



OPEN ACCESS

How much running is too much? Identifying high-risk running sessions in a 5200-person cohort study

Jesper Schuster Brandt Frandsen,¹ Adam Hulme,^{2,3} Erik Thorlund Parner,⁴ Merete Møller ,^{5,6} Ida Lindman ,^{7,8} Josefin Abrahamson ,^{9,10} Nina Sjørup Simonsen,^{4,11} Julie Sandell Jacobsen,^{4,11,12} Daniel Ramskov,¹³ Sebastian Skejød,^{4,11} Laurent Malisoux ,¹⁴ Michael Lejbach Bertelsen,^{4,5} Rasmus Oestergaard Nielsen ,^{4,11}

► Additional supplemental material is published online only. To view, please visit the journal online (<https://doi.org/10.1136/bjsports-2024-109380>).

For numbered affiliations see end of article.

Correspondence to

Dr Rasmus Oestergaard Nielsen; roen@ph.au.dk

Accepted 11 June 2025

Published Online First 7 July 2025

ABSTRACT

Objectives We explored whether a spike in running distance during a single session or over 1 week, compared with the preceding period, was associated with increased risk of running-related overuse injury.

Methods Adult runners were recruited for an 18-month cohort study. Three training-related exposures were defined based on a relative change in running distance, using data collected via Garmin devices: (1) session-specific running distance relative to the longest distance run in the past 30 days; (2) 1-week period relative to the preceding 3 weeks using the acute:chronic workload ratio (ACWR); (3) 1-week period using a week-to-week ratio. Runners were categorised into one of four time-varying states: (1) regression, or up to 10% increase (reference); (2) 'small spike' between >10% and 30% increase; (3) 'moderate spike' between >30% and 100% increase; and (4) 'large spike' >100% increase. Outcome was self-reported overuse running-related injury. A multistate Cox regression model was used to estimate adjusted hazard rate ratios (HRR).

Results Among 5205 runners (mean age 45.8 years, SD=10.4; 22% female), a total of 1820 (35%) sustained a running-related injury during 588 071 sessions. Significantly increased rates were identified for small spikes (HRR=1.64 (95% CI: 1.31 to 2.05, p=0.01)), moderate spikes (HRR=1.52 (95% CI: 1.16 to 2.00, p<0.01)) and large spikes (HRR=2.28 (95% CI: 1.50 to 3.48, p<0.01)) in single-session running distance. A negative dose-response relationship was observed for the ACWR. No relationship was identified for the week-to-week ratio.

Conclusion A significant increase in the rate of running-related overuse injury was found when the distance of a single running session exceeded 10% of the longest run undertaken in the last 30 days.

WHAT IS ALREADY KNOWN ON THIS TOPIC

- ⇒ Distance running has grown in popularity and is practiced by millions of individuals globally for a variety of recreational and competitive purposes.
- ⇒ Running 'too much' before musculoskeletal structures achieve adequate tolerance to withstand the external applied load is recognised as a major contributor to injury occurrence.
- ⇒ Acute:chronic workload ratio and week-to-week ratio are commonly used in scientific studies and implemented in practice (eg, in wearable devices) to guide runners towards a safe increase in running distance.

WHAT THIS STUDY ADDS

- ⇒ Session-specific running distances that are ≥10% of the longest run undertaken in the prior 30 days significantly increase the risk of lower extremity injury.
- ⇒ Caution is advised when relying on recommended training load calculations such as the acute:chronic workload ratio and weekly-gradual changes, as no association, or even inverse associations, between these approaches and injury risk was found.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

- ⇒ Based on our novel findings and the largest study conducted to date on this topic, healthcare professionals, coaches and athletes are encouraged to adopt this new single-session paradigm and promote a safer approach to maximal progression in running distance.

INTRODUCTION

Running is a popular form of exercise, embraced for a variety of reasons including competition, recreation, social engagement and health improvement.^{1 2} Globally, millions run due to its affordability and accessibility.³ Over 90% of regular runners use Global Positioning System (GPS) wearables to monitor training loads, with the aim of enhancing performance and managing the risk of running-related injury.⁴ Despite this, the rate of running-related injury has remained high.^{5 6} Today, injury is the main reason for discontinuing a running

programme.⁷⁻⁹ Therefore, understanding the causes of injury is crucial to offer evidence-based advice, treatment and support for safe exercise habits.

