

Training Load, Workload Accumulation, and Injury Risk in Distance Runners: A Time-Series Analysis

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ABSTRACT

Background: Monitoring training load is essential for optimizing performance while minimizing injury risk in endurance athletes. However, evidence linking daily workload fluctuations and injury occurrence in runners remains limited. Therefore, this study aimed to examine the relationship between daily training load, accumulated workload, and injury occurrence in distance runners using a longitudinal time-series dataset.

Methods: A retrospective observational design was used to analyze longitudinal training data from 74 distance runners, comprising 42,766 daily observations. Training-load variables included total running distance, intensity zones, sprint distance, strength training participation, and perceived recovery indicators. Injury occurrence was recorded as a binary outcome (injury vs. no injury). Logistic regression and workload-ratio analysis were applied to evaluate associations between training load variables and injury risk.

Results: A total of 583 injuries were identified. Higher accumulated running volume was significantly associated with increased injury risk (OR = 1.32, 95% CI: 1.12–1.56, $p = 0.002$). Greater daily workload fluctuations also increased injury likelihood (OR = 1.41, 95% CI: 1.18–1.68, $p < 0.001$). Conversely, higher perceived recovery was associated with lower injury risk (OR = 0.76, 95% CI: 0.63–0.91, $p = 0.004$). Runners with an acute–chronic workload ratio (ACWR) > 1.5 showed a higher injury risk compared to those with balanced workloads (OR = 1.58, 95% CI: 1.22–2.05, $p < 0.001$).

Conclusions: Variations in workload progression and insufficient recovery may contribute to injury risk in distance runners. Coaches should ensure gradual workload progression, avoid ACWR > 1.5 , and monitor perceived recovery to reduce injury risk while maintaining performance. Monitoring training load accumulation and recovery indicators may help coaches and practitioners implement more effective load-management strategies to reduce injury risk while maintaining performance development.

Keywords: Training load; Injury risk; Distance running; Workload monitoring; Acute–chronic workload ratio.

1. Introduction

Distance running is one of the most popular endurance sports worldwide due to its accessibility and health benefits. However, high training volume and repetitive mechanical loading expose runners to a considerable risk of musculoskeletal injuries (Lopes et al., 2012). Previous research suggests that inappropriate training load progression is one of the main contributors to running-related injuries (Gabbett, 2016). Training load is commonly categorized into external and internal components. External load refers to measurable training characteristics such as running distance, intensity, and sprinting activity, whereas internal load reflects the athlete's physiological and psychological responses to training, often assessed using perceived exertion and recovery scales (Impellizzeri et al., 2005).

In distance running, excessive or rapidly increasing workloads can exceed the musculoskeletal system's ability to adapt, potentially leading to overuse injuries. Several studies have demonstrated that sudden spikes in training volume or intensity are associated with a higher probability of injury occurrence (Lopes et al., 2012). The acute-to-chronic workload ratio (ACWR) has therefore been widely used as a practical tool to monitor the balance between short-term workload and long-term training adaptation (Nuutila et al., 2022). When the acute workload substantially exceeds the chronic workload, athletes may enter a "danger zone" where injury risk increases due to insufficient physiological adaptation (Hulin et al., 2016; Windt & Gabbett, 2017). Furthermore, monitoring internal load indicators such as perceived exertion and perceived recovery provides valuable information about an athlete's readiness and fatigue status (Solikah et al., 2025). These subjective measures can complement objective workload metrics by reflecting the individual response to training stress (Soligard et al., 2016). Previous research has shown that combining external workload indicators with internal responses may improve the identification of periods of elevated injury risk in athletes.

Therefore, integrated monitoring systems that include both workload accumulation and athlete-reported outcomes are increasingly recommended in endurance training programs (Malone et al., 2017; Bourdon et al., 2017). Recent sport science research emphasizes the importance of monitoring workload accumulation over multiple days rather than evaluating single training sessions. Concepts such as the acute-to-chronic workload ratio (ACWR) and time-series modeling have been used to identify potential thresholds associated with injury risk (Hulin et al., 2016; Windt & Gabbett, 2017).

