



Lower-Limb Muscle Synergy Characteristics during Sprinting in Front-Side Swing-Dominant and Back-Side Propulsion-Dominant Sprinters

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How to cite this paper: Su, S.J., Zhu, H.W. and Li, X.D. (2026) Lower-Limb Muscle Synergy Characteristics during Sprinting in Front-Side Swing-Dominant and Back-Side Propulsion-Dominant Sprinters. *Open Access Library Journal*, **13**: e15427. <https://doi.org/10.4236/oalib.1115427>

Received: April 30, 2026

Accepted: May 10, 2026

Published: May 13, 2026

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Abstract

Purpose: This study aimed to examine differences in lower-limb muscle synergy characteristics during sprinting between front-side swing-dominant and back-side propulsion-dominant sprinters, and to elucidate the neuromuscular control features underlying distinct lower-limb technical strategies. **Methods:** Eight male sprinters with systematic training backgrounds were recruited and classified as front-side swing-dominant or back-side propulsion-dominant according to the front-side/back-side action ratio during the sprinting phase. High-definition video and surface electromyography were synchronously collected during flying sprint trials to obtain kinematic and lower-limb muscle activation data from the gluteus maximus, biceps femoris, semitendinosus, lateral gastrocnemius, medial gastrocnemius, soleus, rectus femoris, and tibialis anterior. Non-negative matrix factorization was used to extract lower-limb muscle synergy modules. Between-group statistical comparisons focused on motor-module muscle weights, whereas motor-primitive activation patterns were examined descriptively. **Results:** The two groups showed distinct muscle-weight distributions across multiple synergy modules. In SYN_2, front-side swing-dominant sprinters exhibited greater weights for the biceps femoris and semitendinosus, whereas back-side propulsion-dominant sprinters exhibited greater weights for the gluteus maximus and soleus, indicating a clear divergence in posterior-chain recruitment patterns. In SYN_3, back-side propulsion-dominant sprinters showed greater weights for the lateral gastrocnemius, medial gastrocnemius, and soleus, whereas front-side swing-dominant sprinters showed greater tibialis anterior weight, suggesting group-specific differences in ankle-muscle coordination. Additional differences in muscle weights were observed in SYN_4 and SYN_5, involving the rectus femoris, medial gastrocnemius, lateral gastrocnemius, and biceps femoris. **Conclusion:** Front-side swing-dominant and back-side propulsion-dominant sprinters exhibit distinct patterns of

lower-limb muscle synergy organization during sprinting. Front-side swing-dominant sprinters are characterized by greater involvement of the hamstrings, tibialis anterior, and selected triceps surae muscles in swing-to-stance transition control, whereas back-side propulsion-dominant sprinters rely more strongly on the gluteus maximus, soleus, and triceps surae, reflecting a posterior-chain propulsion-oriented coordination strategy. These findings indicate that differences in sprinting technique are not limited to lower-limb kinematic patterns, but are also reflected in muscle synergy recruitment and neuromuscular control strategies, providing a mechanistic basis for sprint technique diagnosis and individualized training optimization.

Subject Areas

Sports Science

Keywords

Sprinting, Muscle Synergy, Sprinting Technique

1. Introduction

Sprinting is a fundamental athletic event that embodies human speed capacity, explosive power, and neuromuscular control, with the competitive objective of covering a prescribed distance in the shortest possible time within the constraints of the rules. As a prototypical high-speed cyclic movement, sprinting requires athletes to rapidly alternate between stance and swing phases within extremely short time intervals, while maintaining and enhancing horizontal velocity through reduced ground contact time, increased step frequency, optimized step length, and effective utilization of ground reaction forces [1] [2]. The sprint phase represents a critical portion of the race in which velocity production and technical stability are highly concentrated, and performance during this phase is jointly influenced by lower-limb segmental coordination, stance-swing phase transition, ground reaction force transmission, and neuromuscular control. Haugen *et al.* reported a strong association between experimentally measured maximal sprinting performance and athletes' season-best 100-m times, indicating that sprint-phase velocity is a key determinant of sprint performance [1].

In sprint technique research, the anterior-posterior kinematic characteristics of the lower limb relative to the extended trunk line are commonly conceptualized as front-side and back-side mechanics. According to the technical framework proposed by Mann and Murphy, lower-limb motion occurring anterior to an extension of the trunk line can be regarded as front-side mechanics, whereas motion occurring posterior to this line can be regarded as back-side mechanics [3]; building on this concept, Haugen *et al.* further quantified front-side and back-side technical features using variables such as maximal thigh flexion, inter-thigh angle at touchdown, thigh and knee angles at toe-off, and maximal thigh extension [1].

Within this framework, the present study defined athletes with more pronounced anterior swing-leg characteristics as front-side swing-dominant sprinters, characterized by greater thigh forward-swing amplitude, a more evident pre-contact downward action, and a faster stance-swing transition; conversely, athletes with more pronounced posterior extension and propulsive characteristics during stance were defined as back-side propulsion-dominant sprinters, characterized by greater hip, knee, and ankle extension in late stance, more evident back-side extension, and stronger horizontal propulsive capacity.

Existing studies based on kinematic and kinetic indicators have primarily characterized movement patterns and mechanical outputs during sprinting, but they have not fully elucidated the muscle coordination, activation timing, and neuromuscular control features underlying distinct technical strategies [4]. Muscle synergy theory posits that the central nervous system may organize complex movements by recruiting a limited set of synergy modules with specific muscle-weighting profiles and temporal activation patterns, thereby reducing the dimensionality of motor control [5] [6]. Based on this framework, muscle synergy analysis can decompose complex multi-muscle activation signals into a small number of modules with distinct spatial weights and temporal activation patterns, providing a quantitative basis for interpreting the coordination organization underlying different technical strategies [5] [6]. The sprinting phase comprises a sequence of tightly coupled tasks, including thigh forward swing, pre-contact posture adjustment, stance-phase braking, horizontal propulsion, and toe-off transition, requiring precise spatiotemporal coordination among multiple lower-limb muscles. Previous research on sprint starts has shown that athletic experience can optimize the spatial structure and temporal activation patterns of muscle synergies, supporting the utility of muscle synergy analysis for revealing the neuromuscular control features underlying sprinting movements [4]. Therefore, muscle synergy theory provides a necessary framework for further examining differences in lower-limb muscle coordination, activation timing, and neuromuscular control between front-side swing-dominant and back-side propulsion-dominant sprinters during sprinting.

