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ORIGINAL RESEARCH ARTICLE | SIMULATION-BASED STUDY

Mechanical Efficiency and Muscle Activation Patterns During Repeated Sprint Exercise

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Abstract

Background: Repeated sprint exercise involves rapid force generation under accumulating metabolic and neuromuscular demands. Mechanical output and surface electromyographic signals may change differently across successive efforts. Objective: This simulation-based study examined modeled sprint performance, a mechanical-efficiency proxy, and lower-limb muscle activation across six repeated sprints. Methods: A synthetic cohort of 48 recreationally trained adults completed a modeled protocol of six 30-m sprints separated by 25 seconds of passive recovery. Sprint time, estimated horizontal mechanical work, an operational efficiency proxy, and normalized vastus lateralis and biceps femoris surface electromyographic amplitude were generated with correlated within-person variation. Results: Mean modeled sprint time increased from 4.46 to 4.79 seconds across efforts. The efficiency proxy decreased from 0.83 to 0.76 arbitrary units; normalized vastus lateralis amplitude increased from 1.00 to 1.12 while biceps femoris amplitude changed from 1.00 to 1.07. Associations between performance decrement and activation changes were weak to moderate. Conclusion: The synthetic analysis illustrates how repeated-sprint performance and EMG patterns may diverge as exercise progresses. The numerical results are properties of the simulation, not observations from recruited participants.

Keywords: repeated sprint ability; mechanical efficiency; surface electromyography; fatigue; sprint biomechanics; synthetic data

How to Cite This Article

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Research transparency: All records and statistical results are synthetic. No participants were recruited, no sprint testing was conducted, and no ethics approval is claimed.

1. Introduction

Repeated sprint exercise requires athletes to reproduce high-intensity locomotor efforts despite short recovery intervals. Performance can deteriorate across successive sprints as mechanical, metabolic, and perceptual demands accumulate. Sprint time is an accessible summary of performance, but it does not identify which aspects of the movement or neuromuscular system account for the observed decrement.

Horizontal force application, step mechanics, contact timing, and lower-limb muscle activation may each change during repeated sprinting. Their relationships are not necessarily linear. An increase in electromyographic amplitude can coexist with lower external performance, for example when the neuromuscular system responds to fatigue by altering activation while mechanical effectiveness declines.

The present manuscript uses a synthetic repeated-measures dataset to illustrate the joint reporting of sprint times, an explicitly operational mechanical-efficiency proxy, and surface electromyographic outcomes. The model is designed to preserve variation across individuals and efforts rather than impose a perfectly uniform fatigue response.

1.1 Research Questions and Analytical Framework

The primary question concerned the pattern of sprint-time change across six modeled 30-m efforts. Secondary questions addressed whether a mechanical-efficiency proxy decreased over the same sequence and whether normalized quadriceps and hamstring EMG amplitudes changed in parallel with external performance.

Mechanical efficiency is used cautiously in this manuscript. True mechanical efficiency requires a defensible ratio between external mechanical work and metabolic energy expenditure. Because no metabolic measurements were modeled, the study reports a unitless mechanical-effectiveness proxy rather than physiological efficiency in the strict thermodynamic sense.

The synthetic framework assumes that sprint times worsen modestly across repetitions, while activation signals may increase as the modeled task becomes more demanding. It also allows different responses in vastus lateralis and biceps femoris to demonstrate that muscle-specific EMG patterns cannot be reduced to a single global fatigue score.

2. Methods: Synthetic Repeated-Sprint Design

A synthetic cohort of 48 recreationally trained adults was constructed. Each modeled record contained six observations corresponding to 30-m sprint efforts separated by 25 seconds of passive recovery. The design therefore comprised 288 repeated sprint observations. Age and training exposure were generated as background descriptors but were not interpreted as real participant characteristics.

Sprint-time values were generated using a participant-specific baseline component, a repetition effect, and within-person residual variability. The same participant-level structure was used to create correlated but nonidentical changes in mechanical and EMG outcomes. The model included both athletes with minimal decrement and athletes with larger modeled decrements.

No field or laboratory procedures occurred. Protocol details describe the hypothetical design represented by the synthetic data and should not be interpreted as documentation of a completed experiment.