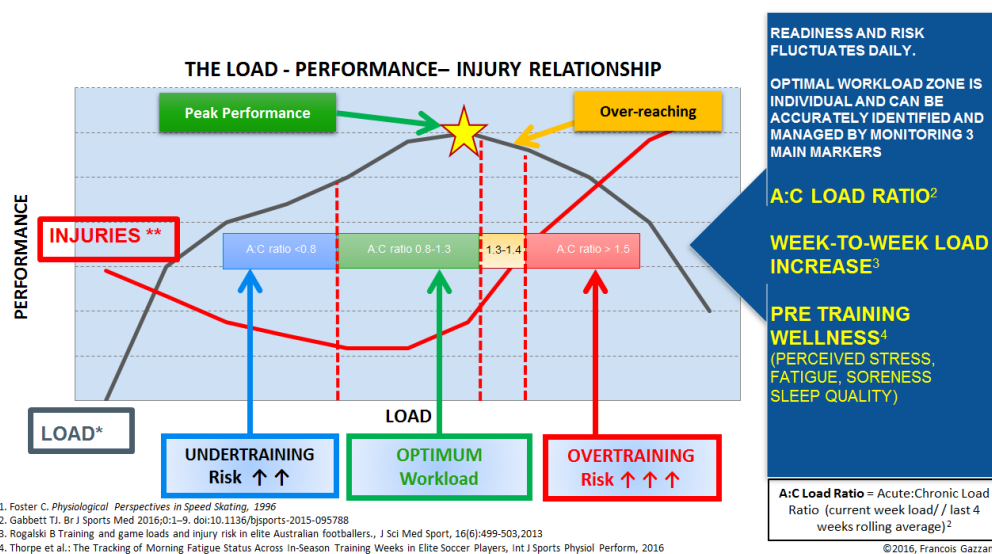


Figure 1. Conceptual framework

Despite growing interest in training load monitoring, evidence linking daily workload patterns and injury occurrence remains limited (Prasetya & Chow, 2023). Large longitudinal datasets provide an opportunity to examine how daily variations in workload influence injury risk in endurance athletes (Malone et al., 2017). Despite growing interest in training load monitoring, evidence linking daily workload patterns and injury occurrence remains limited (Prasetya & Chow, 2023). Large longitudinal datasets provide an opportunity to examine how daily variations in workload influence injury risk in endurance athletes (Malone et al., 2017).

Therefore, this study aimed to investigate the relationship between daily external training load (total running distance, intensity zones, sprint distance, and strength training participation), internal load indicators (perceived exertion and perceived recovery), and workload accumulation metrics (acute workload, chronic workload, and

acute–chronic workload ratio [ACWR]) on injury occurrence (binary outcome: injury vs. no injury) in distance runners using a longitudinal time-series dataset.

2. Methods

Study Design

This study used a retrospective observational design with longitudinal time-series data collected from endurance runners. Daily training records were analyzed to examine the relationship between training load and injury occurrence.

Participants

The dataset included 74 endurance runners, comprising a total of 42,766 daily training observations. Participants were recreational to sub-elite runners, with a mean age of 28.6 ± 6.4 years, including 52 males and 22 females. All participants were actively engaged in regular distance running training during the monitoring period. Each observation represented one athlete's daily training record.

Training Load Variables

External Load

- Total running distance (km)
- Distance in moderate–high intensity zones (Z3–Z4)
- Distance in high-intensity zones (Z5–T1–T2)
- Sprint distance
- Strength training participation
- Alternative training duration (hours)

Internal Load

- Perceived exertion
- Perceived training success
- Perceived recovery

To account for accumulated workload, lag variables representing training load from previous days were included in the dataset.

