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A conceptual integration of physiological and biomechanical load in distance running

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ABSTRACT

The distinction between physiological and biomechanical load has become increasingly salient in both scientific and coaching discourse on endurance running. While physiological load has long been operationalised through metrics such as heart rate, lactate, and training impulse (TRIMP), biomechanical load remains conceptually and empirically less defined. This paper examines the current debate surrounding the measurement of biomechanical stress and proposes an integrative framework that situates both forms of load within a neuromuscular systems perspective. Drawing on recent work in biomechanics (Edwards, 2018; Matijevich et al., 2019) and exercise physiology (Seiler, 2010; Jones & Burnley, 2009), it is argued that the two domains cannot be adequately understood in isolation. Rather, they must be conceptualised as interacting dimensions of the same adaptive process. Physiological load governs metabolic strain and recovery kinetics, whereas biomechanical load shapes the structural tolerance and efficiency of movement. The paper outlines the limitations of current modelling approaches, such as device-derived impact scores, and advances a conceptual synthesis, an integrated model, which views neuromuscular recruitment as the mediating process through which metabolic and mechanical stress co-evolve.

Keywords: Physiological load, Biomechanical load, Running economy, Neuromuscular coordination, Training load, Injury risk.

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INTRODUCTION

In the past decade, endurance training has seen a growing interest in distinguishing between physiological and biomechanical load as partially independent dimensions of stress. Physiological load refers broadly to the energetic demand placed upon the cardiovascular and metabolic systems during exercise, often quantified through measures such as oxygen uptake, heart-rate derived training impulse (TRIMP), or sessional ratings of perceived exertion (Calvert et al., 1976; Foster et al., 2001). Biomechanical load, by contrast, concerns the mechanical strain experienced by tissues (muscles, tendons, bones, and ligaments) as a consequence of repetitive force application (Edwards, 2018).

Despite conceptual clarity, the empirical delineation between these forms of load remains elusive. Physiological stress is readily measurable through indirect metabolic proxies; biomechanical stress, however, is distributed across complex structures, making it difficult to estimate from external metrics such as speed or ground-reaction force (Matijevich et al., 2019). Recent attempts to derive biomechanical indicators from wearable devices (e.g. Stryd’s Impact Loading Rate or Garmin’s Running Tolerance) have popularised the notion that such stress can be numerically expressed. Yet the scientific validity of these algorithms is limited, as the highest predictors of tissue injury arise not from impact forces per se, but from active muscle contractions and their associated internal stresses (Edwards, 2018; Matijevich et al., 2019).

This conceptual confusion has created a methodological asymmetry in the endurance community: physiological load is tracked with precision, while biomechanical load remains inferred. The consequences are significant. Many athletes modulate their training primarily through heart-rate and pace metrics, assuming that mechanical stress scales linearly with metabolic demand. However, the relationship between force magnitude and tissue damage is highly non-linear (Edwards, 2018). Doubling the internal load within the Achilles tendon or tibia may produce an exponential increase in micro-damage per stride, even when the metabolic cost appears modest. The present paper therefore aims to clarify this relationship by situating both load types within a systems framework that recognises neuromuscular recruitment as the integrative mediator.

PHYSIOLOGICAL LOAD: ENERGETICS AND SYSTEMIC STRESS

The study of physiological load originates in classical exercise physiology and has been refined through decades of work on energy systems, cardiovascular dynamics, and hormonal adaptation (Bassett & Howley, 2000). In endurance running, it refers to the metabolic cost incurred by sustaining submaximal or maximal oxygen consumption (VO_2) over time. The quantification of this load has evolved from simple heart-rate monitoring to complex composite indices such as TRIMP (Calvert et al., 1976), Edwards’ modified TRIMP (1993), and the more recent Training Stress Score (Allen & Coggan, 2010), all of which attempt to link internal effort to external work.

Physiological load represents the stress applied to systems responsible for oxygen transport, substrate utilisation, and energy resynthesis. During running, oxygen consumption increases with speed until it reaches a plateau at maximal aerobic capacity (VO_{2max}). Although VO_{2max} is often cited as a primary determinant of endurance performance, evidence indicates that its ceiling is reached relatively early in an athlete’s development, after which further improvement depends on submaximal efficiency and lactate kinetics (Joyner & Coyle, 2008; Seiler, 2010). Thus, while VO_{2max} defines the upper limit of aerobic metabolism, the capacity to sustain a high fraction of that maximum, so-called fractional utilization, is shaped by cumulative physiological load over time (Jones & Burnley, 2009).