Building on this rationale, the present study combined video-based kinematic analysis with synchronized surface electromyography to classify sprinters according to the front-side/back-side action ratio, and applied non-negative matrix factorization (NMF) to extract lower-limb muscle synergy characteristics during sprinting. It further compared front-side swing-dominant and back-side propulsion-dominant sprinters in terms of synergy number and motor-module muscle weights, while motor-primitive activation patterns were examined descriptively to characterize group-level temporal activation tendencies. We hypothesized that distinct sprinting technical strategies would correspond to different organizational patterns of lower-limb muscle synergies. Specifically, compared with back-side propulsion-dominant sprinters, front-side swing-dominant sprinters were expected to exhibit more pronounced swing-phase synergy activation, including earlier or more concentrated activation of muscle groups associated with forward swing,

downward action, and pre-contact preparation; whereas back-side propulsion-dominant sprinters were expected to show more prominent stance-phase propulsion-related synergy features, including increased synergy weights or prolonged activation of muscle groups involved in hip extension, knee extension, and ankle plantar flexion.

2. Methods

2.1. Participants

Eight male sprinters with systematic training backgrounds were recruited for this study, all of whom had personal best 100-m times of 11.3 s or faster. None of the participants had sustained a severe lower-limb sports injury, had a neuromuscular disorder, or reported any other condition likely to affect sprint performance within the preceding 6 months. Trials or participant data were excluded if marked fatigue, abnormal running technique, inaccurate identification of video markers, or severe noise in the sEMG signals was observed during testing. To minimize the potential influence of acute fatigue on the test outcomes, all participants refrained from high-intensity training for 24 h before testing.

The study protocol was approved by the institutional ethics committee, and all participants were informed of the study purpose, testing procedures, potential risks, and principles of research-data confidentiality before testing, after which they provided written informed consent. All study procedures conformed to the ethical standards for human movement science research.

After testing, participants were classified according to the front-side/back-side ratio (FSR) during the sprinting phase and assigned to either the front-side swing-dominant or back-side propulsion-dominant group. The dominant leg was defined a priori as the leg that each participant preferred to use when kicking a ball. All kinematic and sEMG analyses were performed on the dominant leg to ensure consistency across participants.

2.2. Data Acquisition

Video data were recorded throughout the testing session by a professional videographer using a high-definition camera (Sony FX6, Japan) at a sampling frequency of 50 Hz. To ensure analytical rigor and accuracy, all video data were processed and analyzed using the SIMI Motion 10.0 motion analysis system (SIMI Reality Motion Systems GmbH, Germany). Using the software's frame-by-frame analysis and temporal event-marking functions, key temporal parameters and kinematic variables were extracted for each participant within the testing zone.

Surface electromyographic signals were recorded using a BTS surface electromyography system (BTS Bioengineering, Italy), with a bandwidth of 5 - 450 Hz and a sampling frequency of 2000 Hz, to capture muscle activation patterns during the fundamental phases of sprint gait, namely stance and swing. Eight major lower-limb muscles of the dominant leg were selected for sEMG recording; their anatomical names, abbreviations, and primary functions are listed in **Table 1**.

Electrode placement and testing preparation are shown in **Figure 1**. Before electrode placement, the skin over each recording site was shaved and cleaned with alcohol to reduce skin impedance, and electrodes were aligned with the muscle-fiber orientation to enhance signal quality. Maximal voluntary isometric contraction (MVC) tests were performed before the formal trials and were subsequently used for sEMG signal normalization. Standardized MVC tasks were conducted for each recorded muscle. The gluteus maximus was tested during resisted prone hip extension; the biceps femoris and semitendinosus were tested during resisted prone knee flexion; the lateral and medial gastrocnemius were tested during resisted plantar flexion with the knee extended; the soleus was tested during resisted plantar flexion with the knee flexed; the rectus femoris was tested during resisted seated knee extension; and the tibialis anterior was tested during resisted ankle dorsiflexion. Each MVC task was performed for 5 s and repeated two times, with sufficient rest between trials. The highest EMG amplitude obtained for each muscle was used as the normalization reference. MVC-based normalization was used to reduce inter-individual variability caused by electrode placement, skin impedance, and signal amplitude differences, thereby improving the comparability of muscle activation patterns and synergy weights across participants. Although sprinting is a dynamic maximal task, MVC normalization was used only as a scaling procedure for inter-participant comparison rather than as a direct estimate of maximal muscle capacity during sprinting.

Table 1. Lower-limb muscles recorded by surface electromyography and their primary functions.

Muscle	Abbreviation	Primary function	Functional interpretation in the present study
Gluteus maximus	GM	Hip extension; pelvic stabilization	Posterior-chain propulsion; stance-phase hip extension
Biceps femoris	BF	Hip extension; knee flexion	Terminal-swing deceleration; pre-contact control
Semitendinosus	ST	Hip extension; knee flexion	Hip-extension-knee-flexion synergy
Lateral gastrocnemius	LG	Ankle plantar flexion; knee flexion	Ankle stiffness; distal support
Medial gastrocnemius	MG	Ankle plantar flexion; knee flexion	Rapid ground contact; elastic support
Soleus	SOL	Ankle plantar flexion	Stance-phase propulsion; ankle stiffness
Rectus femoris	RF	Hip flexion; knee extension	Thigh forward swing; pre-contact preparation
Tibialis anterior	TA	Ankle dorsiflexion	Pre-contact foot-posture control

Note: The primary functions listed in the table represent the potential kinematic roles of each muscle during the sprinting phase; their specific contributions may vary according to gait phase and technical type.



Figure 1. Participant testing preparation and lower-limb surface electromyography electrode placement.