Excessive training and overlooking physical limitations are key factors in the development of running-related injury, as highlighted in a few qualitative studies.¹⁰⁻¹² This aligns with causal sports injury frameworks developed over the past 15 years, emphasising the 'too much, too soon' theory, which suggests that injury occurs when runners increase distance too rapidly.^{13 14} While widely



© Author(s) (or their employer(s)) 2025. Re-use permitted under CC BY-NC. No commercial re-use. See rights and permissions. Published by BMJ Group.

To cite: Schuster Brandt Frandsen J, Hulme A, Parner ET, et al. *Br J Sports Med* 2025;59:1203–1210.

accepted among clinicians, researchers, coaches and athletes,^{10 15} defining 'too much' remains debated. Traditional sports injury epidemiological studies¹⁶ use the acute:chronic workload ratio (ACWR) and the week-to-week ratio to quantify change in load over time.^{17–19} These methods, adopted by industry and used by runners globally, equate the 'too much' period to 1 week.²⁰ Load progression or regression is calculated by dividing the 1-week load by the applied loads from the previous one to 4 weeks, reflecting the gradual development of overuse injuries across multiple running sessions.^{15 21}

Although weekly training load metrics like the ACWR are widely used, new paradigms in sports injury aetiology should be explored. The unique physical demands of each sport give rise to distinct injury mechanisms. In running, emerging evidence from our research shows that few runners report symptoms before an injury occurs.²² This suggests that runners may be more vulnerable when increasing distance too rapidly within a single session, indicating that the 'too much' period for running injuries may be shorter than the 1-week window commonly used in research and wearable devices. If validated, this 'single-session paradigm' could provide new insights into the development of overuse injuries, offering healthcare professionals more precise guidance for injury prevention and patient well-being.

This study aimed to explore whether a spike in kilometres run, either in a single session or over a 1-week period compared with the preceding period, was associated with an increased rate of overuse running-related injury.

METHODS

Study design

This explorative study uses longitudinal data from the Garmin-RUNSAFE Running Health study with an 18-month follow-up.²³ Runners signed an online informed consent form prior to inclusion and could withdraw at any time during the study period. Enrolment occurred between 4 July 2019 and 1 December 2019, and the study followed up until January 2021. Reporting followed the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) guideline and statistics, interpretation and reporting was checked for consistency using the CHAMP (CHecklist for statistical Assessment of Medical Papers) checklist.²⁴

Participants

Garmin (Olathe, Texas, USA) was responsible for recruiting English-speaking runners who had accepted receiving Garmin-related newsletters by email. In addition, the RUNSAFE research group recruited through European-based running clubs and magazines. Confirmation emails for enrolment were sent to runners if they agreed to participate, and those who answered enrolment questionnaires were considered for inclusion. Eligible participants were expected to: (1) wear a Garmin GPS device and upload running data via the 'Garmin Connect' app; and (2) be willing to respond to weekly questionnaires covering injury/problem status and anatomical location. Participants were excluded if they met any of the following criteria: (1) had an existing musculoskeletal problem at baseline; (2) failed to respond to the baseline questionnaire and/or failed to answer any of the weekly questionnaire; (3) did not record any running activity; (4) had a running-related injury during follow-up yet failed to report the origin as being based on a traumatic or non-traumatic (ie, repetitive mechanism) onset; (5) had more than 10 days between a self-reported injury during follow-up and their last running session; and (6) only ran sessions below the distance

of 500 m or above the distance of 100 km due to the risk of data error.

Procedures

Self-reported data, including age, height and weight, were collected via an enrolment questionnaire. Sex, running experience and previous injuries were reported at baseline, whereas injury/problem status and anatomical location were obtained from the weekly questionnaires. Data on running activity, including kilometres covered in each running session, was collected via wearable Garmin devices. All runners wore Garmin devices capable of transferring data from each running session, assessed in a valid manner by GPS and/or accelerometry, to the runner's smartphones.^{25 26} Data were sent from the Garmin Connect application to Aarhus University servers and the RUNSAFE group via an application programming interface solution (Health API).

Exposure

The primary exposure was the ratio of the distance covered in a single running session relative to the longest session undertaken in the preceding 30 days. The exposure was time-varying; hence runners could change their exposure status each time they completed a running session. The relative change (in per cent) in single-session running distance was calculated using data from the activity records related to running. Data were collapsed such that running sessions with less than 15 min of pause between them were counted as a single session rather than multiple running sessions. This aggregation included data from interval training and other high-intensity sessions. The distance covered in a single running session, for example, 12 000 m, was divided by the longest distance covered in each session undertaken in the 30-day period (eg, 8000 m) preceding the current running day. In the above example, the calculation 12 000 m/8000 m resulted in a ratio of 1.5, signifying a 50% increase in running distance. A relative change of >1 indicated progression (increase), while a change of <1 indicated regression (decrease).

