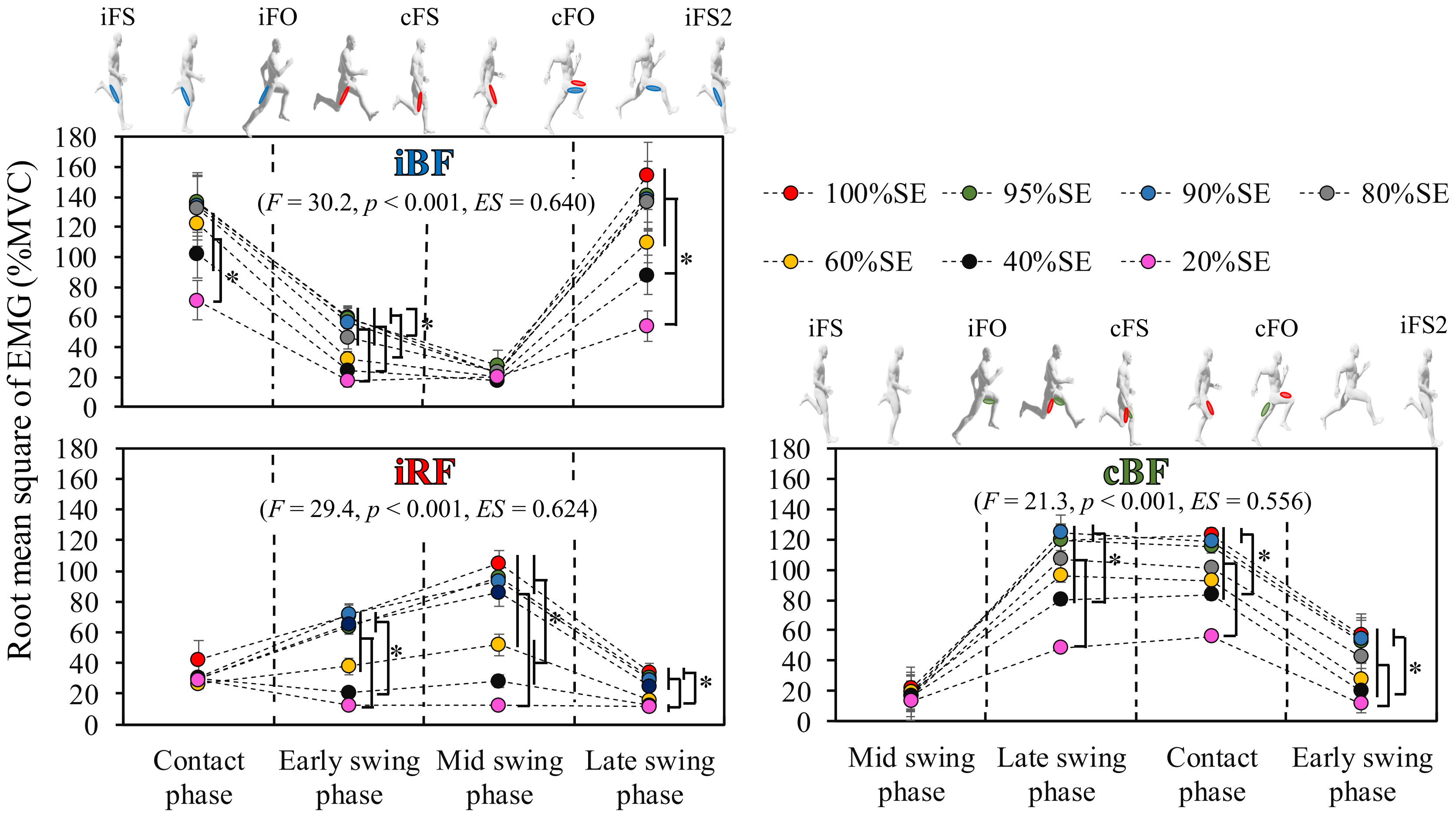

Figure 3-3. Root mean square of the EMG activity (% MVC) at seven different SEs. ✻significant difference was observed.

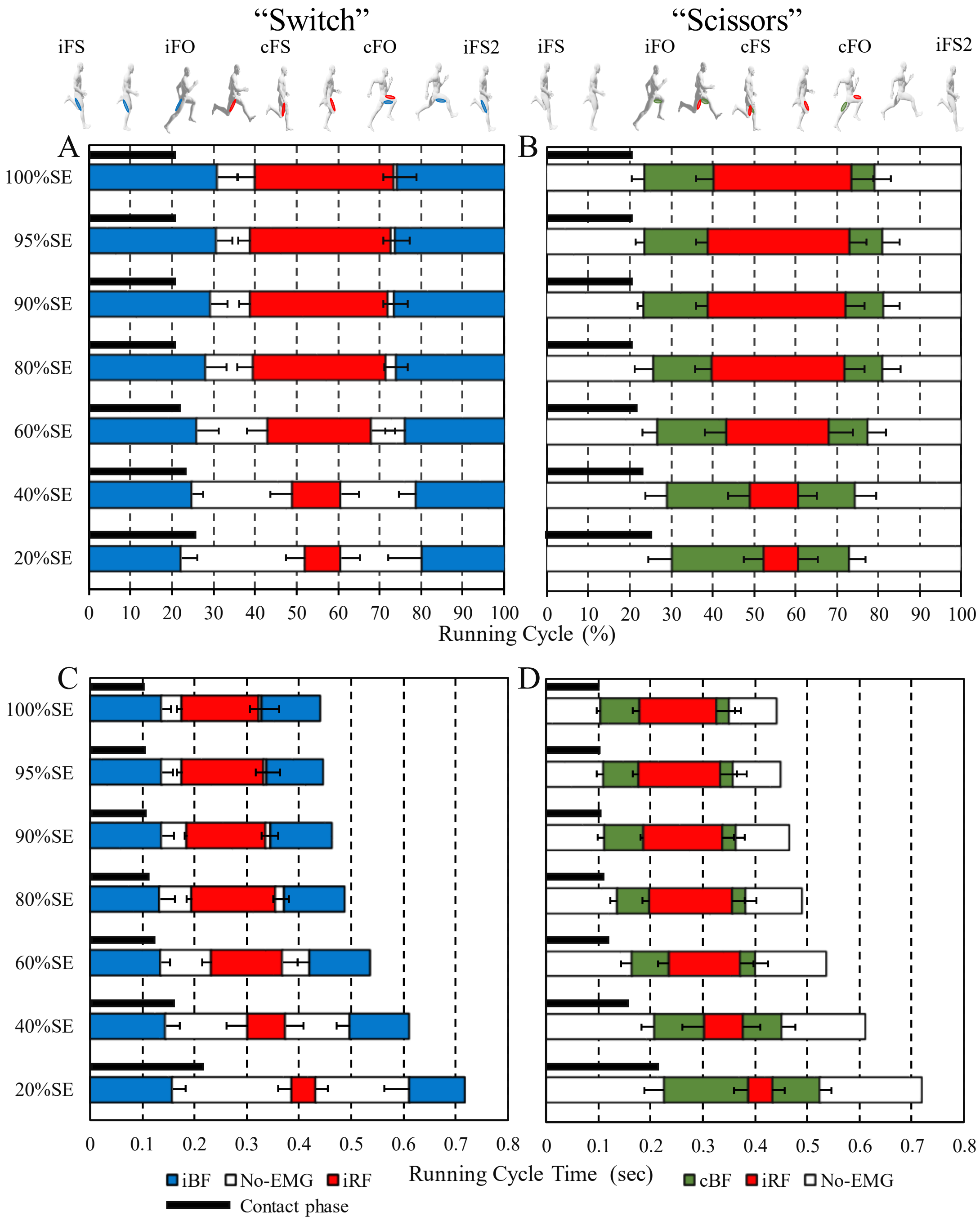

Figure 3-4. Relative timing of EMG onset / offset timings (A and B) and absolute time for length of EMG activity (C and D): (A and C) "Switch: iRF and iBF", and (B and D) "Scissors: iRF and cBF" in one running cycle. The top figures show the timings of foot strike (FS) and foot off (FO) of the ipsilateral (iFS and iFO) and contralateral (cFS and cFO) legs. (A) Blue and red indicate iBF and iRF activities respectively. White indicates the time when both muscles are inactive. Green indicates cBF activity. Note that iRF and cBF activation overlap. Black block indicates contact phase.

Table 3-4. Mean and SD of spatiotemporal variables, relative timing of EMG onset/offset and absolute time for length of EMG activity at seven different SE.

		20 % SE	40 % SE	60 % SE	80 % SE	90 % SE	95 % SE	100 % SE	P value	Main Effect F	Effect size partial η^2
Spatiotemporal variables Fig 3-1	Speed ($m \cdot s^{-1}$)	3.77 ± 0.47 ^{b,c,d,e,f,g}	6.44 ± 0.55 ^{a,c,d,e,f,g}	8.00 ± 0.60 ^{a,b,d,e,f,g}	9.09 ± 0.58 ^{a,b,c,e,f,g}	9.48 ± 0.62 ^{a,b,c,d,g}	9.70 ± 0.55 ^{a,b,c,d}	9.82 ± 0.58 ^{a,b,c,d,e}	< 0.001	457.4	0.964
	Step frequency (Hz)	2.71 ± 0.11 ^{b,c,d,e,f,g}	3.28 ± 0.21 ^{a,c,d,e,f,g}	3.74 ± 0.28 ^{a,b,d,e,f,g}	4.11 ± 0.29 ^{a,b,c,e,f,g}	4.32 ± 0.30 ^{a,b,c,d,f,g}	4.48 ± 0.31 ^{a,b,c,d,e}	4.54 ± 0.27 ^{a,b,c,d,e}	< 0.001	274.0	0.942
	Step length (m)	1.39 ± 0.16 ^{b,c,d,e,f,g}	1.96 ± 0.10 ^{a,c,d,e,f,g}	2.14 ± 0.13 ^{a,b,d}	2.22 ± 0.13 ^{a,b,c}	2.20 ± 0.16 ^{a,b}	2.17 ± 0.16 ^{a,b}	2.17 ± 0.16 ^{a,b}	< 0.001	142.0	0.893
	Contact Time (sec)	0.20 ± 0.02 ^{b,c,d,e,f,g}	0.14 ± 0.02 ^{a,c,d,e,f,g}	0.11 ± 0.01 ^{a,b,d,e,f,g}	0.10 ± 0.01 ^{a,b,c,f,g}	0.10 ± 0.01 ^{a,b,c}	0.09 ± 0.01 ^{a,b,c,d}	0.09 ± 0.01 ^{a,b,c,d}	< 0.001	328.4	0.951
	Flight Time (sec)	0.17 ± 0.02 ^{c,d,e,f,g}	0.17 ± 0.01 ^{d,e,f,g}	0.15 ± 0.02 ^{a,e,f,g}	0.14 ± 0.01 ^{a,b,e,f,g}	0.14 ± 0.01 ^{a,b,c,d,g}	0.13 ± 0.01 ^{a,b,c,d}	0.13 ± 0.01 ^{a,b,c,d,e}	< 0.001	49.9	0.746
Relative timing of EMG onset/offset (%) Fig 3-4 (A, B)	iRF-onset	52.2 ± 4.7	49.0 ± 5.3 ^{c,d,e,f,g}	43.2 ± 5.1 ^{b,d,e,f,g}	39.7 ± 3.9 ^{b,c}	38.9 ± 2.8 ^{b,c}	38.9 ± 2.9 ^{b,c}	40.3 ± 4.1 ^{b,c}	< 0.001	23.6	0.581
	iRF-offset	60.8 ± 4.6	60.7 ± 4.4 ^{c,d,e,f,g}	68.0 ± 5.8 ^{b,d,e,f,g}	71.7 ± 4.9 ^{b,c}	72.1 ± 4.6 ^{b,c}	72.8 ± 4.4 ^{b,c}	72.9 ± 4.3 ^{b,c}	< 0.001	33.2	0.662
	iBF-offset	22.4 ± 3.7 ^{b,c,d,e,f,g}	24.8 ± 2.6 ^{a,d,e,f,g}	26.1 ± 5.3 ^{a,d,e,f,g}	28.3 ± 4.9 ^{a,b,c,f,g}	29.4 ± 4.0 ^{a,b,c}	30.8 ± 3.8 ^{a,b,c,d}	31.1 ± 4.6 ^{a,b,c,d}	< 0.001	23.8	0.584
	iBF-onset	80.3 ± 8.1 ^{c,d,e,f,g}	78.9 ± 4.3 ^{c,d,e,f,g}	76.3 ± 4.9 ^{a,b}	74.2 ± 3.1 ^{a,b}	73.6 ± 2.8 ^{a,b}	74.0 ± 3.0 ^{a,b}	74.5 ± 3.6 ^{a,b}	< 0.001	7.2	0.297
	cBF-onset	30.2 ± 5.7	29.0 ± 5.2 ^{c,d,e,f,g}	26.6 ± 3.5 ^{b,e,f,g}	25.7 ± 4.6 ^{b}	23.4 ± 1.5 ^{b,c}	23.4 ± 2.1 ^{b,c}	23.5 ± 3.1 ^{b,c}	< 0.001	10.5	0.382
	cBF-offset	73.0 ± 3.9	74.4 ± 5.0 ^{c,d,e,f,g}	77.4 ± 4.6 ^{a,b,d,e,f}	80.9 ± 4.6 ^{a,b,c}	81.3 ± 3.8 ^{a,b,c,g}	81.0 ± 4.1 ^{a,b,c,g}	79.1 ± 4.0 ^{a,b,e,f}	< 0.001	18.7	0.524
Absolute time for length of EMG activity (sec) Fig 3-4 (C, D)	iBF (Contact phase)	0.164 ± 0.031	0.146 ± 0.025	0.136 ± 0.025	0.134 ± 0.031	0.138 ± 0.026	0.137 ± 0.022	0.138 ± 0.024	< 0.001	5.4	0.240
	iBF (Swing phase)	0.107 ± 0.040	0.115 ± 0.027	0.115 ± 0.009	0.117 ± 0.017	0.118 ± 0.015	0.108 ± 0.017	0.112 ± 0.020	0.361	1.1	0.060
	cBF	0.274 ± 0.042	0.244 ± 0.032	0.238 ± 0.034	0.245 ± 0.028	0.251 ± 0.035	0.247 ± 0.031	0.246 ± 0.021	0.028	3.0	0.152
	iRF	0.046 ± 0.021	0.074 ± 0.042	0.136 ± 0.038 ^{b}	0.159 ± 0.026 ^{b}	0.151 ± 0.024 ^{b}	0.156 ± 0.019 ^{b}	0.147 ± 0.020 ^{b}	< 0.001	28.9	0.629