Design element	Specified value
Synthetic records	48
Sprint repetitions	6 × 30 m
Passive recovery	25 seconds
Repeated observations	288
Main outcomes	Sprint time, mechanical proxy, normalized EMG

2.1 Measurement Model

Sprint performance was represented by completion time in seconds. A within-person sprint decrement was calculated as the percentage difference between later sprint times and the first sprint. This approach preserves a readily interpretable performance measure without assuming that time alone captures every component of sprint mechanics.

The mechanical-effectiveness proxy was modeled on a unitless scale from zero to one. It represented a standardized index combining estimated horizontal propulsive work and sprint velocity, scaled to the first effort. The index was constructed for illustration and was not treated as a directly measured ratio of mechanical to metabolic energy.

Normalized EMG amplitude was represented by the root-mean-square amplitude relative to the first sprint for vastus lateralis and biceps femoris. Values above 1.00 indicate higher modeled amplitude than at baseline. Such amplitude differences do not directly quantify motor-unit recruitment, neural drive, or fatigue mechanism.

2.2 Statistical Approach

Continuous outcomes were summarized by repetition using synthetic means and standard deviations. The primary within-person contrast compared the first and sixth efforts. Repeated-measures patterns were described using a mixed-model framework with sprint number as a fixed effect and a participant-specific random intercept.

Exploratory associations were represented by correlations between sprint-time decrement, change in the mechanical-effectiveness proxy, and change in normalized EMG amplitude. Emphasis was placed on effect direction and magnitude rather than on significance testing, because inferential probability values derived from synthetic observations cannot establish population-level evidence.

Sensitivity analyses compared the first-to-last contrast with the average of early and late efforts and assessed whether the overall pattern changed after excluding records with unusually large modeled sprint decrements.

3. Synthetic Cohort and Baseline Profile

The synthetic cohort contained 48 adult records with an illustrative mean age of 24.6 years and a modeled weekly training exposure of 6.4 hours. First-sprint time averaged 4.46 seconds. Baseline activation values were normalized to 1.00 for each muscle by definition.

Participant-specific variation was retained across all outcomes. Some records showed relatively stable sprint times, whereas others displayed a progressive slowing. The mechanical-effectiveness proxy was allowed to vary partly independently of sprint time, preventing a deterministic relationship between the two variables.

Table 1 presents the illustrative starting characteristics. These numbers are not estimates of an actual athlete population and should not be used as normative benchmarks.

Characteristic	Synthetic summary
Records	48
Age (years)	24.6 ± 3.8
Weekly training (hours)	6.4 ± 2.1
Sprint 1 time (s)	4.46 ± 0.27
Sprint 1 effectiveness proxy	0.83 ± 0.06
Sprint 1 normalized EMG	1.00 (reference)

3.1 Sprint Performance Across Repetitions

Mean sprint time increased progressively from 4.46 seconds during the first effort to 4.79 seconds during the sixth effort. The modeled absolute difference was 0.33 seconds, equivalent to approximately 7.4% of first-sprint time. The largest increments occurred during the later repetitions rather than being imposed as an identical increase at every effort.

Individual responses varied around the mean trend. A subset of synthetic records displayed little slowing, while others exhibited substantially greater time decrements. This variation is important for interpreting repeated-sprint data because an average trajectory can obscure the dispersion of individual responses.

The modeled pattern is consistent with the general concept of performance decrement during repeated high-intensity exercise, but its numerical magnitude is defined by the simulation assumptions.

Sprint	Mean time (s)	Change from sprint 1
1	4.46	—
2	4.50	+0.04
3	4.56	+0.10
4	4.63	+0.17
5	4.71	+0.25
6	4.79	+0.33

3.2 Mechanical-Effectiveness Proxy

The unitless mechanical-effectiveness proxy declined from 0.83 at the first sprint to 0.76 at the sixth. The relative change was approximately −8.4%. The trajectory was not forced to match sprint-time change exactly; some synthetic records retained a relatively stable proxy despite slower completion times.

This divergence demonstrates the importance of operational definitions. A composite index of horizontal mechanical output can provide a useful descriptive dimension, but it cannot be equated with whole-body metabolic efficiency. Such a distinction is especially important when interpreting repeated high-intensity exercise, where metabolic cost and mechanical performance may change on different timescales.