Video and sEMG data were temporally aligned using a synchronization movement signal performed before the start of each trial. The formal testing protocol consisted of flying sprint trials performed on a synthetic track, while participants wore their own sprint spikes. Participants accelerated over approximately 30 - 40 m before entering the analyzed zone. Kinematic and sEMG data were collected and analyzed primarily within the 40 - 80 m segment, where athletes were expected to reach and maintain maximal or near-maximal sprinting velocity. For each athlete, gait cycles within this segment were selected when movement continuity, running rhythm stability, clearly identifiable touchdown and toe-off events, and high-quality sEMG signals were simultaneously satisfied. Each participant completed three valid trials, with a recovery interval of 5 min between trials to minimize the influence of fatigue on kinematic and electromyographic signals. The 50-Hz video sampling frequency provided a temporal resolution of 20 ms, which was considered sufficient for touchdown and toe-off identification for gait-cycle segmentation and FSR-based technical classification, because these events were verified frame by frame by two experienced analysts and were not used to calculate high-resolution contact-time kinetics. Trials with ambiguous touchdown or toe-off frames were excluded from subsequent analysis.

2.3. Data Analysis

2.3.1. Data Processing

Kinematic data and sEMG signals were preprocessed using Python. Kinematic data were smoothed using a fourth-order zero-phase Butterworth low-pass filter with a cut-off frequency of 10 Hz. Touchdown and toe-off events were identified from the foot-ground contact state in the video recordings and were used to define stance and swing phases. For each participant, two valid gait cycles were selected from each of the three valid trials, yielding six gait cycles per participant for subsequent analysis. The selected cycles were required to show continuous movement, stable running rhythm, clearly identifiable touchdown and toe-off events, and high-quality sEMG signals. Each selected gait cycle was time-normalized to

0% - 100%. To avoid pseudo-replication, gait-cycle-level outcomes were first averaged within each participant, and all between-group statistical comparisons were then performed using participant-level values. The sEMG signals were first high-pass filtered at 50 Hz using a fourth-order zero-phase IIR Butterworth filter, then full-wave rectified, and subsequently low-pass filtered at 20 Hz to obtain the linear envelope [4]. Finally, the sEMG linear envelopes obtained during sprinting were normalized to the maximum electromyographic amplitude recorded for each muscle during the MVC tests.

2.3.2. Technical Classification of Front-Side Swing-Dominant and Back-Side Propulsion-Dominant Sprinters

This study adopted the geometric definition of front-side/back-side mechanics, using the extended trunk line as the reference for distinguishing anterior and posterior lower-limb actions. According to the technical framework proposed by Mann and Murphy, lower-limb motion anterior to an extension of the trunk line can be considered front-side mechanics, whereas motion posterior to this line can be considered back-side mechanics [3]; building on this framework, Haugen *et al.* further quantified front-side and back-side technical characteristics using variables including maximal thigh flexion, inter-thigh angle at touchdown, thigh and knee angles at toe-off, and maximal thigh extension [1].

In the sagittal-plane video recordings, the following angular variables were defined: the line connecting the acromion and hip joint was used to represent the trunk line and was extended downward, whereas the line connecting the hip and knee joints was used to represent the thigh line. The maximum angle of the thigh line swinging anteriorly relative to the extended trunk line was defined as the maximum front-side thigh angle and denoted as F_{\max} ; the maximum angle of the thigh line extending posteriorly relative to the extended trunk line was defined as the maximum back-side thigh angle and denoted as B_{\max} . The absolute value of B_{\max} was used for subsequent calculations.

The front-side/back-side action ratio was then calculated as follows:

$$FSR = \frac{F_{\max}}{F_{\max} + B_{\max}}$$

Here, FSR represents the relative contribution of front-side swing characteristics to back-side propulsion characteristics within the sprint gait cycle. A higher FSR indicates a greater tendency toward front-side swing-dominant lower-limb motion, whereas a lower FSR indicates a greater tendency toward back-side propulsion-dominant lower-limb motion.

To minimize random error arising from any single gait cycle, F_{\max} , B_{\max} , and FSR were averaged across multiple valid gait cycles for each participant. Participants were then classified according to the median FSR: those above the median were assigned to the front-side swing-dominant group, whereas those below the median were assigned to the back-side propulsion-dominant group.

To ensure the reliability of the technical classification, all angular variables were

independently digitized by two researchers with experience in sports biomechanics, and measurement consistency was assessed using the intraclass correlation coefficient. If marked discrepancies were observed between the two analysts, the data were re-examined, and the averaged value was used as the final result.

2.3.3. Muscle Synergy Analysis

NMF was applied to the preprocessed sEMG linear envelopes to extract lower-limb muscle synergy characteristics during the sprinting phase [4] [5]. Following previous muscle synergy studies, the spatial structure of a muscle synergy was defined as the motor module, representing the relative weight of each muscle within a given synergy, whereas the temporal structure was defined as the motor primitive, representing the time-varying activation pattern of each synergy across the gait cycle [4]. Using NMF, multi-muscle sEMG activation patterns were decomposed into a muscle-weight matrix and a temporal-activation matrix.

Specifically, the normalized sEMG signals of each participant were organized into a muscle activation matrix V , in which rows represented the recorded lower-limb muscles and columns represented the time-normalized points of the sprint gait cycle. Matrix V was then approximately factorized using NMF into a motor-module matrix M and a motor-primitive matrix P as follows:

$$V \approx V_r = MP$$

Here, r denotes the number of extracted muscle synergies; M is the motor-module matrix, reflecting the relative contribution of each muscle within each synergy; and P is the motor-primitive matrix, representing the activation timing of each synergy across the sprint gait cycle. Together, M and P characterize the organizational structure of lower-limb multi-muscle coordination during sprinting.

To determine the optimal number of muscle synergies, the reconstruction quality of the original sEMG matrix by NMF was calculated under different numbers of synergies and evaluated using the variance accounted for (VAF) [4] [7]:

$$\text{VAF} = \left(1 - \frac{\|V - V_r\|^2}{\|V - \bar{V}\|^2} \right) \times 100\%$$

Here, V denotes the original muscle activation matrix, V_r denotes the matrix reconstructed by NMF, and \bar{V} denotes the mean matrix of the original data. VAF represents the proportion of variance in the original sEMG signals explained by the reconstructed matrix. A VAF threshold greater than 90% was used as the preliminary criterion, and the minimum number of synergies for each participant was determined in conjunction with the inflection point of the VAF-synergy number curve. When the increase in VAF became markedly smaller after adding an additional synergy, the number of synergies corresponding to that inflection point was selected as the optimal synergy number.