[a] Significantly different from 20%SE (*P* <0.05).

[b] Significantly different from 40%SE (*P* <0.05).

[c] Significantly different from 60%SE (*P* <0.05).

[d] Significantly different from 80%SE (*P* <0.05).

[e] Significantly different from 90%SE (*P* <0.05).

[f] Significantly different from 95%SE (*P* <0.05).

[g] Significantly different from 100%SE (*P* <0.05).

Note that twelve subjects were inactive of iRF in 20 % SE. iRF variables in 20 % SE were excected from statistics analysis

EMG activity (“Switch” and “Scissors”)

Figure 3-5 shows the length of the “Switch” and “Scissors” at seven different SEs. The left figures show the “Switch”, and the right figures show the “Scissors”. First, the significant main effects of SE were observed in “Switch1” ($F = 42.41$, $p < 0.001$, $ES = 0.714$) and “Switch2” ($F = 43.72$, $p < 0.001$, $ES = 0.720$). “Swicth1” and “Swicth2” were significantly different between 40 % SE and 80-100 % SEs, also 60 % SE and 80-100 % SEs. Next, Significant main effect of SE was observed in “Scissors1” ($F = 4.6$, $p = 0.007$, $ES = 0.213$), and “Scissors2” ($F = 7.1$, $p < 0.001$, $ES = 0.293$). “Scissors1” was significantly different between 40 % SE and 80-100 % SE. For “Scissors2”, 100 % SE was significantly shorter than the other five trials. Note that twelve subjects showed no RF activity at 20 % SE. Therefore, 20 % SE was excluded from the statistical analysis.

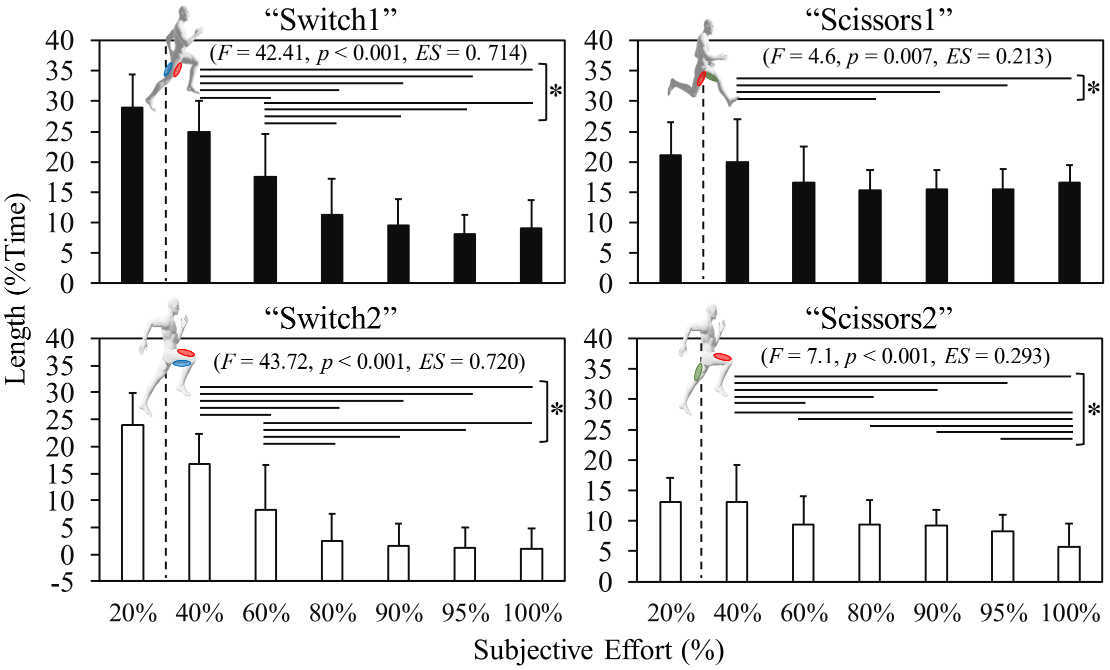

Figure 3-5. Length of the "Switch" and "Scissors" at seven different SEs. ✻ significant difference was observed.

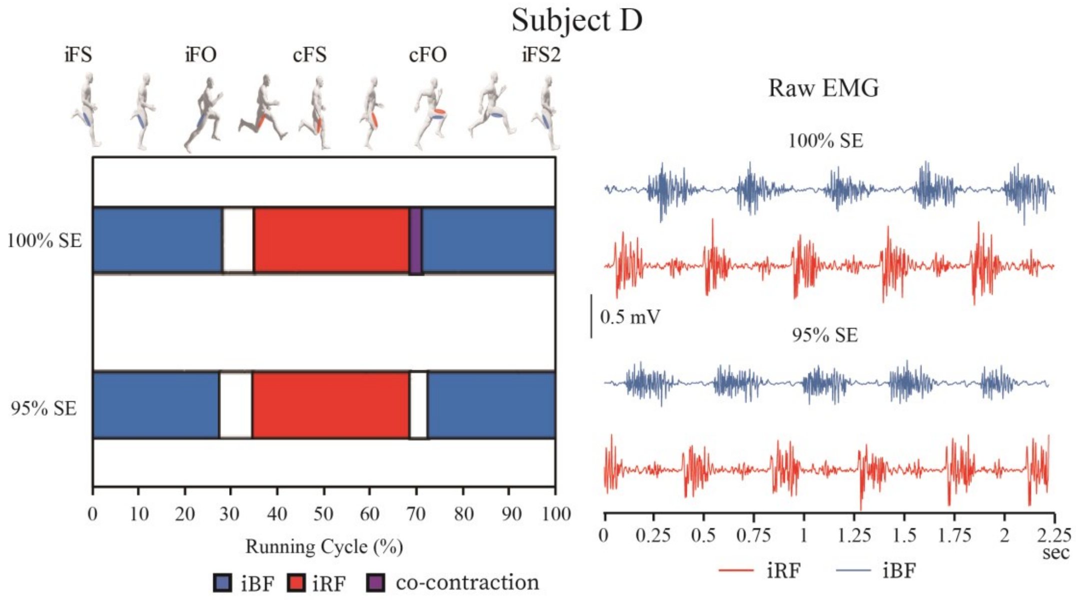

Figure 3-6. Example (Subject D) of raw EMG and onset/ offset timing of iRF and iBF at 95 % SE and 100 % SE.

3-4 Discussion

When SE increased, RS increased with a significant increase in SF as observed in the previous study (Kakehata et al., 2020). In contrast, while SL also increased significantly up to 80 % SE, in rather decreased with the increase in SE above 80 % SE, although insignificant. In other words, SE is closely associated with SF in the higher speed range, which corresponded well to the result in the previous study (Kakehata et al., 2020) (Fig. 3-1).

The increase in RS is acquired by SF increase at high-speed range (Dorn et al., 2012; Mercer et al., 2002; Yanai & Hay, 2004). Thus, SF is important for the acquisition of high RS. Previous studies have shown that at speeds higher than 7 $m{\cdot}s^{-1}$, hip flexion and extension torque increase sharply (Dorn et al., 2012; Schache et al., 2015). Thus, the functions of the hip extensors and flexors are particularly important in achieving high RS. The hip flexion torque is generated by the thigh muscles such as RF, psoas major, sartorius, and iliacus muscles. A previous study showed that sprinters had greater thigh muscle volumes of the hip flexors and extensors and psoas major than novice (Ema, Sakaguchi, & Kawakami, 2018). Moreover, only the RF volume was significantly correlated with the center of gravity speed and peak hip flexion moment for the swing leg. In this study, I also focused on RF, which is the major agonist for the hip flexor muscles (Ema et al., 2018). The RMS of iRF during the swing phase was negligible at 20 % SE (3.77 m·s^{-1}) (Fig. 3-3). Moreover, there were twelve subjects with no iRF activity during the swing phase as a result of the threshold set by the TKEO filter. The RMS of iRF in the early swing phase and mid swing phase increased after 40 % SE (6.44 m·s^{-1}) and 60 % SE (8.00 m·s^{-1}). Interestingly, the activity of iRF further increased sharply from 80 % SE above 9 m·s^{-1} (Fig. 3-2). These results suggest that the iRF activity in the swing phase should be emphasized in order to increase the swing speed of the legs at higher RS (> 9 m·s^{-1}). In addition, hip extensor muscles play an important role in producing the horizontal component of the GRF during sprinting on a treadmill (Morin, Gimenez, et al., 2015). Moreover, subjects with a large horizontal component of the GRF showed high EMG activity of the BF prior to ground contact (Morin, Gimenez, et al., 2015). Our results also showed high EMG activity of the BF during the late swing phase (Fig. 3-2). Therefore, higher BF activity is needed to increase hip extend torque in higher RS.

With increasing SE, the relative length of muscle activation (from onset to offset timing) significantly changed (Figs. 3-4 A, B, and Table 3-4). On the other hand, the absolute time for the length of EMG activity changed only in RF (Figs. 3-4 C, D, and Table 3-4). The SF continued to increase from 80 % SE to 100 % SE (Fig. 3-1). Therefore, the sprinter has required the control ability that switches between agonist and antagonist muscle activity in more limited time during high RS (i.e., SF).