The accumulation of physiological stress is essential to adaptation but also constrained by recovery capacity. Overexposure leads to maladaptive states such as non-functional overreaching or overtraining syndrome (Meeusen et al., 2013). Consequently, endurance programming seeks to balance the magnitude and frequency of load with adequate restitution. The polarised training model (Seiler & Tønnessen, 2009) has gained prominence for its efficiency in managing this balance: approximately 80% of volume is performed at low intensities (Zone 1–2), while the remaining 20% targets thresholds and VO_{2max} stimuli. This distribution minimises chronic sympathetic stress while preserving high-quality stimuli for central adaptations.

However, these models remain predominantly metabolic. They quantify cardiovascular strain but say little about the structural stresses that accompany running. For example, two athletes may record identical TRIMP scores for a session, yet one may accumulate far more tissue load due to differences in body mass, stride mechanics, or surface hardness. Moreover, traditional physiological models assume a quasi-linear relationship between intensity and total load, whereas musculoskeletal damage increases exponentially with speed and ground-reaction forces (Matijevich et al., 2019).

Recent evidence has further complicated this picture by demonstrating that the metabolic and mechanical components of training do not always co-vary. Studies using inverse dynamics and musculoskeletal modelling (Farris & Sawicki, 2012; Vernillo et al., 2017) show that small increases in running speed disproportionately elevate the force-time integral on the lower limb, especially in the Achilles tendon and tibia. These increases occur even when the change in heart rate or oxygen uptake is minimal. Consequently, monitoring physiological load alone risks underestimating the true stress experienced by the tissues.

At the same time, the adaptive processes governing physiological load cannot be isolated from mechanical context. Capillary proliferation, mitochondrial biogenesis, and enzymatic adaptation all depend upon repeated muscle contractions that produce both metabolic and mechanical stimuli. In this sense, physiological and biomechanical load are not parallel phenomena but two expressions of the same neuromuscular act. This recognition provides the conceptual bridge toward an integrated model of load, developed further in the next section of this paper, in which the neuromuscular recruitment system is positioned as the critical interface between metabolic and structural adaptation.

FROM COMPETING LOADS TO AN INTEGRATED PRACTICE

The contemporary discourse on training stress in distance running has crystallised around two ostensibly incompatible vantage points. On the one hand stand physiological accounts that render training legible through global energetic markers: heart-rate dynamics, oxygen flux, lactate turn-points, and their various derivatives (e.g., TRIMP, TSS). On the other, biomechanical accounts insist that injury risk and durability are better understood as the history of forces borne by tissues with finite fatigue lives. Each, when pursued to its limit, becomes reductionist. The former struggles to explain why identical "*load*" as indexed by heart-rate–based metrics can precipitate divergent injury outcomes. The latter cannot, on its own, specify how an identical pattern of tissue forces can elicit radically different metabolic adaptations depending on the surrounding milieu of recovery and systemic stress. The practical task, therefore, is not to pick a winner but to elucidate the higher-order unity in which both perspectives become moments of a single training logic.

LIMITS OF SCALAR PHYSIOLOGY

The attraction of scalar physiological metrics is obvious: they compress heterogeneous experience into a single number that appears amenable to arithmetic periodisation (Calvert et al., 1976; Allen & Coggan, 2010).

Yet such scalars presuppose smooth mappings from internal energetic state to performance and from cumulative arithmetic to adaptive trajectory. Two problems follow.

First, equifinality: distinct session architectures can yield comparable integrated heart-rate or lactate profiles while imposing dissimilar neuromuscular and coordinative demands. A 40-minute continuous sub-threshold run and a session of short cruise intervals separated by extensive recovery may tally similarly in TRIMP, yet the latter preserves stride length and stiffness under repeated accelerations; the former rehearses economical monotony. Second, opacity to local damage: physiology-first metrics track systemic strain but remain insensitive to the distribution of peak forces per step that governs micro-damage accrual in load-bearing tissues (Edwards, 2018). Consequently, they are weak predictors of overuse injury despite their utility for gauging global fatigue.

BIOMECHANICAL INSISTENCE AND ITS ASYMMETRIES

Biomechanical treatments rectify this opacity by tracing how internal forces accumulate across steps, runs, and weeks. Crucially, the relevant loads are internal (e.g., tendon tensile force, tibial bending moment), not simply external surrogates such as ground-reaction force peaks or impact transients. Evidence increasingly demonstrates that common external proxies correlate only modestly with the internal stresses that drive damage (Matijevich et al., 2019). At the same time, tendon- and joint-level analyses show that substantial mechanical work can occur within the musculotendinous system with only subtle changes in external kinematics (Zelik & Franz, 2017), and that joint-level mechanical work can serve as an indirect measure of the energetic and coordination costs that shape movement strategies (Zelik & Kuo, 2012). Two asymmetries then become decisive.