NMF was implemented in Python using the scikit-learn package with non-negative random initialization. To minimize the influence of random initialization on solution stability, the extraction procedure was repeated 100 times for each participant and each candidate synergy number. The solution with the lowest recon-

struction error was retained. The convergence criterion was set as a tolerance of 1×10^{-6} or a maximum of 1000 iterations. Reconstruction quality was assessed using both global VAF and muscle-specific VAF to ensure that the extracted synergies adequately represented the overall sEMG matrix as well as the activation pattern of each individual muscle.

Because NMF components are unordered, the extracted synergies were aligned across participants before group-level comparison. Synergy alignment was performed by comparing motor-module weight vectors using cosine similarity. Synergies were reordered to maximize similarity across participants, and the final SYN_1-SYN_5 labels were assigned according to the matched motor-module profiles. When ambiguity occurred, both the motor-module structure and the corresponding motor-primitive activation pattern were inspected to confirm the alignment.

After synergy alignment, motor-module weights were averaged across valid gait cycles within each participant, and participant-level synergy weights were used for between-group statistical comparisons.

2.4. Statistical Analysis

All statistical analyses were performed using SPSS. The Shapiro-Wilk test was first used to assess whether each scalar variable followed a normal distribution. For normally distributed variables, independent-samples t-tests were used to compare front-side swing-dominant and back-side propulsion-dominant sprinters in Fmax, Bmax, FSR, synergy number, and motor-module muscle weights. For non-normally distributed variables, between-group comparisons were performed using the Mann-Whitney U test. Effect sizes were expressed as Cohen's *d*, and the significance level was set at $P < 0.05$. In the present exploratory analysis, inferential statistics were applied only to scalar variables and motor-module muscle weights. Motor-primitive activation curves were used descriptively to visualize group-level temporal activation tendencies; therefore, no statistical conclusions were drawn regarding time-series differences in motor primitives.

3. Results

3.1. Classification of Front-Side and Back-Side Technical Types

Based on FSR, the eight sprinters were classified into front-side swing-dominant and back-side propulsion-dominant groups. Front-side swing-dominant sprinters exhibited more pronounced thigh forward-swing and pre-contact downward-action characteristics, whereas back-side propulsion-dominant sprinters showed more evident posterior extension and propulsive features during late stance. This classification provided the basis for subsequent comparisons of lower-limb muscle synergy characteristics between the two technical groups during sprinting.

3.2. Extracted Characteristics of Muscle Synergy Modules

NMF of lower-limb sEMG signals during sprinting extracted five muscle synergy modules, denoted as SYN_1-SYN_5. Each synergy module comprised different

lower-limb muscles with distinct weighting profiles, reflecting the multi-muscle coordination patterns recruited to accomplish swing, pre-contact preparation, stance-phase braking, propulsion, and toe-off transition across the sprint gait cycle.

Overall, front-side swing-dominant and back-side propulsion-dominant sprinters exhibited different muscle-weight distributions across multiple synergy modules, indicating that distinct sprinting strategies are reflected not only in anterior-posterior kinematic patterns but also in the spatial organization of muscle synergies. Among these modules, SYN_2 showed the most pronounced between-group differences, with greater hamstring weights in front-side swing-dominant sprinters and greater gluteus maximus and soleus weights in back-side propulsion-dominant sprinters.

3.3. Differences in the Spatial Structure of Muscle Synergies between Technical Groups

In SYN_1, front-side swing-dominant sprinters showed significantly greater weights for the medial gastrocnemius and soleus than back-side propulsion-dominant sprinters (medial gastrocnemius: $P = 0.043$; soleus: $P = 0.030$), whereas back-side propulsion-dominant sprinters showed a significantly greater tibialis anterior weight than front-side swing-dominant sprinters ($P = 0.003$). No significant between-group differences were observed for the remaining muscles in SYN_1.

In SYN_2, between-group differences were primarily concentrated in the posterior-chain musculature. Front-side swing-dominant sprinters exhibited significantly greater weights for the biceps femoris and semitendinosus than back-side propulsion-dominant sprinters (biceps femoris: $P = 0.001$; semitendinosus: $P = 0.001$), whereas back-side propulsion-dominant sprinters exhibited significantly greater weights for the gluteus maximus and soleus than front-side swing-dominant sprinters (gluteus maximus: $P = 0.001$; soleus: $P = 0.048$). These findings indicate that SYN_2 primarily reflects differences in posterior-chain recruitment between the two technical groups, with front-side swing-dominant sprinters showing greater hamstring involvement and back-side propulsion-dominant sprinters showing greater gluteus maximus and soleus involvement.

In SYN_3, back-side propulsion-dominant sprinters exhibited significantly greater weights for the lateral gastrocnemius, medial gastrocnemius, and soleus than front-side swing-dominant sprinters (lateral gastrocnemius: $P = 0.007$; medial gastrocnemius: $P = 0.005$; soleus: $P = 0.033$), whereas front-side swing-dominant sprinters exhibited a significantly greater tibialis anterior weight than back-side propulsion-dominant sprinters ($P = 0.001$). These findings suggest that SYN_3 primarily captures differences in the coordinated recruitment of ankle musculature between the two groups, with back-side propulsion-dominant sprinters showing greater triceps surae involvement and front-side swing-dominant sprinters showing greater tibialis anterior involvement.

In SYN_4, front-side swing-dominant sprinters exhibited significantly greater weights for the lateral gastrocnemius and rectus femoris than back-side propulsion-dominant sprinters (lateral gastrocnemius: $P = 0.001$; rectus femoris: $P =$

0.001), whereas no significant between-group differences were observed for the remaining muscles. These findings indicate that the between-group differences in SYN_4 were primarily localized to the rectus femoris and lateral gastrocnemius, suggesting that front-side swing-dominant sprinters showed more pronounced co-involvement of the anterior thigh musculature and distal plantar-flexor-related muscles within this module.