Length of “Switch1” and “Switch2” were significantly shorter at high SEs as compared with those at 40 % and 60 % SE (Fig. 3-5). Since “Switch” is the time difference between the onset/offset timing of the agonist and antagonist muscle. Therefore, “Switch” can be regarded as an indicator of the “relaxation” of muscle activity. As the SE increases, the running cycle time becomes shorter and the relative length of RF and BF activity increases with increasing SE (Figs. 3-3 and 3-4). As a result, co-contraction occurs during the late swing phase at higher SE, it means that the “relaxation” time decreases (Fig. 3-5).

Co-contraction of RF and BF is effective for hip and knee joint stiffness during the contact phase (Pinniger et al., 2000). However, it would be expected to be disadvantageous for quick leg swing movements during the swing phase. In the present study, subjects were forced to adjust their RS based on a “subjective effort (SE)” scales, leading to a discrepancy between SE and RS (objective performance) in several subjects (Subject D, F, I, J, and P, Table 3-1). SE was mainly controlled by SF. However, subject D, I, and P achieved higher SF at 95 % SE (Table 3-2) and had faster RS as well at 95 % SE (Table 3-1). At the high SE increased, these athletes may disrupt the coordination of proper timing of muscle contraction and relaxation, leading to excessive co-contraction and consequently inducing performance decline. Therefore, I showed the raw EMG waveforms of iRF and iBF and the timing of muscle activity for subject D (Fig. 3-6). It is possible that an athlete such as subject D, whose contraction-relaxation coordination is more optimal in sub-maximal SE than in maximal SE, may be able to achieve higher running performance (RS) at a sub-maximal SE. The previous study also demonstrated the sprinting with sub-maximal SE (90 % SE or more) may lead to the best performance, because the optimal combination of the SF & SL is different among individual (Kakehata et al., 2020). Likewise, the optimal timing of muscle activity timing would also depend on individual differences, furthermore, this would affect the sprinting performance. Similar to "Switch", "Scissors1" and "Scissors2" at 80-100 % SEs were also significantly shorter than at 40 % SE (Fig. 3-5). This was probably due to the increased relative time (onset/offset timing) as well as absolute time that the RF was active for hip flexion (Fig. 3-4). A previous study also showed that the onset timing of RF activity was earlier at a speed of 6.0 $m{\cdot}s^{-1}$ than at lower speeds of 1.5 to 5.0 $m{\cdot}s^{-1}$ (Andersson et al., 1997). The present study recorded greater RF activity at even higher RS (9 $m{\cdot}s^{-1}$). Present results suggest that RF act as a trigger for high-speed sprinting. Furthermore, interestingly, "Scissors2" was significantly shorter at 100 % SE (Fig. 3-5). One possible explanation for this is that the emphasis on hip flexion, i.e. the recovery of the leg swing, in 100 %

SE resulted in a longer duration of RF activity during the late swing phase, which resulted in a shorter “Scissors2” time in the late swing phase.

Furthermore, this long RF activity may have also affected the co-contraction with BF (“Switch2”). A clear “Switch” would need to achieve a good interaction between onset and offset, i.e., contraction and relaxation. Previous research indicated that muscle relaxation is an active process requiring a cortical activation similar to or even greater and more widespread than that of muscle contraction (Toma et al., 1999). In addition, the muscle relaxation in one limb suppressed muscle activity in the other limbs (Kato, Muraoka, Higuchi, Mizuguchi, & Kanosue, 2014; Kato, Watanabe, Muraoka, & Kanosue, 2015; Kato, Watanabe, & Kanosue, 2015). Moreover, novice badminton players showed continuous, unnecessarily high contractions of the triceps brachii when they swung a racket, whereas skilled players exhibited minimal unnecessary contractions (Sakurai & Ohtsuki, 2000). Therefore, athletes should consider the techniques for achieving high running performance, not only in terms of strong muscle activation but also in terms of active relaxation. In conclusion, it can be said that RF activity, that is., both timings and amplitudes are essential to accentuate hip flexion, especially at high RS (9 $m\cdot s^{-1}$>). However, too long RF activity may interfere with BF activity during the late swing phase, deteriorating running performance.

3-5 Conclusion

This chapter showed that SE reflects on the change in SF as well as RS, which was achieved by varying the timing and amplitudes (RMS) of RF activity. At higher speed sprinting stronger muscle activity (RMS) in both RF and BF were observed, which would produce stronger hip extension and flexion. Although the strong activity of RF is required at high RS, too long activation of the RF may induce co-contraction in the late swing phase, which may inhibit performance. In conclusion, athletes should consider the techniques for achieving high running performance, not only in terms of strong muscle activation, but also in terms of active relaxation.

Chapter 4

Timing of Rectus Femoris and Biceps Femoris Muscle Activities in Both Legs in 100-m dash.

4-1 Introduction

Although the 100-m dash is the shortest sprint race in track events, the race can be divided into 3 phases (acceleration phase, maximal speed [Max] phase and deceleration [Dec] phase) based on the distance-speed relationship (Ae et al., 1992). First, RS increases dramatically after the start in the acceleration phase (Ae et al., 1992; Bae et al., 2011; Bissas et al., 2017). Then, RS reaches maximum in the Max phase of 50-70 m section among world elite sprinters (Ae et al., 1992; Bae et al., 2011; Bissas et al., 2017). Interestingly, the maximum RS cannot be maintained long enough, and RS gradually decreases towards the finish (the Dec phase) (Ae et al., 1992; Bae et al., 2011; Bissas et al., 2017). Indeed, official race analysis of men's 100-m dash in the 2009 World Championships reported that all sprinters (i.e., 119 race data) showed deceleration in the final part (80-100 m section) of the race compare to the 40-60 m or 60-80 m section (Hommel et al., 2012). Even when Usain Bolt won the final with the current world-record of 9.58 seconds, he reached maximal RS of 12.29 $m\cdot s^{-1}$ in the 60-70 m section, and the speed decreased down to 11.96 $m \cdot s^{-1}$ in the final section (90-100 m) (Graubner & Nixdorf, 2011).

The main factor determining the record of 100-m dash is of course the maximal RS (Healy et al., 2019; Slawinski et al., 2017), and many sprint trainings focus on how to improve the maximal RS (Haugen, Seiler, et al., 2019; IAAF, 2009). It is, however, also important for running 100-m fast to make the decrease in RS in the Dec phase as small as possible. Then, what happens in the Dec phase? In the world record race, Bolt showed SF of 4.49 Hz at 60-80 m section, whereas it decreased to 4.23 Hz at 80-100 m section (Hommel et al., 2012). On the other hand, SL became longer at 80-100 m section (2.85 m) than that at 60-80 m section (2.77 m) (Hommel et al., 2012). Six other finalists of the same race also showed decreases in SF in the final part of the race (Hommel et al., 2012). Therefore, a decrease in RS in the Dec phase is inevitable even in the world class sprinters, and it would be due to a decrease in SF. Hence, to lessen the inevitable decrease in RS in the Dec phase, sprinters should maintain the SF as high as possible.

Previous study summarized the various factors determining the SF, such as muscle contraction rate, muscle recruitment, fatigue, and running movement technique (i.e., recovery mechanics) (Ross et al., 2001) (Fig. 1-8 in Chapter 1). Endo, Miyashita, and Ogata (2008) investigated changes in the lower extremity movements in the Max phase

(50 m) and the Dec phase (85 m) of the maximal effort sprinting, they found that both RS (50 m : 10.14 $m{\cdot}s^{-1}$ vs 85 m : 9.90 $m{\cdot}s^{-1}$) and SF (50 m : 4.58 Hz vs 85 m : 4.40 Hz) decreased in the Dec phase. Moreover, the hip flexion power also decreased in the Dec phase, accompanying delayed the timing of the hip flexion torque and the onset of negative power exertion (Endo et al., 2008). These results presume the difference of the running movement (i.e., muscle activity timings) would cause the decreasing SF in the Dec phase.

Various factors influence the SF (Ross et al., 2001). Previous studies indicate that timing of thigh muscle activity is associated with SF (Andersson et al., 1997; Chumanov, Wille, Michalski, & Heiderscheit, 2012; Kakehata, Goto, et al., 2020) . Chumanov, Wille, et al. (2012) reported that the onset of RF activity occurred earlier in the running with an intentional 5-10 % greater SF than the running with preferred SF. Moreover, the greater the RS and SF, the earlier the onset of the RF (Andersson et al., 1997). The RF sustains the impact at the ground contact (Nummela et al., 1994), whereas in the swing phase RF has a primal role in hip flexion to swing the thigh forward rather than in knee extension (Mero & Komi, 1987). On the other hand, BF one of the antagonist muscles of the RF, shows strong activity with hip joint extension in the late swing and the contact phases to obtain greater ground reaction forces (Mero & Komi, 1987; Mero et al., 1992; Morin, Gimenez, et al., 2015; Nummela et al., 1994). Similarly to the RF, the onset of BF also occurs earlier in running with higher SF running (Chumanov, Wille, et al., 2012). Therefore, the timings of thigh muscle activity would be important to determine the SF.

We have recently demonstrated that timing of the RF and BF activities influence the SF at the maximal RS (30-50 m section) (Kakehata, Goto, et al., 2020). In particular, i) the earlier the RF activity timing in a running cycle, the higher the SF, and ii) inter-leg muscle activity timings, that is, time difference between the RF activity in the swing leg and the BF activity in the contact leg significantly correlated with SF. Moreover, iii) it is important for accomplish switching between hip flexion (RF) and hip extension (BF) in same leg clearly during at the late swing phase to obtain higher SF (Kakehata, Goto, et al., 2020).

Since the SF is affected by the timing of thigh activity (Andersson et al., 1997; Chumanov, Wille, et al., 2012; Kakehata, Goto, et al., 2020), the decrease in SF occurring in the Dec phase would be related to the timing of thigh muscle activity. Hence, the purpose of this study was to analyze the changes in EMG activity timings of the RF and BF in both legs together with spatiotemporal variables (RS, SF, and SL) in the Max and the Dec phases of 100 m dash. Since there has been no study that recorded muscle activity throughout the entire 100-m, I first challenged this and succeeded in clear recording (Fig.

4-3). I had three hypotheses that decrease SF in Dec phase would be caused changing EMG activity timings. i) the activity timing of RF in a running cycle would be delayed in the Dec phase, because hip flexion and onset of negative power exertion was delayed in Dec phase (Endo et al., 2008), ii) inter-leg muscular coordination; that is, time difference between the RF activity in the swing leg and the contralateral BF activity in the contact leg would be changed in the Dec phase, and iii) agonist-antagonist muscle coordination; that is, time length of the switching between hip flexion muscle (RF) activity and hip extension muscle (BF) activity in the same leg would be changed in the Dec phase.

4-2 Methods

Ten male well-trained Japanese Track & Field athletes (World Athletics [WA] Score: 1030.3 ± 73.2 pts, height: 1.75 ± 0.05 m, body mass: 67.3 ± 2.9 kg, age: 20.3 ± 1.2 years) volunteered to participate in the study (Table 4-1). Note that the 1030 points are equivalent to a record of 10.53 sec in the men's 100 meters. The participating athletes specialized in the 100 meters, 200 meters, 400 meters, 400 meters hurdles, and pole vault events.

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.

Table 4-1. Individual data and measured 100-m time.

Subject	Event	Personal best	WA Score (Points)	Age (yr)	Height (m)	Body mass (kg)	Measured 100m time(s)
A	400mH	50.79	1087	22	1.80	70	11.32
B	100m	10.83	937	21	1.69	64	11.41
C	100m	10.72	971	20	1.71	65	11.54
D	PV	4.70	894	21	1.72	66	11.51
E	400m	45.79	1126	21	1.67	67	10.85
F	200m	21.00	1068	21	1.82	72	10.95
G	200m	20.96	1073	20	1.75	63	11.08
H	100m	10.43	1063	20	1.71	69	10.88
I	200m	21.28	1027	19	1.82	70	10.80
J	200m	21.07	1057	18	1.76	67	11.26
		mean	1030.3	20.3	1.75	67.3	11.16
		SD	73.2	1.2	0.05	2.9	0.28

Procedure

After a self-selected warm-up, subjects ran one 100-m sprint with the maximal effort from a crouching start with a starting block (NF155B, NISHI, Japan) in the straight lane of an official 400 m track. The subject started to run on a signal with the sound of a track and field starting pistol (NG5085B, NISHI, Japan).