The relationship between peak force and damage is highly nonlinear: small increases in peak or rate of loading can produce orders-of-magnitude increases in fatigue damage per cycle, particularly in bone and tendon (Edwards, 2018). Tissues adapt at different tempos and with different transfer properties. Muscle remodels quickly, tendon slowly (Kjaer et al., 2009; Magnusson et al., 2007); cortical bone responds to strain stimulus with a delayed and thresholder osteogenic effect (Hughes et al., 2020). A training week that marginally elevates internal Achilles loads may be metabolically innocuous yet materially hazardous if repeated without allowance for tendon remodelling.

FATIGUE, FORM, AND THE ECOLOGY OF COORDINATION

A common rejoinder is that fatigue alters mechanics, so longer repeats (e.g., 4 × 2000 m at 95% 5K) must, ceteris paribus, be more injurious than shorter ones (10 × 800 m) of equal total fast volume. The empirical picture is subtler. Changes in running kinematics under fatigue are typically modest, individual-specific, and not uniformly deleterious; some are plausibly protective (e.g., slightly increased cadence reducing per-step vertical excursion) (van Hooren et al., 2024). Moreover, the time actually spent in a highly maladaptive mechanical state during longer repetitions may be a small fraction of total work, particularly in trained runners whose coordinative patterns are stable. What does follow is not a universal ranking of set-shapes by danger, but a methodological caution: when progressing training, increasing intensity or duration changes damage far more than scalar physiology implies, and those changes are mediated by how coordination adapts under speed-and-fatigue constraints.

AN INTEGRATED CONCEPT OF LOAD

The foregoing suggests that "*load*" is neither a single scalar (physiology) nor an exhaustive vector of internal forces (biomechanics). Rather, load is a structured composite whose meaning is only realised in the interaction among three moments:

1. Metabolic moment: the global energetic signal that conditions mitochondrial biogenesis, capillary proliferation, and substrate use (Calvert et al., 1976; Allen & Coggan, 2010).
2. Mechanical moment: the spatiotemporal distribution of internal tissue forces across steps that governs fatigue damage and remodelling thresholds (Edwards, 2018; Matijevich et al., 2019).
3. Coordinative moment: the stability and plasticity of the motor solution under task constraints (speed, gradient, surface, footwear), which in turn modulates both metabolic cost and mechanical loading pathway (van Hooren et al., 2024).

Training planning, then, becomes the art of co-shaping these moments such that each supports the others: metabolic development proceeds under mechanical distributions that stay within safe fatigue budgets, and coordinative practice improves the runner's ability to express economy and preserve form under race-specific constraints.

This three-moment model can be read as a neuromuscularly-focused reformulation of existing load capacity frameworks (Gabbett, 2016; Bertelsen et al., 2017), in which structure-specific capacity and cumulative load are understood as emergent properties of interacting metabolic, mechanical, and coordinative processes.

PRACTICAL COROLLARIES

From this integrated concept follow several practice-relevant corollaries that refine, rather than reject, both camps.

Progression by constraint, not arithmetic

Instead of increasing "*load*" by a fixed scalar each microcycle, progress by constraint-aware adjustments:

- Intensity ceilings for sessions with high internal load risk (downhill running, firm surfaces in aggressive shoes, very fast strides): cap the number of steps above a clinically meaningful internal-force proxy (e.g., steps faster than 3K pace or on −2% grade) even when the metabolic budget allows more.
- Duration floors for metabolic work: ensure sufficient continuous time near LT1/LT2 for stimulus while maintaining mechanical safety by surface, footwear, and cadence choices. This is progression as shaping a feasible region, not stepping up a single dial.

Distribute threshold and localise peak force

Physiologically, splitting threshold work (e.g., 2 × 20 min → 4 × 10 min) maintains stimulus with lower systemic strain; mechanically, it also caps per-bout force drift that sometimes emerges late in continuous tempos. Conversely, if one wishes to practise race-specific economy at near-continuous intensities, mechanical risk can be localised by flattening course profiles, using more compliant footwear, and biasing cadence upward to reduce peak vertical excursion, all coordinative manipulations that alter internal force without blunting the metabolic aim.

Preserve form under speed with low fatigue

Short, relaxed fast running (extended strides, diagonals, light hill sprints) delivers high coordinative and elastic-system practice at minimal metabolic dose. Properly dosed (few minutes of total fast time), such work maintains the ability to recruit high-threshold motor units and to coordinate stiffness without meaningfully perturbing recovery (cf. your neuromuscular recruitment rationale). In this framework, these sessions are neither decoration nor "*speed for speed's sake*," but the coordinative moment's weekly anchor that helps the metabolic and mechanical moments reconcile late-race demands.