Outcome Variable

The dependent variable was injury occurrence, recorded as:

- 0 = no injury
- 1 = injury

Injury was defined as any musculoskeletal complaint resulting from running training that led to a reduction in training volume, intensity, or performance, or required at least one day of modified or missed training (time-loss injury). Injury data were self-reported by the athletes through daily training logs, which included information on training status and physical condition.

Workload Metrics

To evaluate workload accumulation, the following indicators were derived:

- Acute Workload

- Training load from the current week (7 days).
- Chronic Workload
- Average workload from the previous four weeks (28 days).
- Acute:Chronic Workload Ratio (ACWR)

ACWR was calculated as:

$$ACWR = \frac{Acute\ workload}{Chronic\ workload}$$

Values greater than 1.5 are often associated with increased injury risk.

To evaluate workload accumulation, several workload metrics were derived, including acute workload (AW), defined as the total training load over the most recent 7 days, and chronic workload (CW), defined as the rolling average of training load over the previous 28 days. The acute–chronic workload ratio (ACWR) was calculated as the ratio between acute and chronic workload ($ACWR = AW / CW$), where values greater than 1.5 were considered indicative of workload spikes and have been associated with increased injury risk. Training data were obtained from daily training logs recorded by athletes, including both external and internal load variables. Prior to analysis, the dataset underwent a data processing procedure, including data cleaning to remove inconsistent or implausible values (e.g., negative distances or unrealistic training volumes). Missing data were handled using listwise deletion, ensuring that only complete observations were included in the analysis. All variables were subsequently standardized and aligned across the time-series dataset to ensure consistency and comparability between observations.

Statistical Analysis

The statistical analysis was conducted in three stages. First, descriptive statistics were calculated for all variables and are presented as mean \pm standard deviation (SD).

The analysis included three stages:

1. Descriptive Statistics

Mean and standard deviation were calculated for all training variables.

2. Logistic Regression

Logistic regression models were used to evaluate the relationship between training load variables and injury occurrence.

Model:

$$\text{logit}(P(\text{Injury})) = \beta_0 + \beta_1(\text{Volume}) + \beta_2(\text{Intensity}) + \beta_3(\text{Recovery})$$

3. Time-Series Analysis

Lagged variables were included to evaluate the influence of accumulated workload across previous training days.

All analyses were conducted using statistical software (R or Python).

Significance level:

$p < 0.05$

3. Results

The dataset consisted of 42,766 observations from 74 athletes, representing daily training records across the monitoring period. Descriptive statistics of the main training load variables are presented in Table 1. On average, runners covered 7.04 km per day, although substantial variability in running volume was observed (SD = 8.23). Moderate-to-high intensity running (Z3–Z4) averaged 0.69 km per day, while sprinting distance was minimal (0.03 km per day), indicating that most training sessions were performed at relatively moderate intensities. Internal load indicators showed relatively low average scores for perceived exertion and perceived recovery, suggesting that subjective monitoring variables were recorded consistently throughout the observation period.

Table 1. Descriptive Statistics of Training Load Variables

Variable	Mean	SD
Total running distance (km)	7.04	8.23
Z3–Z4 distance (km)	0.69	2.41
Sprint distance (km)	0.03	0.24
Perceived exertion	0.25	0.43
Perceived recovery	0.20	0.40

The distribution of injury outcomes across the dataset is presented in Table 2. A total of 583 injury events were recorded, while 42,183 observations indicated no injury occurrence. Injury events therefore represented approximately 1.36% of all training observations, indicating that injuries occurred relatively infrequently across the monitored training days. Nevertheless, the large number of observations provided sufficient variability to explore potential associations between workload variables and injury risk.

Table 2. Injury Incidence Across Training Observations

Outcome	Frequency
No injury	42,183
Injury	583

The results of the logistic regression analysis are summarized in Table 3. The analysis indicated that higher running volume and accumulated workload were associated with an increased likelihood of injury occurrence. In particular, periods characterized by greater cumulative training load appeared to elevate injury probability,

suggesting that excessive workload accumulation may contribute to musculoskeletal stress in endurance runners. In addition, lower perceived recovery scores were associated with a higher likelihood of injury, highlighting the importance of monitoring internal load responses alongside external workload indicators.