Data collection

Surface muscle EMG data were sampled at 2000 Hz using wireless EMG sensors (Trigno Wireless Sensor, Delsys, USA). A portable wireless data logger (Trigno Personal Monitor, Delsys, USA) was attached to the subject's lower back to record EMG for the entire 100-m (Fig. 4-1). 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 inter-electrode impedance. EMG signals for the four muscles were checked after placing the electrodes. In order to eliminate the influence of motion artifact as much as possible, the EMG sensors were fixed with surgical tape and under wrap tape (Fig. 2-2). Two panning high-speed cameras (LUMIX DMC FZ-300, Panasonic, Japan) were used to determine the moments of FS and FO from the side of the running track at 240 Hz. Then, Camera 1 was used to record the 0-50 m section, also camera 2 was used to record the 50-100 m section. Before starting the trial, in order to synchronize the FS and FO timing with the EMG data, the flash of the wireless all-around light presenter (Synchronizer, DKH, Japan) was recorded with the video cameras. The EMG data and the signal of the synchronization device were fed into an analyzed software program (EMGworks®, Delsys, USA).

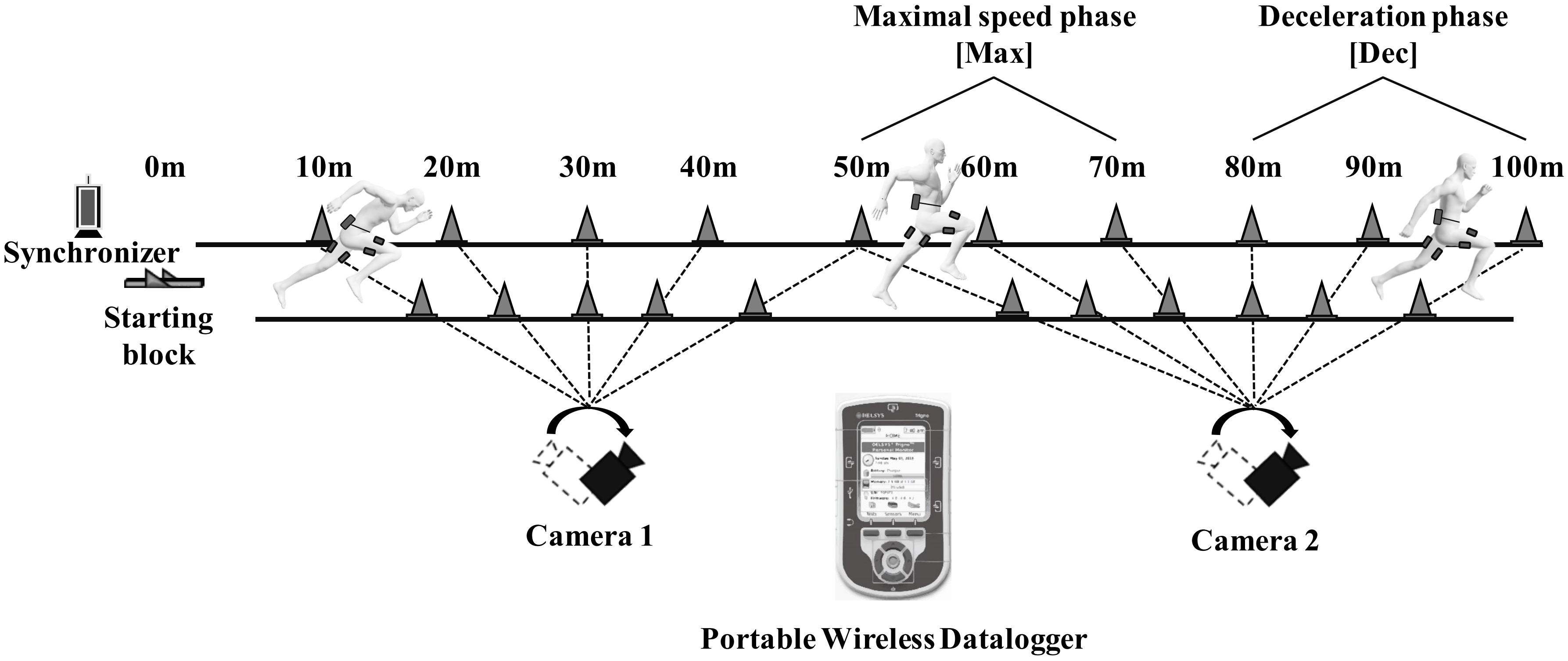

Figure 4-1. Schematic diagram of the experimental set up in Chapter 4.

Data processing

Spatiotemporal variables

RS ($m \cdot s^{-1}$), SF (Hz), SL (m), CT (sec), and FT (sec) were calculated for each 10 m section as noted in Chapters 1 and 2. Based on the result of the distance-speed relationship (Fig. 4-2. A), since all subject reached maximal RS during the 50-70 m section, I defined the Max phase (50-70 m section) and the Dec phase (80-100 m section), respectively (Fig. 4-1). I obtained mean spatiotemporal variables in two phases (Max and Dec).

EMG variables

Normalized onset and offset timings of iRF, iBF and cBF in the running cycle (%) and “Switch1”, “Switch2”, “Scissors1”, and “Scissors2” (%) were calculated for two phases (Max and Dec) used identical methods in Chapter 1 and 2.

Statistical analysis

A paired-sampled t-test was used to determine the difference between the two phases (Max vs Dec). The ES (Cohen’s *d* value) was calculated to show the practical difference between phases. I set practical significance value as trivial (< 0.19), small

(0.20-0.59), moderate (0.60-1.19), large (1.20-1.99), and very large (2.0-4.0) based on a previous study (Hopkins, Marshall, Batterham, & Hanin, 2009). All statistical analyses were performed using statistical processing software (SPSS ver.25, IBM, USA). I set a significance level of 0.05.

4-3 Results

Spatiotemporal variables

Measured 100-m time was 11.16 ± 0.28 sec (Table 4-1). Figure 4-2 showed spatiotemporal variables during 100-m dash. RS increased sharply after the start and it reached maximal (10.29 ± 0.20 $m \cdot s^{-1}$) at 50-60 m section (Fig. 4-2 A). After that, RS gradually decreased toward the finish (9.96 ± 0.23 $m \cdot s^{-1}$ at 90-100 m section). SF already reached 4.5 Hz at 0-10 m section and it also peaked at 10-20 m section (4.67 ± 0.09 Hz). SF was also gradually decreased toward the finish (Fig. 4-2 B). On the other hand, SL and FT were gradually increased toward the finish (Fig. 4-2 B and C), whereas CT was decreased sharply after 10-20 m section and it minimized at 40-50 m section (0.091 ± 0.007 sec) (Fig. 4-2 C). Table 4-2 showed mean and SD of the spatiotemporal variables and EMG variables in the Max phase and the Dec phase. RS, SF, and CT were significantly decreased in Dec (RS: $p < 0.001$, $d = 0.86$, SF: $p < 0.001$, $d = 0.75$, FT: $p = 0.001$, $d = 0.77$). In contrast, SL and FT were not significantly difference between phases (SL: $p = 0.161$, $d = 0.15$, CT: $p = 0.100$, $d = 0.26$).

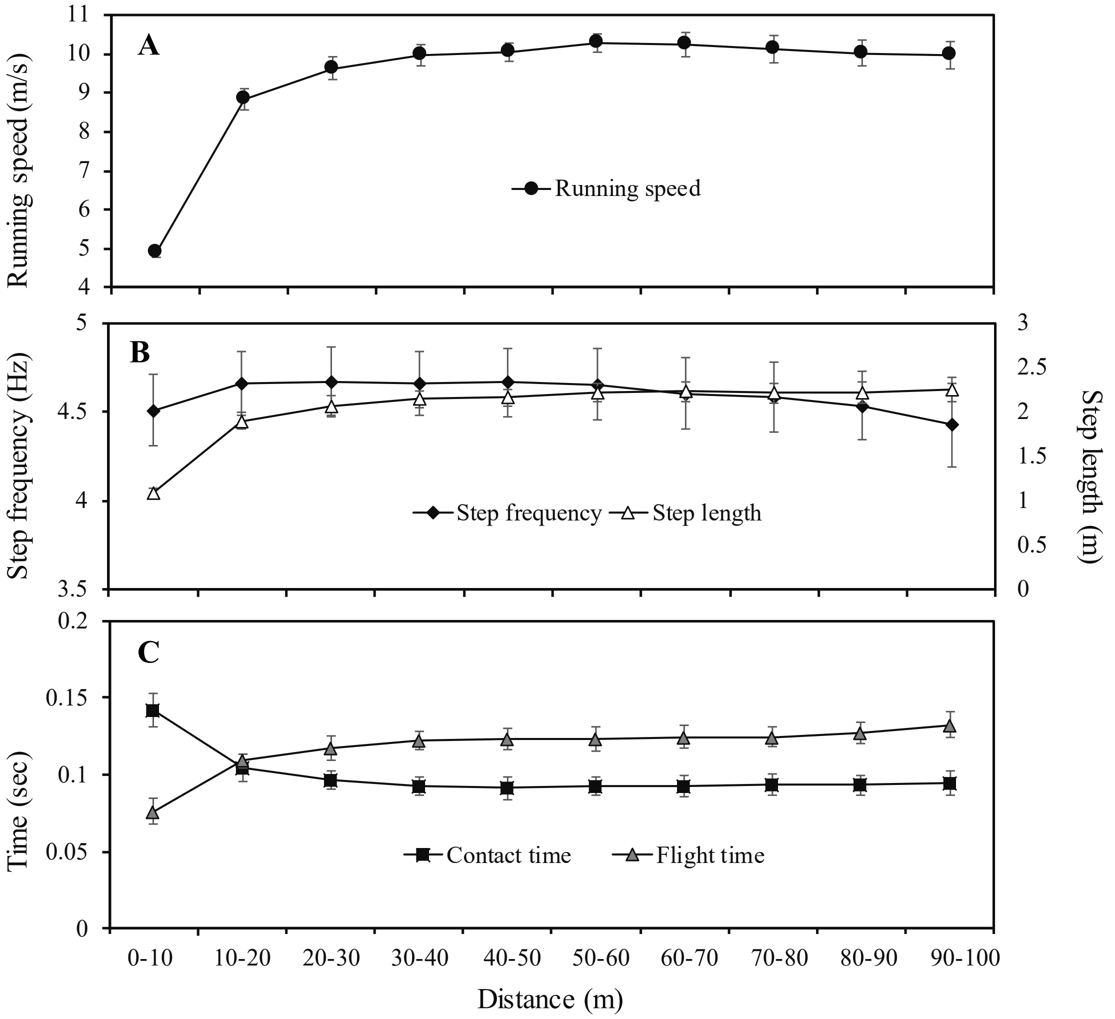

Figure 4-2. Mean and SD of the spatiotemporal variables during 100-m dash. (A) RS, (B) SF, SL, and (C) CT and FT.