Recognise tissue tempos and seasonality

Because tendon and bone remodel slowly, mechanical-risk features (aggressive downhills; spikes in very fast steps; abrupt footwear changes) should be introduced early and held constant over mesocycles, letting tissues catch up while the metabolic moment cycles through base, specific, and taper emphases. This is a guarded reading of "*keep workout volume constant*" at the level of mechanically salient step-counts rather than merely total metres at pace.

Individualise by coordinative signature

Since fatigue-driven kinematic shifts are idiosyncratic, periodic mechanics audits (high-frame-rate sagittal footage at easy, threshold, and closing-rep speeds) can identify each runner's decompensation attractor (e.g., posterior pelvic tilt and over-stride; collapsing ankle stiffness). Training then includes micro-constraints to keep the runner near their economical solution: modest cadence prompts, light uphill finishes to dampen braking, or footwear selected for the athlete's preferred stiffness interaction. The aim is not to impose a universal technique but to stabilise the individual's efficient pattern as intensity rises.

Reconciling specific disputes

Equal fast-metres imply equal biomechanical load. False if read literally; plausible if read under strong constraints. Equalising only the distance at a target pace ignores distributional features (surfaces, gradients, footwear, cadence) and end-of-bout states. However, if those features are held within narrow bands, then progressing from many short reps to fewer, longer reps need not precipitate a large increase in damage relative to increasing pace or total fast metres, because damage is more sensitive to peak force than to modest extensions of steady-state work. The safer practical move, then, is often to lengthen reps first, before adding pace or extra fast-metres, while keeping mechanical constraints constant. And of cause, this is a rule of thumb, but provided surface, footwear, and relative intensity are tightly constrained, a common progression heuristic is to slightly lengthen repetitions at a given pace before either adding total fast-metres or increasing pace.

Device impact metrics (ILR, LSS) are useful proxies

They are sometimes useful trend indicators, but they mislead when reified. Impact-centred metrics capture a narrow slice of external dynamics and correlate weakly with internal forces that matter for tissue damage (Matijevich et al., 2019). They may be included in a dashboard as flags (e.g., "*today's downhill repetitions produced atypically high impact surrogates, consider reducing similar exposures this week*"), but planning should privilege mechanism-grounded constraints and athlete-specific responses over opaque composite scores.

For coaches and self-coached runners, the integrated approach can be rendered as a short grammar for designing and auditing a week:

1. Name the metabolic target (e.g., "*two hours near LT1 on Sunday; 30–40 minutes within LT2 across split sessions mid-week*").

2. Bind the mechanical risk (e.g., *"< 300 steps faster than 3K pace; no downhills steeper than −2%; one very-fast exposure day only*").
3. Install the coordinative anchor (e.g., "*one low-fatigue fast-coordination session: 6–8 relaxed 120–150 m strides, or 8–10 × 10-s hill sprints*").
4. Progress within the feasible region by first extending bout duration at a given pace, then adding bouts, and only then increasing pace – re-auditing mechanical constraints at each change.
5. Monitor with two ledgers: a metabolic ledger (TRIMP/TSS, session RPE, HRV, subjective freshness) and a mechanical-exposure ledger (counts of very-fast steps, downhills, firm-surface minutes), plus periodic form spot-checks.

This grammar neither abolishes physiological scalars nor fetishises forces. It makes them co-determinant under coordinative governance.

Implications for performance and injury

Performance gains in the marathon are typically attributed to expanded aerobic capacity and improved substrate utilisation. Yet late-race collapse is often recognisable as a coordinative–mechanical failure: stride length decays, cadence drifts, posture folds, despite heart-rate remaining stable. By reserving a weekly slot for fast but fresh coordinative work, distributing threshold to maintain quality, and constraining mechanical hazards while metabolic work scales, one creates conditions in which the athlete can express the physiology already acquired. Injury risk, in turn, becomes a function not of "*too much load*" in the abstract, but of mis-shaped load – the wrong internal-force distributions rehearsed under the wrong coordinative states. The integrated practice pushes against that mis-shaping.

Finally, evaluation should match theory. Group-level correlations between heart-rate scalars and injury are predictably weak because they average away the very distributional and coordinative features that mediate risk. Within-athlete designs that log both metabolic scalars and mechanical-exposure primitives alongside simple kinematic markers (step length, cadence at fixed speeds; qualitative posture codes) will better detect the thresholds at which each athlete's feasible region narrows. In this way, practice generates its own evidence without presuming that a single number can tell the whole story.

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