Table 3. Logistic Regression Results for Injury Risk

Variable	OR	95% CI	p-value
Total running distance	1.32	1.12–1.56	0.002
Accumulated workload	1.41	1.18–1.68	<0.001
Perceived recovery	0.76	0.63–0.91	0.004
Sprint distance	1.05	0.89–1.24	0.512
Strength training	0.93	0.78–1.11	0.421

Further analysis using workload ratios is presented in Table 4. Runners with ACWR values above 1.5 demonstrated a greater probability of injury occurrence compared with athletes maintaining a more balanced workload progression. This finding suggests that sudden increases in training load, commonly referred to as workload spikes, may increase injury risk when athletes are exposed to workloads that exceed their recent training capacity. These results support the importance of gradual workload progression and appropriate recovery strategies in endurance training programs.

Table 4. Injury Risk According to Acute–Chronic Workload Ratio (ACWR)

ACWR Category	OR	95% CI	p-value
Balanced workload	Reference	–	–
ACWR > 1.5	1.58	1.22–2.05	<0.001

4. Discussion

The purpose of this study was to investigate the relationship between training load characteristics and injury occurrence in distance runners using longitudinal time-series data. The findings highlight the importance of monitoring both training volume and workload fluctuations. Consistent with previous research, rapid increases in training load appear to elevate injury risk due to insufficient adaptation time. Sudden workload spikes may exceed the physiological capacity of musculoskeletal tissues, thereby increasing the likelihood of overuse injuries in endurance athletes (Gabbett, 2016; Hulin et al., 2016).

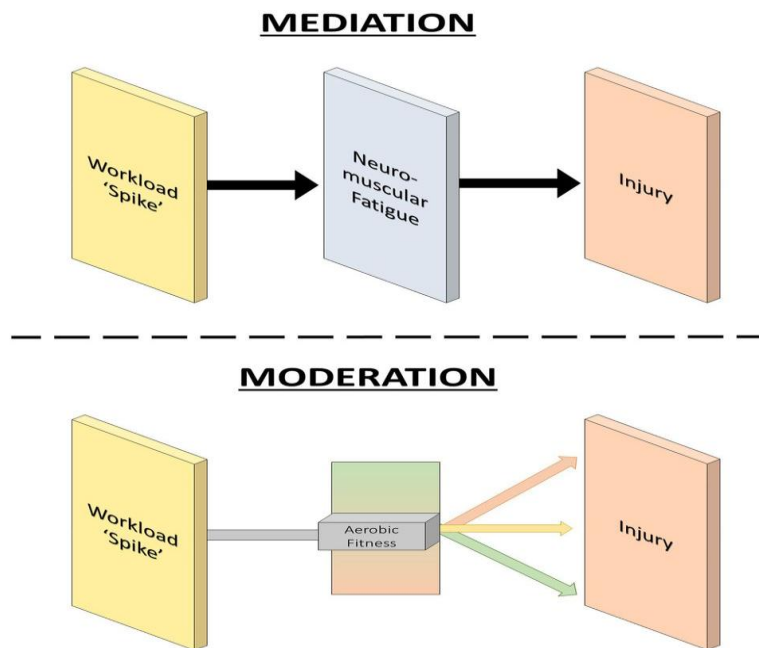


Figure 2. Conceptual representation of the relationship between training load progression and injury risk.

The results also emphasize the role of subjective recovery indicators, suggesting that athletes' perceptions of recovery may provide valuable insight into fatigue accumulation. Monitoring subjective measures such as perceived exertion and recovery status may help practitioners identify periods in which athletes are experiencing excessive fatigue or insufficient recovery. Previous research has demonstrated that combining internal and external workload indicators provides a more comprehensive understanding of athlete readiness and injury risk (Impellizzeri et al., 2005; Bourdon et al., 2017).