The model therefore treats the proxy as an exploratory outcome. It supports discussion of measurement structure without implying that the simulation has quantified physiological efficiency.

Sprint	Effectiveness proxy
1	0.83
2	0.82
3	0.81
4	0.79
5	0.78
6	0.76

3.3 Muscle Activation Patterns

Normalized vastus lateralis EMG amplitude increased from 1.00 to 1.12 across the six modeled efforts. Biceps femoris amplitude increased more modestly, from 1.00 to 1.07. The simulation included substantial within-person variation in both muscle signals, reflecting the fact that EMG responses are sensitive to measurement and task factors.

Changes in amplitude were not treated as direct evidence of greater motor-unit recruitment. Surface EMG is influenced by electrode placement, signal cancellation, muscle geometry, movement artifact, and normalization procedures. The same observed amplitude may arise from different physiological configurations.

The muscle-specific differences illustrate why EMG outcomes should be reported separately and interpreted alongside mechanical performance rather than used as an independent explanation of fatigue.

Sprint	Vastus lateralis	Biceps femoris
1	1.00	1.00
2	1.02	1.01
3	1.04	1.03
4	1.07	1.04
5	1.09	1.06
6	1.12	1.07

3.4 Relationships and Sensitivity Checks

Across synthetic records, the modeled association between sprint-time decrement and decline in the effectiveness proxy was moderate (r = −.48 when proxy change retained its signed direction). The association between time decrement and vastus lateralis EMG change was smaller (r = .29), while the corresponding biceps femoris relationship was weak (r = .17).

Using mean performance from the first two and final two efforts preserved the direction of the modeled sprint-time and proxy changes. Excluding the most extreme simulated sprint decrements reduced the mean performance loss but did not reverse the overall pattern.

These sensitivity checks demonstrate how repeated-sprint findings can be tested against alternative summary choices. They do not provide independent validation of the underlying assumptions because the same synthetic process generated all observations.

Illustrative association	Correlation
Time decrement–proxy change	−.48
Time decrement–VL EMG change	.29
Time decrement–BF EMG change	.17

4. Discussion

The synthetic repeated-sprint protocol produced a progressive slowing of sprint times, a reduction in the mechanical-effectiveness proxy, and modest increases in normalized EMG amplitude. The trajectories were related but not identical. This distinction is central to the interpretation of repeated-sprint performance, because external output and muscle electrical activity describe different features of the task.

An increase in EMG amplitude alongside declining sprint performance can be compatible with several explanations, including altered activation strategy, task demands, and signal properties. It does not isolate a specific neural or muscular cause. Similarly, reduced effectiveness-proxy values do not establish a reduction in thermodynamic efficiency.

The modeled correlations were moderate or smaller, reinforcing that no single indicator captured the entire response. In empirical investigations, combined mechanical and electrophysiological measurements would require rigorous synchronization, normalization, and attention to measurement reliability.

In applied performance monitoring, repeated-sprint time provides a straightforward description of an athlete's ability to sustain short high-intensity efforts. Complementary mechanical measures may help characterize changes in force application, while EMG may offer information about muscle activity under carefully standardized conditions. The measures should not be interpreted as interchangeable.

The principal limitation of this manuscript is its synthetic dataset. All means, correlations, and trends are outcomes of the selected data-generation rules. No athletes performed the protocol, and the results cannot support claims about the magnitude of fatigue responses in a real population.

Additional simplifications include the absence of metabolic measurements, direct force-platform data, and a fully specified EMG acquisition pipeline. The proxy outcome was deliberately labeled to avoid implying that true mechanical efficiency had been measured.

The simulation demonstrates an internally coherent approach to reporting repeated-sprint performance alongside mechanical and EMG outcomes. Under the specified assumptions, sprint time increased across six efforts, the mechanical-effectiveness proxy declined, and normalized activation amplitudes rose modestly. These patterns illustrate analytical possibilities rather than empirical training or fatigue effects.

Ethics: No human participants or personal data were involved. Funding: No external funding was received for this illustrative manuscript. Conflicts of interest: None declared for the synthetic demonstration. Data availability: The reported dataset is synthetic.

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Publication note: This is a simulation-based manuscript. The names and bibliographic record are illustrative and do not establish an actual 2023 publication.