In SYN_5, front-side swing-dominant sprinters exhibited a significantly greater medial gastrocnemius weight than back-side propulsion-dominant sprinters ($P = 0.001$), whereas back-side propulsion-dominant sprinters exhibited significantly greater weights for the biceps femoris and rectus femoris than front-side swing-dominant sprinters (biceps femoris: $P = 0.004$; rectus femoris: $P = 0.015$). These findings indicate that, in SYN_5, the two groups differed in the distribution of synergy weights across the medial gastrocnemius, posterior thigh musculature, and anterior thigh musculature.

Collectively, front-side swing-dominant and back-side propulsion-dominant sprinters exhibited varying degrees of muscle-weight differences across SYN_1-SYN_5, with these differences primarily involving the hamstrings, gluteus maximus, triceps surae, rectus femoris, and tibialis anterior. Muscle-weight variables showing significant between-group differences within each synergy module are presented in **Table 2**, and the overall distributions of motor modules and motor primitives are shown in **Figure 2**.

Table 2. Significant differences in muscle weights across synergy modules between front-side swing-dominant and back-side propulsion-dominant sprinters

Synergy module	Muscle	Front-side swing-dominant	Back-side propulsion-dominant	<i>P</i> value
SYN_1	Medial gastrocnemius	0.152 ± 0.186	0.058 ± 0.079	0.043
SYN_1	Soleus	0.210 ± 0.246	0.068 ± 0.139	0.030
SYN_1	Tibialis anterior	0.100 ± 0.133	0.265 ± 0.195	0.003
SYN_2	Gluteus maximus	0.069 ± 0.060	0.782 ± 0.126	0.001
SYN_2	Biceps femoris	0.676 ± 0.100	0.201 ± 0.190	0.001
SYN_2	Semitendinosus	0.685 ± 0.065	0.088 ± 0.142	0.001
SYN_2	Soleus	0.057 ± 0.084	0.199 ± 0.207	0.048
SYN_3	Lateral gastrocnemius	0.171 ± 0.227	0.390 ± 0.242	0.007
SYN_3	Medial gastrocnemius	0.149 ± 0.216	0.378 ± 0.252	0.005
SYN_3	Soleus	0.132 ± 0.165	0.365 ± 0.417	0.033
SYN_3	Tibialis anterior	0.638 ± 0.217	0.187 ± 0.201	0.001
SYN_4	Lateral gastrocnemius	0.311 ± 0.218	0.069 ± 0.116	0.001
SYN_4	Rectus femoris	0.498 ± 0.200	0.140 ± 0.102	0.001
SYN_5	Biceps femoris	0.084 ± 0.085	0.259 ± 0.196	0.004
SYN_5	Medial gastrocnemius	0.755 ± 0.150	0.480 ± 0.195	0.001
SYN_5	Rectus femoris	0.087 ± 0.116	0.247 ± 0.208	0.015

Note: Data are presented as mean ± standard deviation. SYN_1-SYN_5 denote the five muscle synergy modules; only muscle-weight variables showing statistically significant between-group differences are listed.