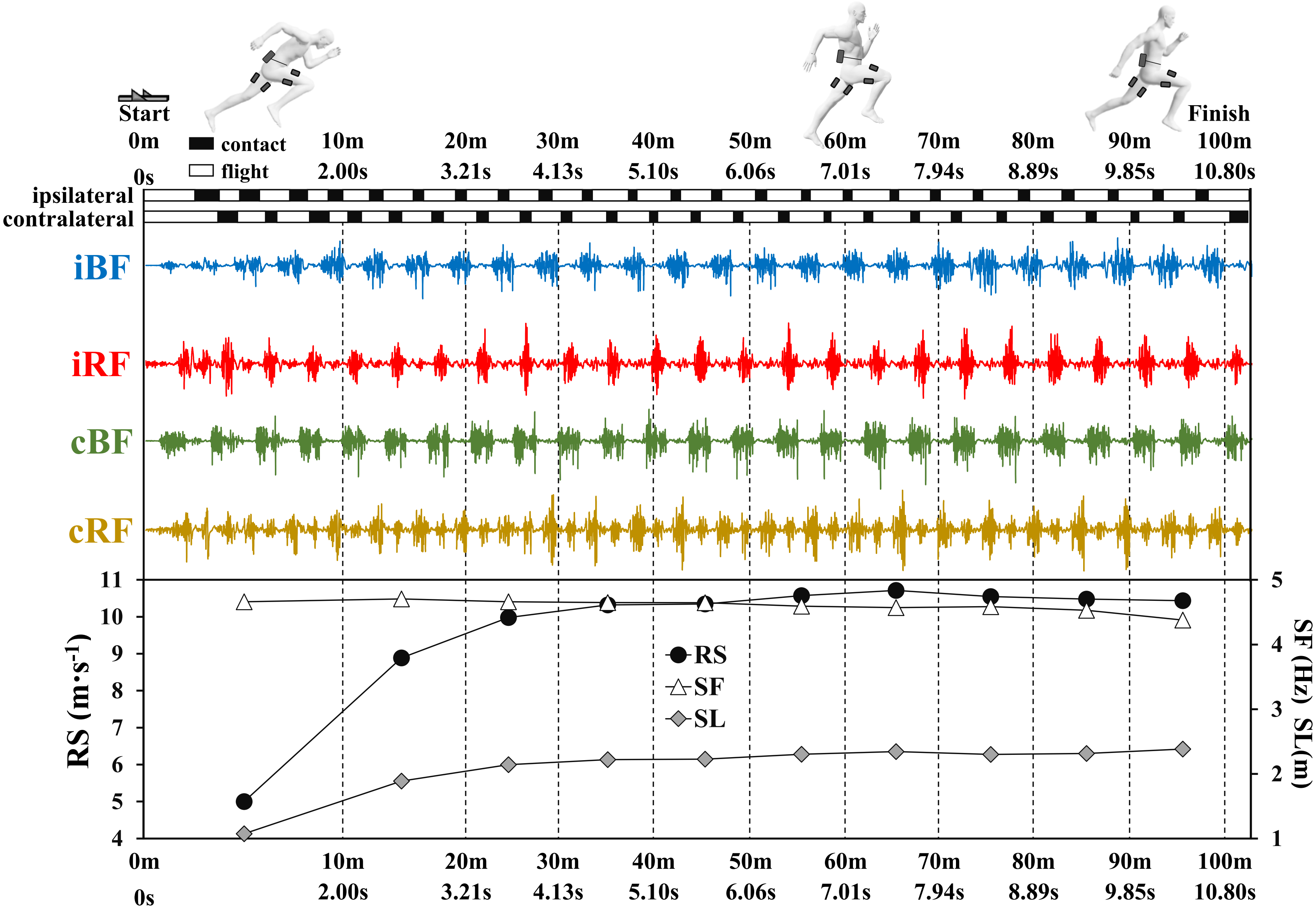

Figure 4-3. Example of the four muscle raw EMG signals and spatiotemporal variables during 100-m dash in the fastest subject (Subject B). Black and white block indicates contact and flight phase. Blue, red, green, and gold indicate iBF, iRF, cBF, and cRF activities respectively.

Table 4-2. Spatiotemporal and EMG variables (Mean ± SD) difference between Max and Dec phases.

	Max (50-70m)			Dec (80-100m)			Paired-T		Effect size
Variables	Mean		SD	Mean		SD	*p*		Cohen's *d*
Spatiotemporal variables									
Speed (m/s)	10.26	±	0.28	9.99	±	0.34	**< 0.001**	*	0.86 ‡
Step frequency (Hz)	4.63	±	0.20	4.48	±	0.21	**< 0.001**	*	0.75 ‡
Step length (m)	2.22	±	0.10	2.23	±	0.12	0.161		0.15
Contact Time (sec)	0.092	±	0.006	0.094	±	0.007	0.100		0.26 †
Flight Time (sec)	0.124	±	0.008	0.130	±	0.007	**0.001**	*	0.77 ‡
EMG variables									
iRF-onset (%)	37.3	±	2.6	40.5	±	6.0	**0.024**	*	0.70 ‡
iRF-offset (%)	72.7	±	3.5	75.5	±	4.3	**0.020**	*	0.70 ‡
iBF-offset (%)	28.3	±	4.5	32.2	±	5.3	**0.047**	*	0.79 ‡
iBF-onset (%)	73.8	±	1.6	75.4	±	4.6	0.301		0.47 †
cBF-onset (%)	22.5	±	1.3	24.9	±	3.4	0.096		0.91 ‡
cBF-offset (%)	78.7	±	4.6	82.2	±	4.1	**0.015**	*	0.83 ‡
"Switch1" (%)	9.0	±	5.3	8.3	±	5.5	0.647		0.12
"Switch2" (%)	1.0	±	4.0	-0.1	±	4.7	0.214		0.26 †
"Scissors1" (%)	14.8	±	3.4	15.6	±	2.9	**0.048**	*	0.27 †
"Scissors2" (%)	5.9	±	4.4	6.8	±	4.4	0.578		0.19

† Small effect size (0.20-0.59)

‡ Moderate effect size (0.60-1.19)

EMG variables

Raw EMG signals of four muscle (RF and BF in both legs) and lap times every 10 m as well as chronological change of the RS, SF, and SL during the entire 100-m dash in the fastest subject (subject B) was show in Figure 4-3. Relative activation timings (%) and actual averaged EMG waveforms (% Maximal EMG amplitude) of the ipsilateral leg (i.e., iRF and iBF) and both legs (i.e., iRF and cBF) of all individual data and mean ± SD were presented in Figure 4-4 and Figure 4-5. Moreover, Figure 4-6 shows the onset/offset timings to compare between Max and Dec phases. Note that it was based on identical data as Figures 4-4 and 4-5. As for the iBF and iRF activity of the ipsilateral leg (Fig. 4-3), the iBF continued to be active until 28.3 ± 4.5 % (Max phase) vs 32.2 ± 5.3 % (Dec phase). 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 the early swing phase (Max: 37.3 ± 2.6 % vs Dec: 40.5 ± 6.0 %) to late swing phase (Max: 72.7 ± 3.5 % vs Dec: 75.5 ± 4.3 %). Then, toward the iFS2 (100 %), iBF began to become active again at the late swing phase (Max: 73.8 ± 1.6 % vs Dec: 75.4 ± 4.6 %). Four subjects (A, B, F, and H) iRF and iBF showed co-contraction (negative “Switch2” values) in Max, whereas six subjects (A, B, F, G, H, and I) showed it in Dec phase. This mean that the iBF became active before the iRF finished its activity, while the remaining subjects showed clear switching from the iRF to the iBF (positive “Switch2” values).

Regarding iRF and cBF activity in both legs (Fig. 4-5), the contralateral contacting leg BF (cBF) were active during a wider phase both in Max phase (22.5 ± 1.3 % to 78.7 ± 4.6 %) and Dec phase (24.9 ± 3.4 % to 82.2 ± 4.1 %) than the ipsilateral swinging iRF activities in Max and Dec phases. However, only subject D showed later iRF-offset than cBF-offset. Therefore, the cBF always activated before the iRF, and continued activation until after iRF termination in the Max, similar feature also observed in the Dec phase.

Figure 4-6 illustrated comparing the onset/offset timings between Max and Dec phases. Significantly differences were observed in iRF-onset (p = 0.024, d = 0.70), iRF-offset (p = 0.020, d = 0.70), iBF-offset (p = 0.047, d = 0.79), and cBF-offset (p = 0.015, d = 0.83). Moreover, significant difference was observed in “Scissors1” (p = 0.048, d = 0.27), whereas there was no significant different “Switch1” (p = 0.647, d = 0.12), “Switch2” (p = 0.214, d = 0.26), and “Scissors2” (p = 0.578, d = 0.19, Table 4-2).

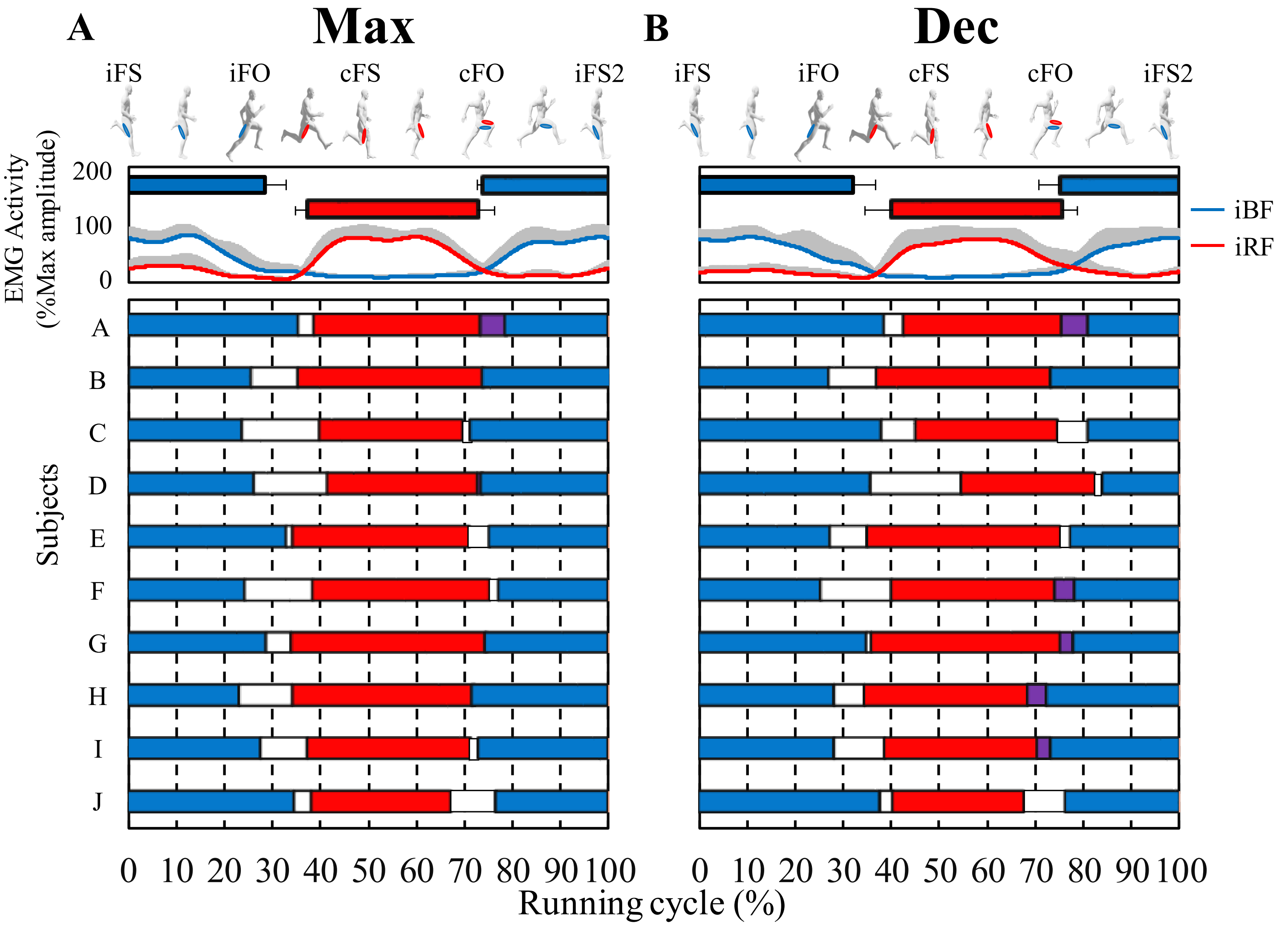

Figure 4-4. Difference of onset and offset timings of iRF and iBF between Max (A) vs Dec (B) phases of all individual data (bottom figure) and the mean ± SD (top figure). Note that these results are corresponded with Figure 4-6 A.