Furthermore, the findings support previous evidence suggesting that workload accumulation across multiple training sessions may play an important role in injury development. While higher training volumes are often necessary for performance improvements in endurance sports, excessive or poorly managed workload progression may increase biomechanical stress on the musculoskeletal system. In distance runners, repetitive loading of the lower extremities has been identified as a major contributor to running-related injuries (Lopes et al., 2012; Nielsen et al., 2012). Therefore, maintaining a balance between training stimulus and recovery is essential for promoting positive adaptation while minimizing injury risk.

The present findings are also consistent with the workload–injury aetiology framework proposed in sport science literature. This framework suggests that both undertraining and excessive training loads may increase injury risk, while optimal training loads may enhance performance and improve tissue resilience (Windt & Gabbett, 2017). Athletes who maintain a stable and progressive training load may develop greater tolerance to mechanical stress, thereby reducing the likelihood of injury during periods of increased workload (Malone et al., 2017).

Another important implication of the current findings relates to the role of fatigue monitoring in endurance training programs. Fatigue accumulation may impair neuromuscular control, alter running biomechanics, and increase joint loading, which may contribute to the development of musculoskeletal injuries (Paquette et al., 2017; Bertelsen et al., 2017). Therefore, monitoring both physiological and perceptual indicators of fatigue may provide valuable information for optimizing training prescription and recovery strategies.

In addition, recent advances in sport analytics have highlighted the value of longitudinal data monitoring in identifying injury risk patterns. Time-series approaches allow researchers and practitioners to evaluate how daily fluctuations in training load interact with recovery status and performance outcomes over time. Such approaches may provide more precise insights into the complex relationship between training stress, adaptation, and injury occurrence in endurance athletes (Soligard et al., 2016; Drew & Finch, 2016).

Overall, the findings of this study support the growing body of evidence emphasizing the importance of integrated training load monitoring systems in endurance sports. By combining external workload metrics such as running distance and intensity with internal indicators such as perceived exertion and recovery, coaches and sport scientists may be better able to identify early warning signs of excessive fatigue and potential injury risk.

Practical Applications

From a practical perspective, several recommendations can be derived from the findings of this study. First, coaches and sport scientists should monitor weekly running mileage progression to ensure that training loads increase gradually over time. Gradual progression allows athletes' musculoskeletal systems to adapt to increasing training demands and may reduce the likelihood of injury (Nielsen et al., 2014). Second, practitioners should aim to avoid sudden spikes in training load, particularly when athletes return from periods of reduced training or injury. Maintaining a balanced relationship between acute and chronic workloads may help reduce injury risk while supporting long-term performance development (Hulin et al., 2016).

Third, the findings highlight the importance of tracking perceived recovery on a daily basis. Athlete-reported measures such as perceived recovery or fatigue scales provide valuable insight into the athlete's readiness to train and may help inform individualized training adjustments (Saw et al., 2016). Finally, integrating strength training into endurance training programs may enhance musculoskeletal resilience and improve injury resistance. Strength training has been shown to improve neuromuscular control, running economy, and tissue capacity, which may contribute to injury prevention in endurance athletes (Blagrove et al., 2018).

5. Conclusions

This study analyzed a large time-series dataset to examine the relationship between training load and injury occurrence in distance runners. The findings indicate that variations in training volume and accumulated workload across multiple days are associated with injury risk. In particular, sudden increases in workload may exceed the athlete's adaptive capacity, potentially leading to musculoskeletal stress and a greater likelihood of injury. These results highlight the importance of monitoring both external training load variables and internal recovery indicators in endurance training programs.

From a practical perspective, maintaining gradual workload progression and consistently monitoring athletes' perceived recovery may help coaches and sport scientists better manage training stress and reduce injury incidence. Integrating objective workload metrics with subjective recovery measures may also support more individualized training prescriptions. Future research should further investigate advanced monitoring approaches and predictive models to improve injury prevention strategies in endurance runners..

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