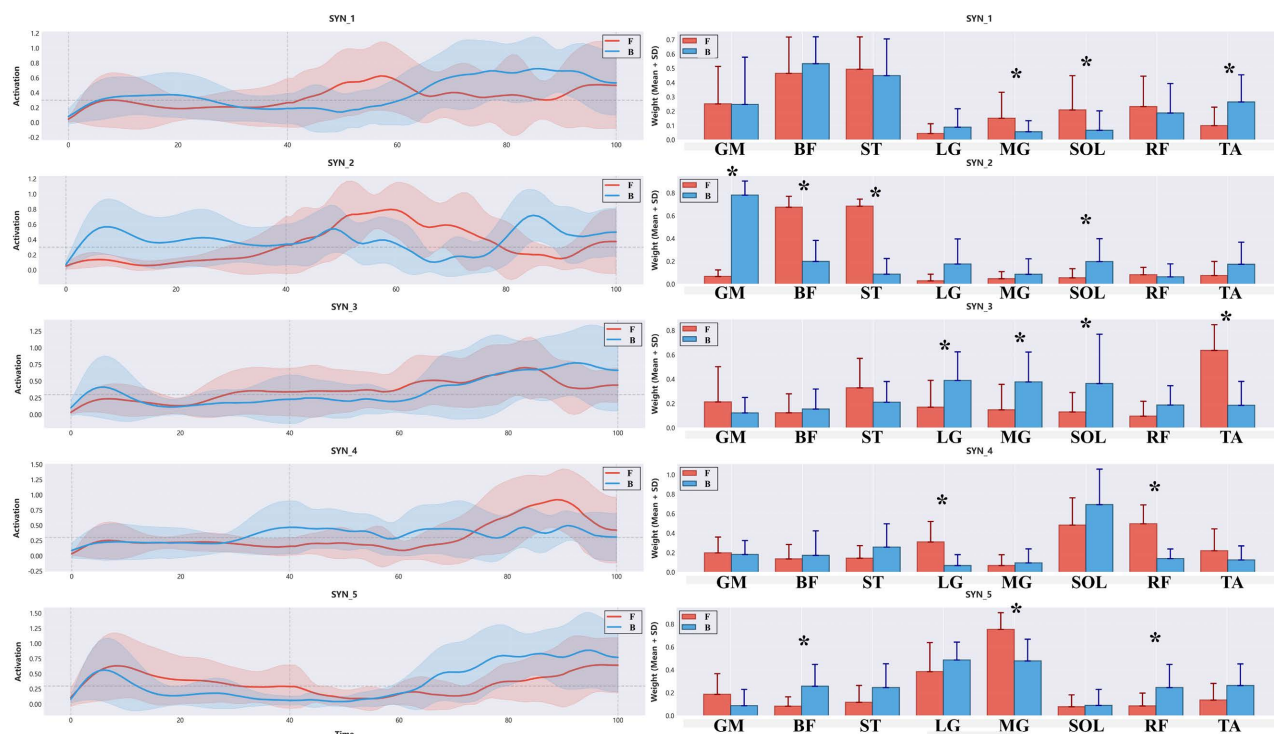


Figure 2. Comparison of the spatiotemporal structure of muscle synergies between front-side swing-dominant and back-side propulsion-dominant sprinters. Note: The left panel shows the temporal structure of muscle synergies, namely the motor primitives; the right panel shows the spatial structure of muscle synergies, namely the motor modules. SYN_1-SYN_5 denote the five muscle synergy modules. Red indicates front-side swing-dominant sprinters, and blue indicates back-side propulsion-dominant sprinters. GM, gluteus maximus; BF, biceps femoris; ST, semitendinosus; LG, lateral gastrocnemius; MG, medial gastrocnemius; SOL, soleus; RF, rectus femoris; TA, tibialis anterior. Dashed lines are used to assist in identifying key phases of the gait cycle.

3.4. Temporal Structure Characteristics of Muscle Synergies between Technical Groups

As shown by the motor-primitive curves in the left panel of **Figure 2**, front-side swing-dominant and back-side propulsion-dominant sprinters exhibited different activation-timing trends in several synergy modules. In SYN_1, front-side swing-dominant sprinters showed relatively higher activation during the middle portion of the gait cycle, whereas back-side propulsion-dominant sprinters showed a gradual increase in activation during the latter half of the gait cycle. In SYN_2, the activation peak in front-side swing-dominant sprinters was mainly concentrated in the middle portion of the gait cycle, whereas back-side propulsion-dominant sprinters showed pronounced activation features in both the early and late portions of the gait cycle.

In SYN_3, the temporal activation curves of both groups showed phase-dependent changes, but the primary between-group differences were reflected in the distribution of muscle weights within the synergy module. In SYN_4, front-side swing-dominant sprinters showed a more pronounced increase in activation during the later portion of the gait cycle. In SYN_5, both groups exhibited activation during the early portion of the gait cycle, whereas back-side propulsion-dominant sprinters showed a higher sustained activation trend during the later portion of

the gait cycle.

The motor-primitive curves were used to characterize the overall temporal features of synergy activation in the two groups. Because the inferential analysis in the present study focused on motor-module muscle weights, the observed motor-primitive differences should be interpreted as descriptive trends rather than statistically confirmed time-series differences. Future studies should apply one-dimensional statistical parametric mapping or other time-series analytical approaches to further test between-group differences in motor-primitive temporal structure.

4. Discussion

This study classified sprinters as front-side swing-dominant or back-side propulsion-dominant according to the front-side/back-side action ratio, and extracted lower-limb muscle synergy characteristics during sprinting using NMF. The results showed that the two groups differed in muscle weights across multiple synergy modules, indicating that distinct sprinting technical strategies are reflected not only in external kinematic characteristics but also in the coordinated recruitment patterns of lower-limb muscles. In particular, in SYN_2, front-side swing-dominant sprinters exhibited greater weights for the biceps femoris and semitendinosus, whereas back-side propulsion-dominant sprinters showed greater weights for the gluteus maximus and soleus, suggesting marked differences in the functional organization of the posterior-chain musculature between the two technical strategies. Moreover, differences in the weights of the medial gastrocnemius, lateral gastrocnemius, soleus, tibialis anterior, and rectus femoris in SYN_1, SYN_3, SYN_4, and SYN_5 further indicate that the two groups may adopt distinct neuromuscular control strategies for regulating ankle stiffness, preparing pre-contact posture, and coordinating the stance-swing phase transition.

4.1. Differences in Posterior-Chain Recruitment Patterns between Front-Side Swing-Dominant and Back-Side Propulsion-Dominant Sprinters

SYN_2 was the synergy module that most clearly differentiated the two technical strategies in the present study. Within this module, front-side swing-dominant sprinters showed significantly greater weights for the biceps femoris and semitendinosus than back-side propulsion-dominant sprinters, whereas back-side propulsion-dominant sprinters showed significantly greater weights for the gluteus maximus and soleus than front-side swing-dominant sprinters. These findings indicate that although both groups rely on the posterior chain during high-speed sprinting, the dominant muscles and functional emphases within the posterior-chain system differ between technical strategies.

The gluteus maximus is a key proximal muscle involved in hip extension and pelvic stabilization, and is closely associated with hip extension, trunk postural control, and stance-phase stability during running [8]. The greater gluteus maximus weight observed in SYN_2 among back-side propulsion-dominant sprinters

suggests that their stance-phase propulsion may rely more heavily on the active recruitment of proximal hip extensors. This is consistent with the technical profile of back-side propulsion-dominant sprinters, who exhibit more pronounced hip, knee, and ankle extension during late stance and a more evident back-side extension pattern. In other words, back-side propulsion-dominant sprinters may enhance stance-phase horizontal propulsive capacity through a gluteus maximus-dominant hip-extension synergy; meanwhile, the greater soleus weight further suggests an important role in ankle plantar flexion and lower-limb stiffness maintenance, thereby forming a posterior-chain propulsion pattern extending from proximal hip extension to distal push-off.

By contrast, the greater biceps femoris and semitendinosus weights observed in SYN_2 among front-side swing-dominant sprinters suggest that their posterior-chain function is not primarily expressed as gluteus maximus-dominant stance-phase push-off, but rather as hamstring-mediated control of the swing-to-stance transition. The biceps femoris and semitendinosus are biarticular hamstring muscles spanning both the hip and knee joints, contributing to hip extension as well as knee flexion. Previous studies have shown that, during the terminal swing phase of high-speed running, the hamstrings are exposed to high mechanical demands and generate hip-extension and knee-flexion moments through eccentric activity, thereby decelerating thigh forward swing and shank forward motion and providing control for pre-contact lower-limb posture adjustment [9] [10]. Therefore, the greater hamstring weights observed in front-side swing-dominant sprinters may reflect a stronger demand for hip-extension-knee-flexion coordination during late swing and the pre-contact phase, facilitating active downward action after thigh forward swing, pre-contact foot control, and preparation for rapid transition into stance.