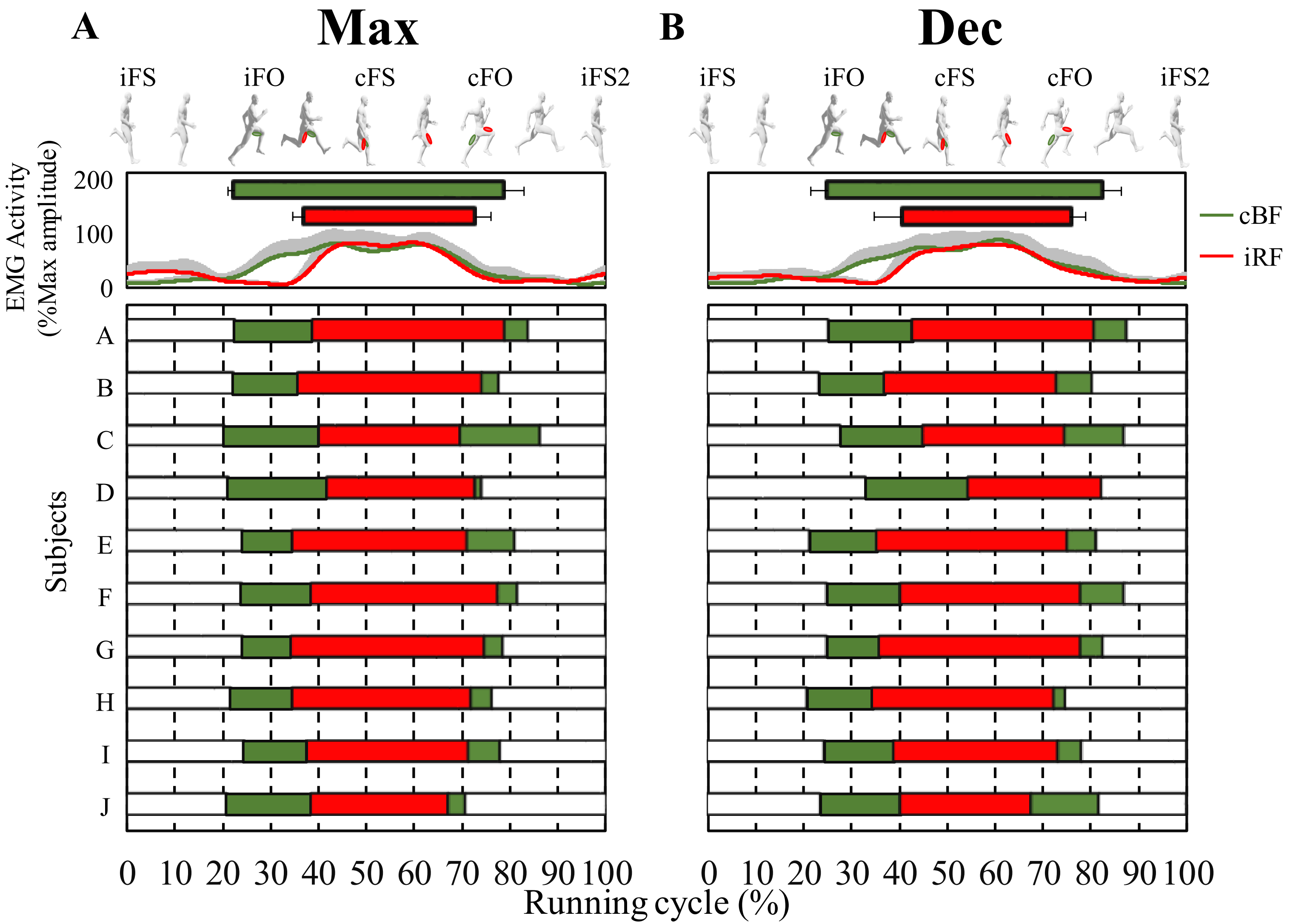

Figure 4-5. The difference of onset / offset timings of iRF and cBF between Max (A) vs Dec (B) phases of all individual data (bottom figure) and mean ± SD (top figure). Note that these results are corresponded with Figure 4-6 B.

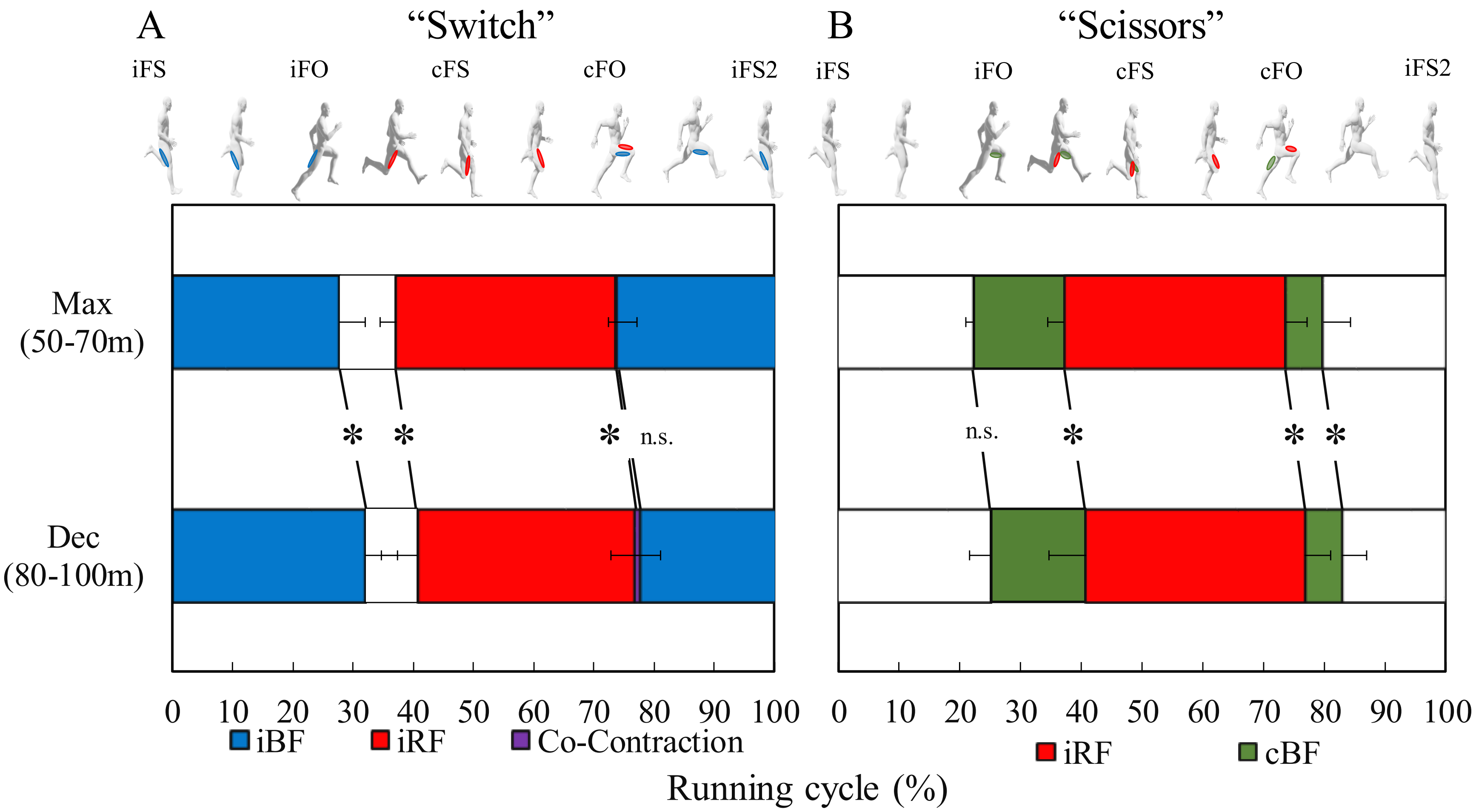

Figure 4-6. The difference of mean and SD of onset and offset timings of iRF, iBF and cBF between Max vs Dec phases. (A) Blue and red indicate iBF and iRF activities respectively. White indicates the time when both muscles are inactive. Purple indicates co-contraction. (B) Green indicates cBF activity. White indicates the time when both muscles are inactive. Note that iRF and cBF activation overlap. ✻ : A significant difference was observed between Max vs Dec phases. These results correspond with Table 4-2.

4-4 Discussion

The primary purpose of this Chapter was to clarify the differences in the timing of muscle activities of RF and BF in both legs between the Max (50-70 m) and Dec (80-100 m) phases. To our best knowledge, this is the first attempt to record EMG activity in the entire 100-m dash, which was succeeded thanks to the recent development of recording technique (Fig. 4-3).

RS and SF significantly decreased in the Dec phase (RS: 9.99 ± 0.34 $m \cdot s^{-1}$, SF: 4.48 ± 0.21 Hz) as compared with those in the Max phase (RS: 10.26 ± 0.28 $m \cdot s^{-1}$, SF: 4.63 ± 0.20 Hz), in consistent with the results of previous studies (Ae et al., 1992; Graubner & Nixdorf, 2011; Hommel et al., 2012). On the other hand, SL and CT had no significant difference between the two phases. However, FT was significantly increased in the Dec phase. Therefore, decreased RS in the Dec phase would be mainly caused the decrease in SF with increased FT.

In this Chapter, it was hypothesized that the thigh EMG activity timing in the Dec phase would change from the Max phase together with a decrease in SF, because SF was shown to be associated with changes in thigh EMG activity timings in Chapter 2, 3, and previous study (Kakehata, Goto, et al., 2020). Indeed, iRF-onset, iRF-offset, iBF-offset, and cBF-offset shifted to the later timing in the running cycle in the Dec phase compared to the Max phase (Fig. 4-6 & Table 4-2). The RF acts as a hip flexor during swing phase to swing the thigh forward (Mero & Komi, 1987), however, both iRF-onset (p = 0.024, d = 0.70) and iRF-offset (p = 0.020, d = 0.70) were seen at the later in the running cycle in the Dec phase, which suggest produce a delay in the leg recovery in the swing phase. Previous research have shown that thigh angle decreased in repeated sprinting (i.e., in fatigue condition) (Pinniger et al., 2000). Moreover, Endo et al. (2008) pointed out one of the deceleration factors of the 100-m dash is delay of the hip flexion movement (i.e., recovery mechanics) in the swing phase. One possible explanation for these findings is that RF activity in the swing leg occurred at later timing in the Dec phase (Fig. 4-6 & Table 4-2). If the movement of swing leg was delayed, swing time would be prolonged and, thus, SF would decrease. Hence, the delayed timing of RF activity would be a factor of the decreased SF.

While the RF acts as hip flexor in the swing phase, the BF acts as a hip extensor during the late swing phase and the contact phase to propel the body (Dorn et al., 2012; Howard et al., 2018; Mero et al., 1992; Nummela et al., 1994; Schache, Dorn, Blanch, Brown, & Pandy, 2012). Hip extensor muscles (e.g., BF) have been regarded as important for swinging the leg backwards to obtain large ground reaction forces (Morin, Gimenez, et al., 2015). I observed the longer activity of iBF and cBF during the contact phase of the Dec phase than the Max phase, it would produce greater hip extension to push the ground. While CT had no significant difference between the Max and Dec phases, FT was significantly increased in the Dec phase. Athletes should swing leg forward (i.e., RF activity for hip flexion) as soon as the finish of pushing the ground (i.e., BF activity for hip extension) (Mann, 2011). However, longer BF activity would cause greater thigh extension, placing the lower limb far behind the total body center of gravity. This would require greater range of lower-limb motion for the next ground contact, which inevitably increase FT in the Dec phase. To sum up, in the Dec phase, SF decreases with increase in FT that is caused with the delayed timing of BF activity. Thus, the change in the BF activity would also be the factor of the decreased SF.

