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ORIGINAL RESEARCH ARTICLE | SIMULATION-BASED STUDY

Exercise-Induced Fatigue and Changes in Lower-Limb Kinematics During Endurance Running

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Abstract

Background: Prolonged running can alter neuromuscular control and movement patterns, but fatigue-related changes differ across runners and kinematic variables. Objective: To illustrate a repeated-measures analysis of lower-limb kinematics during an endurance-running fatigue protocol using synthetic observations. Methods: A fully simulated cohort of 64 adult recreational runners was modeled at baseline, mid-run, and a late-run fatigue stage. Outcomes comprised knee flexion at initial contact, peak stance knee flexion, hip adduction, ankle dorsiflexion, step frequency, and perceived exertion. Linear mixed-model contrasts and within-run associations were represented descriptively. Results: In the synthetic dataset, mean perceived exertion increased from 9.2 to 17.1 units, peak stance knee flexion increased from 42.0° to 45.1°, hip adduction increased from 9.8° to 12.0°, and step frequency declined from 172 to 168 steps/min. Individual trajectories overlapped substantially. Conclusions: Under the defined simulation assumptions, accumulated running fatigue coincided with modest changes in selected kinematic variables. These outputs illustrate analytical reporting and are not measurements from actual runners.

Keywords: endurance running; fatigue; lower-limb kinematics; gait biomechanics; perceived exertion; simulation

How to Cite This Article

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Research transparency: All records and outcomes are synthetic. No human participants were recruited, tested, or followed.

1. Introduction

Running mechanics emerge from interactions among musculoskeletal capacity, task constraints, speed, and the runner's neuromotor strategies. During sustained exercise, fatigue may influence the regulation of joint motion and temporal characteristics of gait. Changes in kinematics are not necessarily uniform, because individuals can redistribute movement demands in different ways.

Fatigue is a multifaceted state rather than a single physiological event. Perceived exertion, local muscular fatigue, cardiovascular strain, and central adjustments can follow different time courses. A runner may maintain speed while modifying cadence or joint excursion, whereas another may reduce pace with comparatively stable joint angles.

Lower-limb kinematic outcomes commonly examined in running include knee flexion, hip adduction, ankle motion, and step frequency. Each measure depends on operational definitions, running conditions, and measurement technique. A modest average change may also conceal opposing individual responses.

This manuscript uses a synthetic repeated-measures framework to illustrate how fatigue-stage contrasts and individual variability can be reported without claiming that the generated values were observed in an actual endurance-running study.

1.1 Objectives and Analytical Rationale

The primary objective was to examine modeled within-run differences in knee and hip kinematics across three fatigue stages. Secondary objectives addressed ankle dorsiflexion, step frequency, and associations with perceived exertion. A third objective was to demonstrate how mixed-model estimates can coexist with heterogeneous individual trajectories.

The conceptual framework assumes that accumulating exertion may coincide with changes in lower-limb movement, but it does not impose a universal compensatory strategy. In the simulation, knee flexion and hip adduction were allowed to increase modestly, step frequency to decline slightly, and ankle motion to show comparatively small average change.

These directional assumptions are not presented as new physiological discoveries. They define a transparent example of a repeated-measures dataset in which statistical descriptions can be internally consistent while causal interpretation remains limited.

2. Methods: Synthetic Cohort and Protocol

Sixty-four synthetic records represented recreational adult endurance runners. Each record contained three repeated observations: an early-run baseline, a mid-run assessment, and a late-run fatigue-stage assessment. The model assumed a continuous treadmill-running task at an individually standardized moderate-to-vigorous intensity.

Runner age, body mass, training history, and preferred step frequency were generated within plausible adult ranges. The synthetic protocol retained the same nominal running speed at the three measurement stages to reduce direct confounding by pace, although the data do not reproduce actual physiological responses to controlled-speed running.

Repeated outcomes were generated using participant-level random intercepts and correlated residual terms. This structure allowed each modeled runner to retain a characteristic movement pattern while also exhibiting stage-related changes and measurement variability.

No real recruitment, informed-consent procedure, motion-capture recording, or fatigue test took place. The protocol is a simulation design rather than a report of a completed human-participant experiment.

Design element	Synthetic specification
Records	64 adult runners
Assessment points	Early, middle, late run
Task	Constant-speed endurance run
Primary outcomes	Knee and hip joint angles
Analysis	Repeated-measures contrasts

2.1 Kinematic and Fatigue Measures

Knee flexion at initial contact was represented as the sagittal-plane angle at the first frame of stance. Peak stance knee flexion was the maximum modeled flexion angle during stance. Hip adduction represented frontal-plane motion during the stance phase. Ankle dorsiflexion was defined as peak modeled dorsiflexion during stance.

Step frequency was represented in steps per minute. Perceived exertion was modeled on a 6–20 rating scale and served as an index of subjective exercise intensity rather than a direct measure of peripheral or central fatigue.

All kinematic angles were expressed in degrees. The synthetic data-generation process included participant-level offsets, stage effects, and measurement variation. Consequently, stage means are descriptive summaries of constructed values and not normative reference values.

The simulated outcome set was intentionally limited. Ground-reaction forces, joint moments, muscle activity, and metabolic responses were not generated, so mechanical loading and physiological fatigue mechanisms could not be inferred.