These findings indicate that front-side swing dominance does not imply a reduced role of the posterior chain; rather, it reflects a functional shift of the posterior chain from late-stance push-off propulsion toward segmental control and temporal regulation during late swing and the pre-contact phase. In contrast, back-side propulsion dominance is characterized by a more prominent stance-phase propulsive synergy involving the gluteus maximus and soleus. This difference suggests that the two technical strategies involve distinct organizational patterns of posterior-chain recruitment: front-side swing dominance emphasizes hamstring-mediated control during the swing-to-stance transition, whereas back-side propulsion dominance highlights the leading role of the gluteus maximus in hip-extension and push-off propulsion.

4.2. Differences in Distal Muscle Groups Reflect Distinct Ankle Stiffness and Pre-Contact Control Strategies

In addition to differences in proximal posterior-chain muscles, this study also identified marked between-group differences in the weights of the triceps surae and tibialis anterior. In SYN_1, front-side swing-dominant sprinters showed sig-

nificantly greater weights for the medial gastrocnemius and soleus than back-side propulsion-dominant sprinters, whereas back-side propulsion-dominant sprinters showed a significantly greater tibialis anterior weight. In SYN_3, back-side propulsion-dominant sprinters showed significantly greater weights for the lateral gastrocnemius, medial gastrocnemius, and soleus than front-side swing-dominant sprinters, whereas front-side swing-dominant sprinters showed a significantly greater tibialis anterior weight. These findings suggest that distal ankle control in the two technical strategies is not characterized simply by a sustained increase in a single muscle, but rather by module-specific functional specialization.

The triceps surae is a key muscle group for maintaining ankle stiffness, regulating forefoot support, and transmitting ground reaction forces during the stance phase of sprinting. Musculoskeletal simulation studies have shown that the soleus and gastrocnemius are major contributors to center-of-mass propulsion and support during the latter half of stance [11]. The generally higher weights of the lateral gastrocnemius, medial gastrocnemius, and soleus in SYN_3 among back-side propulsion-dominant sprinters suggest a greater reliance on the ankle plantar flexors for push-off and propulsion during the middle-to-late stance phase. This coordination pattern may enhance lower-limb extension output during stance; however, excessive reliance on ankle plantar flexion and back-side extension may prolong late-stance motion, thereby compromising rapid forward swing and pre-contact preparation for the subsequent step.

The significantly greater tibialis anterior weight observed in SYN_3 among front-side swing-dominant sprinters suggests a greater emphasis on pre-contact ankle dorsiflexion control and foot-posture adjustment. Moderate activation of the tibialis anterior during late swing helps maintain the foot in a dorsiflexed position, improves pre-contact controllability of the foot segment, and facilitates rapid forefoot touchdown and transition into stance. Therefore, the greater tibialis anterior weight in front-side swing-dominant sprinters may be associated with active pre-contact downward action, an active paw-back motion, and a faster stance-swing phase transition.

In SYN_4, front-side swing-dominant sprinters showed significantly greater weights for the lateral gastrocnemius and rectus femoris, further suggesting stronger synergistic coupling between thigh forward swing during the swing phase and distal stiffness regulation before ground contact. As a biarticular muscle spanning the hip and knee joints, the rectus femoris contributes to both hip flexion and knee extension, and its increased weight may reflect a greater demand for anterior-chain recruitment during thigh forward swing, downward action, and pre-contact preparation in front-side swing-dominant sprinters. Meanwhile, the increased weight of the lateral gastrocnemius may facilitate the rapid establishment of ankle stiffness around ground contact, thereby enhancing distal-segment stability and force-transmission efficiency during early stance. Previous research has reported an association between passive plantar-flexor stiffness and sprint performance, indicating that the mechanical properties of the distal ankle-calf muscle-tendon

complex may influence sprinting speed [12].

In SYN_5, front-side swing-dominant sprinters showed a significantly greater medial gastrocnemius weight than back-side propulsion-dominant sprinters, whereas back-side propulsion-dominant sprinters exhibited significantly greater weights for the biceps femoris and rectus femoris. This finding may reflect distinct control strategies between the two groups during the later portion of the gait cycle or the stance-swing transition. Front-side swing-dominant sprinters may rely more strongly on the medial gastrocnemius for distal elastic support and rapid transition into ground contact. The ankle plantar flexors, particularly the soleus and gastrocnemius, can reduce muscle-fiber mechanical work and optimize contractile conditions through the storage and release of elastic energy in the tendon, which may constitute an important mechanism of distal elastic support during high-speed running [13]. By contrast, back-side propulsion-dominant sprinters may require co-recruitment of the biceps femoris and rectus femoris to maintain hip-knee stability and facilitate transition after posterior extension. This pattern suggests that, after a more pronounced push-off, back-side propulsion-dominant sprinters may require greater coordinated control between the anterior and posterior thigh muscles to initiate the subsequent forward swing transition.

4.3. Effects of Different Technical Strategies on Neuromuscular Control Efficiency during Sprinting

From the perspective of neuromuscular control efficiency, front-side swing dominance and back-side propulsion dominance should not be interpreted merely as different levels of technical proficiency, but rather as distinct technical organization strategies shaped by individual strength profiles, gait rhythm, and stance-swing transition demands under high-speed sprinting conditions. Back-side propulsion-dominant sprinters exhibit a pronounced posterior-chain propulsive synergy involving the gluteus maximus, soleus, and triceps surae, which may enhance stance-phase hip extension, ankle plantar flexion, and horizontal propulsive capacity. This pattern may increase single-step propulsive output during stance, but its technical benefit depends on the temporal coupling between back-side extension and subsequent front-side recovery. If posterior lower-limb extension during late stance is excessive, it may prolong the time required for the limb to transition from the back-side region to the front-side swing region after toe-off, thereby compromising step-frequency maintenance and stance-swing transition efficiency.