Difference of the “Scissors” between Max and Dec phase

Inter-leg muscular coordination; shorter time difference between the onsets of RF activity in the swing leg and the BF activity in the contact leg is important for achieving high SF as shown in Chapter 2 (Kakehata, Goto, et al., 2020). Therefore, I focused on the “Scissors1” and “Scissors2” as the indicators of the coordination of both leg muscles and had a hypothesis that “Scissors1” and “Scissors2” would be changed in the Dec phase. Indeed, in parallel with the decrease in SF in the Dec phase, “Scissors1” became significantly longer in the Dec phase than the Max phase. “Scissors1” is time difference of onset timing of the hip flexion (iRF) and onset timing of the contralateral leg BF (cBF) for hip extension. In other words, iRF activity was seen later timing relative to the cBF activity in the Dec phase. As a result, it is suggested that swing leg relative to the contralateral (contact) leg was located more backwards.

A previous study comparing the running movements of sprinters and distance runners reported that the relative position of the swing leg knee to the contact leg knee at the foot strike was closer in sprinters than in distance runners (Bushnell & Hunter, 2007). Moreover, previous study also pointed out that one of the factors of determining SF is recovery mechanics (i.e., swing the thigh forward) (Ross et al., 2001). If recovery movement was delayed, duration of the swing time will be prolonged, it induces the decrease SF. Altogether, moving the swing leg forward more quickly would lead to more rapid preparation for the next ground contact, this would result in higher SF. Furthermore, previous study showed that shorter time difference between swing leg activity and contact leg activity is important to obtain higher SF during maximal speed sprinting (Kakehata, Goto, et al., 2020). However, the time difference between swing leg activity (iRF) and contact leg activity (cBF) (“Scissors1”) became longer in the Dec phase than the Max phase. These results imply that onset timing of recovery leg activity (iRF) was delayed against the contact leg activity (cBF). Hence, we suggest that the coordination of the hip flexor (e.g., RF) and hip extensor (e.g., BF) is important for maintain higher SF at the Dec in the 100-m dash. These findings would provide new insight to coaches and athletes that the inter-leg muscular coordination would be one of the key factors to improve running performances. Finally, this is practical implication for the coaches and athletes should consider the concept of the inter-leg muscle activity training.

Difference of the “Switch” between Max and Dec phase

It is important accomplish switch between hip flexion (iRF) and hip extension (iBF) of the same leg at the late swing phase ("Switch2") smoothly (without co-contraction) to obtain higher SF (Kakehata, Goto, et al., 2020). Hence, I had the third hypothesis that “Switch” also will be changed, because co-contraction would be more likely to occur in the Dec phase. However, neither “Switch1” nor “Switch2” were significantly different between two phases (“Switch1”: $p = 0.647$, $d = 0.12$, “Switch2”: $p = 0.214$, $d = 0.26$), which indicates that the third hypothesis was not accepted. However, I found that six subjects (A, B, F, G, H, I) showed co-contraction (negative “Switch2” values) in the Dec (Fig. 4-4). “Switch2” indicates the time difference from iRF-offset to iBF-onset for extending the hip joint in preparation for the next ground contact during the late swing phase. I found that "Switch2" showed negative values (i.e., co-contraction) in the Dec phase (-0.1 ± 4.7 %), in contrast to positive value in the Max phase (1.0 ± 4.0 %), but these values are not significantly different. Therefore, whether co-contraction would be more likely happen in the Dec phase should be analyzed more in detail in future.

4-5 Conclusion

This Chapter aimed to clarify the differences of the timing of muscle activities of RF and BF in both legs and spatiotemporal variables during the maximal speed (Max) phase (50-70 m section) and deceleration (Dec) phase (80-100 m section) of the 100-m dash. I found that RS decreased in the Dec phase with decreased SF. Timings of iRF-onset, iRF-offset, iBF-offset, and cBF-offset in the Dec phase shifted to the later in a running cycle than the Max phase. Furthermore, time difference between the swing leg activity (iRF-onset) and the contact leg activity (cBF-onset) ("Scissors1") was longer in the Dec phase than in the Max phase. As a result, the delay in the recovery movement of the swing leg is considered to be the cause of the decrease in SF. These results suggest that the limiting factors of the 100-m dash in the Dec phase (i.e., decreased RS and SF) would be the delayed timing of the RF and BF activity as well as changed in the inter-leg muscular coordination (i.e., time difference between the RF activity in the swing leg and the BF activity in the contact leg).

Chapter 5

General Discussion

The purpose of this thesis is 1) to clarify the RF and BF activity in both legs during sprinting, and 2) to elucidate the muscular control of the RS or SF in maximal RS (Chapter 2), various speed conditions (Chapter 3) and entire 100-m dash (Chapter 4) among Track & Field athletes.

In Chapter 2, I investigated the two possible muscular control variables 1) “Switch” (switching between RF and BF activities in one leg) and 2) “Scissors” (coordinate of muscle activity in both legs) were correlate with SF at maximal RS. In other words, I demonstrated that smoother switching between iRF and iBF in late swing phase and coordinated or synchronization inter-leg muscle activity (between iRF and cBF) were important to achieve high SF.

In Chapter 3, I investigated how RF and BF activities in both legs would change as well as “Scissors” and “Switch” when the subjective effort (SE), that is, RS is varied. I demonstrated that at higher speed sprinting ($9 > \mathrm{m{\cdot}s^{-1}}$) stronger muscle activity in both RF and BF were observed, which would produce stronger hip extension and flexion. Although the strong activity of RF is required at high RS, too long activation of the RF may induce co-contraction (“Switch2”) in the late swing phase, which may inhibit performance. Therefore, it is necessary to achieve appropriate onset and offset timings of the RF and BF in order to attain the high RS (i.e., SF).

In Chapter 4, I examined to clarify the differences in the timing of muscle activities of RF and BF in both legs and spatiotemporal variables during the maximal speed phase (50-70 m) and deceleration phase (80-100 m) of the 100-m dash. I found that the decrease in RS during the deceleration phase was due to a decrease in SF, which was considered to be caused by a delayed timing of RF and BF activity to the latter of the running cycle. In other words, one of the limiting factors in 100-m dash performance is delaying of the activity of the iRF of the swing leg against the activity of the cBF of the contact leg during the deceleration phase.

5-1 Implications of this thesis

Since sprinting is the *"running at speed over a short distance at maximal speed"* (Tomlinson, 2010), most of the training in Track & Field domain is naturally done at maximal effort (i.e., intensity) to improving maximal RS (Haugen, Seiler, et al., 2019; IAAF, 2009; Schiffer, 2009). Similarly, research on sprinting tend to focus on how to enhance the physiological limit (e.g., external power output, amount of GRF, hip extensor torque) (Morin, Gimenez, et al., 2015; Morin, Slawinski, et al., 2015; Slawinski et al., 2017). Sprint performance is influenced by several neural systems (e.g. muscle recruitment, muscle contraction speed, muscle contraction/relaxation rate) (Coh et al., 2010; Ross et al., 2001). Moreover, since sprinting is a cyclic movement in which the roles of the left and right legs (contact leg and swing leg) alternate (Hay, 1993), it is important to understand not only antagonistic muscle activities in one leg but also the coordination of muscle activities in both legs. The functions of the hip extensors and flexors are particularly important in achieving high RS (Dorn et al., 2012; Schache et al., 2011). Therefore, it is important to understand how the controls (i.e., proper onset/offset timings) of the thigh muscles in both legs. To the best of our knowledge, no studies have done on how the EMG activities and timings in both legs are controlled and how it is associated with sprint performance.

Hence, this doctoral thesis studied sprinting as “coordinated movements of both legs”, and I proposed new muscular control variables (“Switch” and “Scissors”), then analyzed them in various conditions.

i. “Switch”: length of time for switching activities between hip extensor muscle (iBF) and hip flexor muscle (iRF) in one leg (shown in Chapter1, Fig. 1-10 A).

ii. “Scissors”: length of the time difference between activities of hip extensor muscle (cBF) in one leg and hip flexor muscle (iRF) in the other legs (shown in Chapter1, Fig. 1-10 B)

Why is “Switch” important?

EMG activity amplitude (RMS) and timing of the RF and BF corresponded well with changing RS (i.e., SF) (Chapter 3). Similarly, the results of several previous studies (Andersson et al., 1997; Kuitunen et al., 2002; Kyrolainen et al., 2005; Mero & Komi, 1987; Schache et al., 2011; Schache et al., 2014), EMG activities of the muscle at high RS ($9 > m\cdot s^{-1}$) were prolonged, and their amplitudes (RMS) became stronger as compared with those at slower speeds. In particular, both length and amplitudes of RF activity increased sharply in higher RS range ($9 > \mathrm{m{\cdot}s^{-1}}$) (Chapter 3); this result is consistent with the previous findings that hip flexion and extension torque increase sharply at a higher speed than 7 $\mathrm{m{\cdot}s^{-1}}$ (Dorn et al., 2012). Altogether, strong RF activation during the swing phase would be necessary to increase swing leg speed to obtain higher RS (Ema et al., 2018). Although stronger RF activity is essential in high RS (i.e., SF) (Chapter 3), redundant RF activity influenced "Switch2" in the late swing phase. In addition, longer RF activity (delayed iRF-offset) possibly resulted in the co-contraction of the RF and BF in several subjects (Chapter 4). Moreover, "Switch2" had a positive correlation between SF at maximal RS (Chapter 2). In summary, despite the increase in RS (i.e., SF), i.e. the decrease in running cycle time, the relative period of EMG activity was prolonged. Altogether, the length of the "Switch2" became shorter, it would cause co-contraction occurring at high RS (i.e., SF). Therefore, the control ability to clearly switch activities between RF and BF may be a key factor in achieving high SF.

"Switch2" was longer in sub-maximal effort sprinting than maximal effort sprinting (Chapter 3). In other words, "co-contraction" was improved in sub-maximal effort sprinting (Chapter 3). Kakehata et al. (2020) pointed out the optimal combination of SF and SL differ among individuals because several athletes obtained their fastest RS at a sub-maximal effort. Similarly, the optimal timing of muscle activity also showed individual differences (Figs. 2-6 and 3-6), which would also affect sprinting performance. Hence, athletes should consider the techniques for achieving high running performance, not only in terms of strong muscle activation but also in terms of active relaxation.

Muscle relaxation is more difficult than muscle contraction, because muscle relaxation is influenced by the muscle activities of other limbs (Kato et al., 2014; Kato, Watanabe, Muraoka, et al., 2015; Kato, Watanabe, & Kanosue, 2015), and it is an active process requiring a cortical activation similarly to or even greater and more widespread than that of muscle contraction (Toma et al., 1999). Present study showed switching in the late swing phase “Switch2” influenced the sprinting performance (i.e., SF) (Fig. 2-7 D in Chapter 2). Interestingly, iRF-offset had a significantly negative correlation with RS and SF (Figs. 2-7 A and B in Chapter 2). These results imply that the offset of muscle activity also influences sprinting performance. Therefore, athletes and coaches should emphasize not only “muscle contraction” but also “muscle relaxation” during sprinting, especially in the late swing phase.

Why is “Scissors” important?

Both “Scissors1” and “Scissors2” became shorter with the increase RS (i.e., SF). In other words, the time difference between iRF-onset and cBF-onset, iRF-offset and cBF-offset became shorter with increase RS (i.e., SF) (Chapter 3). Moreover, I found that “Scissors1” and “Scissors2” had negative and positive correlations, respectively, with SF at maximal RS (9.87 $m\cdot s^{-1}$) (Fig. 2-7 F in Chapter 2). Furthermore, I also found “Scissors1” became longer (i.e., iRF-onset timing delayed relative to cBF-onset timing) in the Dec phase (RS: 9.99 $m\cdot s^{-1}$ SF: 4.48 Hz) as compared to the Max phase (RS: 10.26 $m\cdot s^{-1}$, SF: 4.63 Hz) (Table 4-2 in Chapter 4). Thus, SF is influenced by inter-leg muscle coordination, that is, iRF activity timing relative to cBF activity.