2.2 Statistical Analysis

Descriptive summaries were organized by fatigue stage using means and standard deviations. Stage-related differences were represented as late-minus-early contrasts, with attention to direction, magnitude, and variability rather than statistical significance alone.

A linear mixed-effects framework with a participant-level random intercept was specified to account for repeated observations within the same synthetic runner. Fatigue stage was treated as a categorical fixed factor. An alternative model considered perceived exertion as a continuous covariate.

Change-score correlations were used to describe whether runners with larger increases in perceived exertion also showed larger modeled kinematic changes. Because the dataset was constructed with prespecified covariance, inferential tests would describe the synthetic sample rather than support generalization to a runner population.

Interpretation emphasized the difference between statistical association, practical importance, and causal explanation. Repeated measurement improves description of trajectories but does not, on its own, identify the biological source of a change.

3. Results: Fatigue-Stage Descriptives

Perceived exertion increased across the three synthetic assessments, with a mean of 9.2 at the early stage, 13.8 at the middle stage, and 17.1 at the late stage. The progression was designed to represent increasing subjective strain during a prolonged run.

Peak stance knee flexion increased from 42.0° to 45.1° between early and late stages. Mean hip adduction increased from 9.8° to 12.0°. Step frequency decreased from 172 to 168 steps per minute. Changes in ankle dorsiflexion were smaller than those of the knee and hip variables.

The means conceal meaningful overlap among individual trajectories. Some synthetic runners showed little change in joint motion, whereas others showed larger shifts. The dataset therefore illustrates why group averages should be accompanied by distributional information.

Outcome	Early	Middle	Late
Perceived exertion	9.2	13.8	17.1
Peak knee flexion (°)	42.0	43.4	45.1
Hip adduction (°)	9.8	10.8	12.0
Ankle dorsiflexion (°)	19.4	19.8	20.1
Step frequency (steps/min)	172	170	168

3.1 Stage Contrasts and Individual Variation

The late-minus-early contrast was +3.1° for peak stance knee flexion and +2.2° for hip adduction. The corresponding change in ankle dorsiflexion was +0.7°, while step frequency declined by 4 steps per minute.

The direction of the modeled knee and hip changes was relatively consistent at the group level, but individual differences remained substantial. Participant-specific baseline offsets and stage-response terms produced overlapping distributions rather than complete separation across assessments.

Illustrative correlations between the increase in perceived exertion and kinematic changes were small to moderate. This pattern reflects the model assumption that subjective strain and joint motion share some variation but are not interchangeable indicators.

The numerical contrasts provide a coherent worked example of fatigue-stage reporting. They do not estimate the magnitude of gait adaptation expected in a real running population.

Late vs early outcome	Synthetic mean difference
Peak knee flexion	+3.1°
Hip adduction	+2.2°
Ankle dorsiflexion	+0.7°
Step frequency	−4 steps/min
Perceived exertion	+7.9 units

3.2 Mixed-Model Interpretation

The illustrative mixed-model contrasts retained positive late-stage coefficients for peak knee flexion and hip adduction and a negative coefficient for step frequency. Participant-level random intercepts represented stable differences among modeled runners.

An alternative specification including perceived exertion reduced some stage coefficients, as expected when exertion and stage were correlated by construction. This adjustment does not establish that exertion mediates the effect of running duration, because both variables were defined within the same simulation structure.

Model residuals were allowed to vary across outcomes. The smallest relative stage contrast occurred for ankle dorsiflexion, illustrating that not every kinematic measure must respond similarly to the same modeled exposure.

The mixed-model framework is useful for separating average stage patterns from individual baselines. Its interpretive value in empirical research depends on the validity of the recorded measurements, missing-data assumptions, and appropriateness of the covariance structure.

4. Discussion

The synthetic results illustrate modest changes in selected lower-limb kinematics during a prolonged running task. Increasing perceived exertion coincided with greater modeled peak stance knee flexion and hip adduction and a small decline in step frequency.

Such a pattern is compatible with the broader idea that runners may adjust movement organization as exercise demands accumulate. However, joint angles alone cannot identify whether a movement change reflects fatigue, deliberate pacing, altered stiffness, discomfort, or measurement variation.

Individual heterogeneity is central to interpreting fatigue-related gait changes. Athletes differ in training history, strength, technique, and tolerance of prolonged exercise. Averages can summarize a group but should not be treated as a universal movement strategy.

The simulation does not link the modeled kinematic changes to injury risk or performance deterioration. Those outcomes would require additional measurements, appropriate follow-up, and a design capable of testing the relevant hypotheses.

The defining limitation is the use of fully synthetic observations. All stage effects, distributions, and correlations were introduced through the data-generation framework. No treadmill protocol was performed and no motion-capture measurements were collected. The results are not empirical evidence of fatigue-related changes in running mechanics.

The model further simplifies speed regulation, physiological fatigue, foot-strike patterns, and the complex three-dimensional nature of gait. It includes three observation points and does not represent the full continuous evolution of movement during exercise.

Within these limits, the manuscript demonstrates an internally consistent approach to describing repeated kinematic outcomes. The synthetic late-run stage showed increased knee flexion and hip adduction, a small increase in ankle dorsiflexion, and reduced step frequency, with considerable modeled individual variation.

Ethics: No human participants or identifiable records were involved. Funding: No external funding was received for the illustrative manuscript. Conflicts of interest: None declared for this simulation manuscript.

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