Front-side swing-dominant sprinters, by contrast, exhibited a more pronounced swing-to-contact transition synergy involving the hamstrings, tibialis anterior, rectus femoris, and selected triceps surae muscles. This pattern may shorten the time spent in the back-side region, improve the quality of pre-contact preparation, and facilitate the rapid transition of the lower limb from swing to stance. During sprinting at maximal or near-maximal velocity, athletes must accomplish stance-phase braking, propulsion, and toe-off transition within an extremely short

ground contact time. Previous research has shown that higher top running speeds are achieved primarily through greater support forces applied to the ground, rather than simply through faster leg repositioning in the air [14]. Therefore, excessively prolonging late-stance push-off may not effectively enhance horizontal velocity and may instead disrupt gait rhythm. The hamstring-tibialis anterior-triceps surae synergy observed in front-side swing-dominant sprinters may therefore be more conducive to maintaining high-speed running rhythm and technical stability.

However, the present findings do not imply that front-side swing dominance is necessarily superior to back-side propulsion dominance. Haugen *et al.* have shown that front-side and back-side technical variables do not exhibit a simple linear relationship with sprint performance [1]. A more appropriate interpretation is that front-side swing dominance and back-side propulsion dominance represent two distinct neuromuscular control strategies. The former places greater emphasis on segmental adjustment and temporal control during swing and pre-contact preparation, whereas the latter emphasizes proximal hip extension and distal plantar-flexor propulsion during stance. Both strategies may support high-level sprint performance, but their efficiency depends on the degree of matching among an athlete's individual strength profile, gait rhythm, joint range of motion, and stance-swing transition capacity.

4.4. Training Implications

The present findings have practical implications for sprint technique diagnosis and event-specific training. First, for back-side propulsion-dominant sprinters, training should not focus solely on further increasing maximal strength of the gluteus maximus and triceps surae, but should also enhance the ability of the posterior chain to transition from stance-phase propulsion to rapid forward swing and pre-contact preparation. Training may incorporate hurdle runs, rapid high-knee drills, A-skips, fast leg-switch drills, and downward-action running drills to reduce excessive posterior limb displacement during late stance and to reinforce thigh forward swing, active pre-contact downward action, and stance-swing phase transition.

Second, for front-side swing-dominant sprinters, training should continue to strengthen the eccentric braking and temporal control capacity of the hamstrings during late swing and pre-contact preparation at high speed [9] [10]. Nordic hamstring exercises, Romanian deadlifts, slider leg curls, and resistance-band-assisted rapid paw-back drills may be used to improve the control capacity of the biceps femoris and semitendinosus during hip-extension-knee-flexion coordination, pre-contact paw-back action, and active downward movement. Importantly, hamstring training should not focus solely on increasing maximal strength, but should also emphasize activation timing, contraction velocity, and coordination with hip motion under high-speed conditions.

Third, ankle stiffness and distal pre-activation capacity should be emphasized

in training for both groups of sprinters. Back-side propulsion-dominant sprinters may use low-amplitude repeated jumps, isometric ankle-support exercises, and rapid forefoot-contact hopping drills to improve the triceps surae's capacity to regulate stiffness within short ground contact times; front-side swing-dominant sprinters may strengthen coordinated control between the tibialis anterior and triceps surae through resisted dorsiflexion, ankle-stiffness control drills, and rapid paw-back running drills, thereby optimizing pre-contact foot posture and post-contact force transmission efficiency.

4.5. Limitations and Future Directions

This study has several limitations. First, the sample size was small, with only four athletes in each of the front-side swing-dominant and back-side propulsion-dominant groups; therefore, the present findings should be interpreted as exploratory and require validation in future studies with larger samples and athletes of different competitive levels. Second, the technical classification in this study was primarily based on two-dimensional sagittal-plane video analysis and the front-side/back-side action ratio, which can reflect anterior-posterior lower-limb movement tendencies but cannot fully replace three-dimensional kinematic and kinetic analyses. In particular, the definition of the back-side propulsion-dominant type was mainly based on back-side extension characteristics and was not directly validated using ground reaction forces, joint work, or joint moments. Future studies should integrate three-dimensional motion capture, force platforms, and musculoskeletal modeling to further clarify the relationships between front-side swing and back-side propulsion techniques and their associated mechanical outputs.

In addition, this study primarily focused on differences in the spatial modules of muscle synergies, namely changes in the weights of individual muscles within each synergy module. Although the motor-primitive curves suggested potential between-group differences in activation timing for certain synergy modules, more rigorous statistical testing of the synergy activation curves is still required using one-dimensional statistical parametric mapping or other time-series analytical approaches. Future research should integrate the temporal structure of muscle synergies with joint kinematics and ground reaction forces to further elucidate the coupling relationships among motor modules, motor primitives, and mechanical output across different sprinting strategies.

5. Conclusions

This study demonstrated that front-side swing-dominant and back-side propulsion-dominant sprinters exhibit distinct lower-limb muscle synergy characteristics during sprinting. The differences between the two groups were reflected not only in lower-limb kinematic characteristics during sprinting, but also in the distribution of muscle weights within the synergy modules. Front-side swing-dominant sprinters showed greater involvement of the hamstrings, including the biceps femoris and semitendinosus, in certain synergy modules, suggesting a greater re-

liance on synergistic control during thigh forward swing, pre-contact lower-limb segment adjustment, and active downward action; in contrast, back-side propulsion-dominant sprinters exhibited more pronounced recruitment of the gluteus maximus, soleus, and triceps surae, indicating greater reliance on stance-phase hip extension, ankle plantar flexion, and posterior-chain propulsion mechanisms.

More broadly, distinct lower-limb technical strategies may induce functional reorganization of muscle synergy modules during sprinting. Front-side swing dominance was primarily characterized by synergy features related to the swing-to-contact transition, which may optimize pre-contact preparation and stance-swing phase transition; by contrast, back-side propulsion dominance was primarily characterized by posterior-chain propulsion-related synergy features, which may enhance stance-phase propulsive capacity. These findings suggest that technical differences during the sprinting phase fundamentally reflect differences in muscle synergy recruitment and neuromuscular control strategies, providing a mechanistic basis for sprint technique diagnosis and individualized training optimization.

Funding

This study was funded by the 27th Session of the Extracurricular Academic and Technological Activities for Students at Zhejiang Normal University (No.144).

Conflicts of Interest

The authors declare no conflicts of interest.

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