These findings suggest the important ability to achieve high SF; how to control the muscular timing in both legs, that is, earlier the activity of the iRF in relation to the cBF activity would be better for acquiring high RS. Therefore, sprinter should be considered not only muscle activity timing in one leg, but also in the coordination between both legs to improve sprint technique. These findings would provide new insights into the coaching field of the sprint.

5-2 Implications for sprint training

The present results obtained in competitive sprinters, whose competition record of 100-m dash was10.46 seconds (Chapter 2 and 3) and 10.53 seconds (Chapter 4) would have important implications for the application of obtained knowledge to sprint training. In the following, I will suggest specific sprint training to improve proper muscle onset/offset timings.

First, to minimize the time difference between the onset of muscle activity in the support (iRF) and swing (cBF) legs mini-hurdle drill training may be effective. A previous study demonstrated that mini-hurdle drill had acute positive effects of sprint performance, that is, maximal effort sprint after prescribed mini-hurdle drills ran over 10 × 10 mini-hurdles (height 22 cm) as fast as possible increased maximal RS (3.2 %) and maximal SF (3.3 %) in male senior sprinters (Yoshimoto, Takai, & Kanehisa, 2016). Then, it would be assumed to EMG activity timings also would be modified (clear switching between iRF-offset and iBF-onset or minimize time difference between cBF-onset and iRF-onset) with increasing SF in mini-hurdle running. If it is so, these results corresponded with our findings that the time difference between muscle activity in the contact leg (iRF) and swing leg (cBF) had a significant correlation with SF. Hence, with mini-hurdle drills training (Fig. 5-1) athletes may improve proper muscle activity timings, leading to a faster recovery leg and, consequently, an increase in SF in normal sprinting maximal RS. With regards to the switching RF and BF activities in one leg more smoothly, a drill with a mini-hurdle placed at narrow intervals may be effective for increasing SF (Fig. 5-1). The shorter the mini-hurdle intervals, SL will decrease, and SF will increase. This means trainees will have to switch between RF and BF activity in limited running cycle times. 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 (Chumanov, Schache, et al., 2012). Thus, training with mini-hurdle drills would have a potential not only for improving “Switch” or “Scissors”, but also for injury prevention.

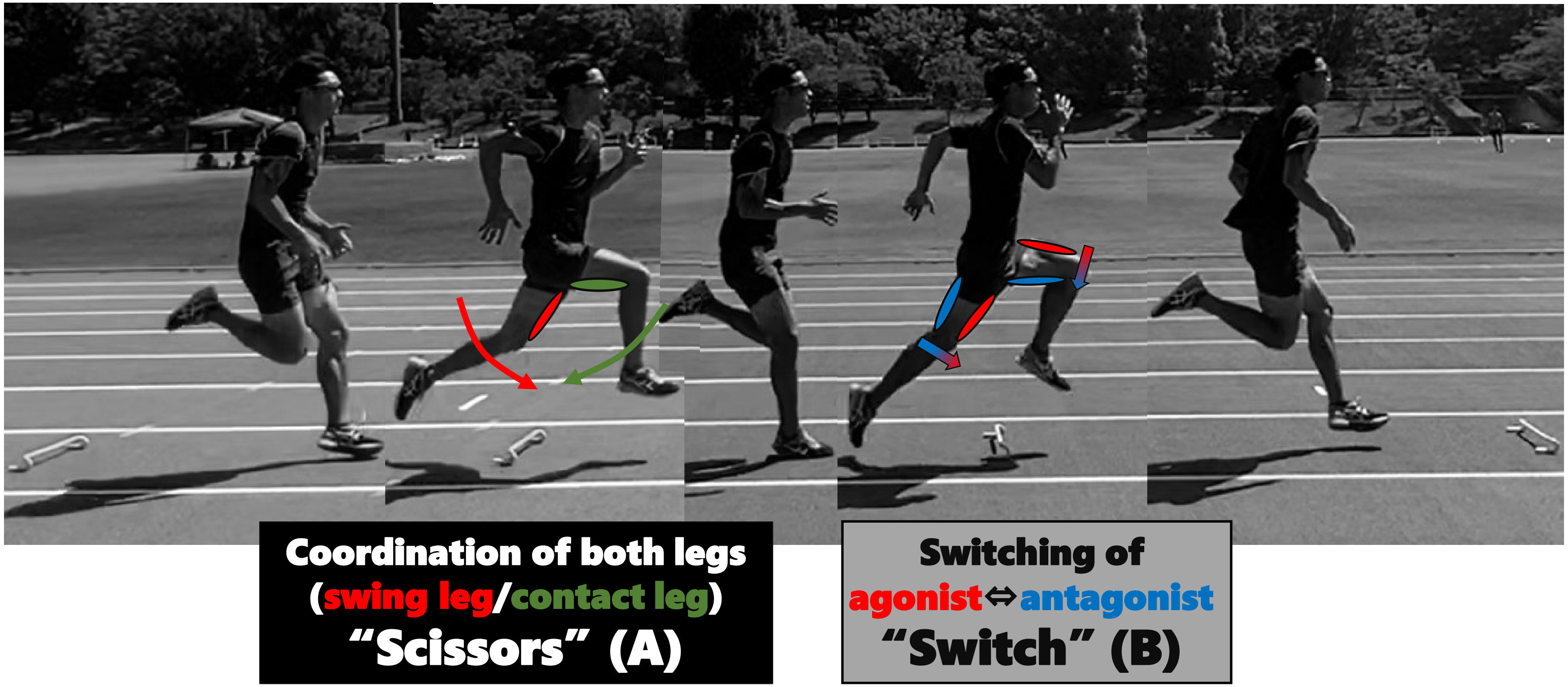

Figure 5-1. A serial photographs of mini-hurdle drill training and concepts of coordination of both legs (“Scissors”, A), and switching of agonist and antagonist muscle activity in one leg (“Switch”, B), respectively.

5-3 Limitations

The present study found significant correlations between the timing of RF and BF activities and SF (Chapter 2). The EMG activities during the “Scissors”, timing of agonist muscle activities in both legs, and those during the “Switch”, an activity change between RF and BF in one leg, were correlated with SF. 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? RS is the product of SF and SL (Hunter et al., 2004a), and the combination of the SF and SL differ among subjects this study in Chapter 2 (Fig. 2-5), Chapter 3 (Table 3-1, 2, and 3) and those of previous studies as well (Bezodis, Kerwin, Cooper, & Salo, 2018; Hunter et al., 2004a; Kakehata, Kobayashi, et al., 2020; Kunz & Kaufmann, 1981; Salo et al., 2011). This difference may be caused by the difference in running movements or in morphological features among individuals. Therefore, it is necessary to consider not only the timing of muscle activity but also other factors such as GRF that determine the SL (Hunter et al., 2005; Morin et al., 2011; Morin, Slawinski, et al., 2015) or running kinematics (e.g., lower limb movement) (Bushnell & Hunter, 2007; Hunter et al., 2004a; Schache et al., 2015). However, I did not measure the GRF or lower limb joint movements.

In the present study, SL 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 the GRF.

Second, are the characteristics of “Scissors” and “Switch” observed in this study specific only to the relatively high-level sprinters participating in this study, or are they common to low-level runners or even to non-athletes as well? In the present study, I recruited only competitive male senior athletes who trained specifically in athletics. Their competition levels were equivalent to a record of 10.46 seconds (Chapter 2 and 3) and 10.53 seconds (Chapter 4) in the men's 100-m referenced from the WA Score (the points for each Track & Field event record). Based on previous studies of muscle activity patterns during running (Howard et al., 2018), one would expect that the “Scissors” and “Switch” themselves would be commonly observed in human running. Further research would be required what “Scissors” and “Switch” during running is commonly observed among non-athletes or youth athletes their running ability is underdeveloped. It is also interesting whether “Scissors” and “Switch” would be changed after specific training.

5-4 General Conclusion

My doctoral thesis showed that the most important performance factor in sprinting: running speed, was controlled mainly by step frequency. In general, I found the two muscular control ability determine the step frequency during sprinting.

1) The control ability of the activation timing of agonist muscles of both legs, that is, earlier swing leg activation (iRF) relative to the contact leg activation (cBF) (“Scissors”).

2) The control ability to switch clearly between agonist muscle (iRF) and antagonist muscle (iBF) in one leg (“Switch”).

In conclusion, sprinting should be considered from the how to control the thigh muscular coordination of inter-leg not only of one leg.

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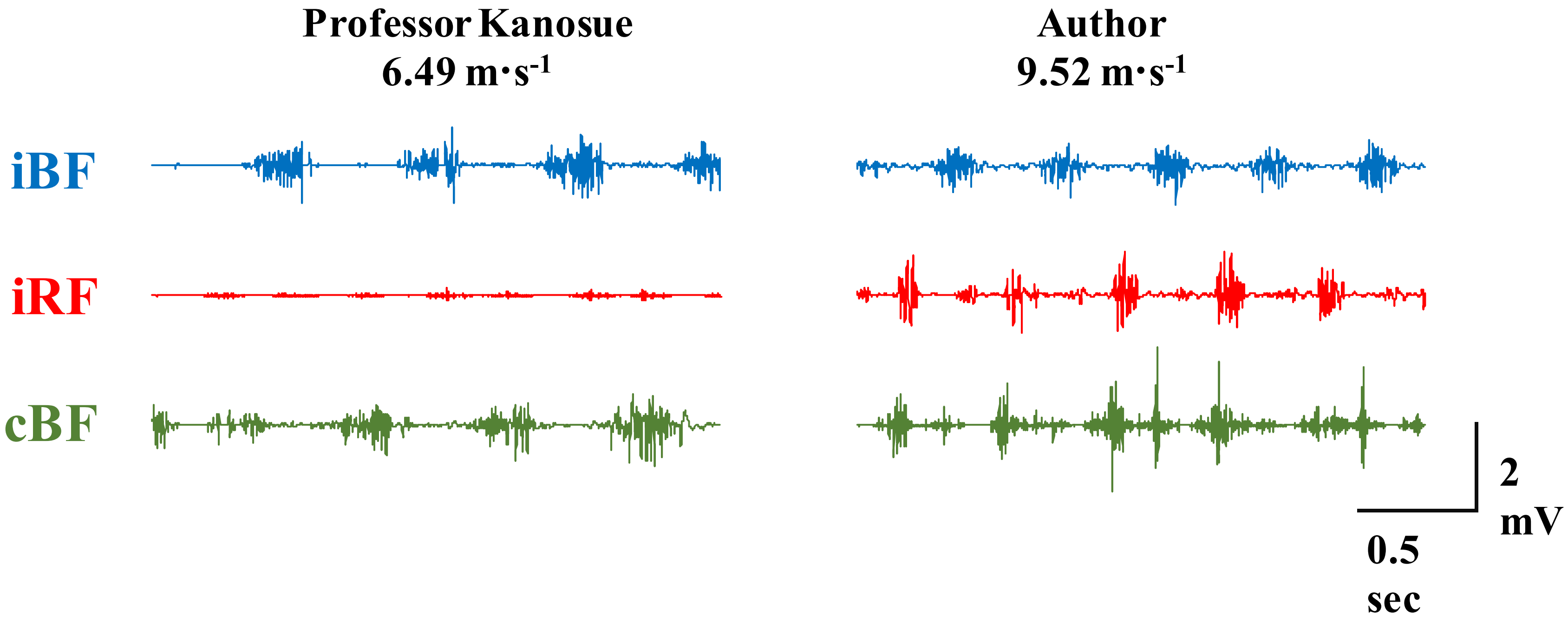
Appendix



Appendix Figure. Professor Kanosue and author's raw EMG activity during maximal effort sprinting at Waseda University on June 9th, 2017 as a pilot study of this thesis.