As the injury rate as a function of relative change in running distance deviated from a linear relationship, relative changes were categorised into one of the following five transition states: (1) regression (running less than the longest run), or up to 10% progression (reference); (2) small spike corresponding to a progression between >10% and 30%; (3) moderate spike corresponding to a progression between >30% and 100%; (4) large spike corresponding to a progression above 100%; and (5) not possible (NP) to calculate a relative change since the denominator was zero (NP-state). A 10% cut-off was used given the significance of the '10% rule' in running communities,²⁰ whereas a 30% increase was selected since progression in weekly averaged running distance exceeding this amount has been associated with increased risk of injury.^{17 18 27} A 100% cut-off was chosen as it represents doubling in running distance. As cut-off values can be discussed, the relative injury hazard as a function of change in running distance as a continuous variable will be visualised in the results section.

In addition to the calculation of single-session changes, the uncoupled ACWR was calculated using the most recent 1-week acute workload (sum of distance in all running sessions) and the prior 3-week chronic workload as described by Gabbett *et al.*²⁸ Finally, the week-to-week ratio was calculated using the same 1-week acute workload as used in the ACWR divided by the sum of distance in all running sessions in the week prior to this as described by Nielsen *et al.*¹⁸ For ACWR and week-to-week

ratios, the same cut-offs as described above for calculation of change in single-session running distance were used when categorising runners into a transition state after each running session.

Outcome

The main outcome was the first-occurring self-reported overuse running-related injury, while injuries based on a traumatic onset were considered as competing risks. Information about injury status was assessed through an automated weekly questionnaire. Runners classified themselves into one of three categories based on the following question: 'In the past week, have you had a musculoskeletal injury, or have you experienced a problem to muscles, tendons or bones that is fully or partly caused by running?' The categories were: (1) injury-free; (2) uninjured yet with problems; or (3) injured. Of these, the categories injury-free and uninjured were merged in the sense that only those reporting an injury (number 3) had an outcome. Runners were informed that a problem was less severe than an injury, defined as being painful and irritating; however, running activities continued unabated in terms of volume, intensity and frequency. Injuries were painful and irritating, leading to a reduction in running activity (ie, volume, intensity, frequency). The injured runner was required to specify the mechanism of injury, categorised as either overuse (non-traumatic) or traumatic (such as torsion, a fall or blow). The definition of a running-related problem and injury was informed by the running injury consensus definition by Yamato *et al* as well as the Oslo Trauma Research Center questionnaire.^{29 30} When an injury was not reported on the day of the running session, it was linked to the last recorded running session up to 10 days before the injury. If an injury was reported more than 10 days after the completion of a running session, the runner was excluded.

Confounding

Visualising the causal assumptions in a directed acyclic graph (DAG) has been recommended within the causal inference domain of medicine.²⁴ In the present study, the confounders included in the DAG were: previous problems, body mass index (BMI), sex, age and years of running experience (online supplemental S1). Previous running-related problems prior to baseline were included as a confounder given that this is a well-known risk factor for running-related injury and may be associated with running distance.³¹ Likewise, there may be differences in injury risk between the sexes, including the intensity and duration of longer runs.^{32 33} A higher BMI places greater stress on musculoskeletal structures compared with a lower BMI which, all else equal, has been consistently associated with an elevated risk of injury.^{31 32} Finally, age and running experience were included as confounders, as these factors have been associated with injury development.^{32 33} The requirements regarding events per variable were fulfilled owing to a considerable number of injuries in the present dataset.³⁴

Statistical analysis

As the present study was exploratory, no sample size or power calculation was made a priori. While change in running distance was calculated as a ratio based on kilometres run, data were analysed using running sessions as the time scale. A multistate Cox regression model was applied using time to first injury consisting of two absorbing states (main injury and competing risk injury) and the five transient states earlier outlined under 'Exposure'.^{35–37} The assumption of proportional rates was

assessed using log-log plots of the Grambsch and Therneau test based on Schoenfeld residuals. While producing the figures, sessions with NP-state increases or increases of more than 900% were excluded to enable a stable Cox model. Data management and analysis were made in R V.4.3.3 (Austria, Vienna). R-code can be found in online supplemental S2, while results from various sensitivity analyses can be found in online supplemental S4–S8.

Equity, diversity and inclusion statement

The author team comprises individuals of different genders (five women and eight men) and nationalities (Denmark,

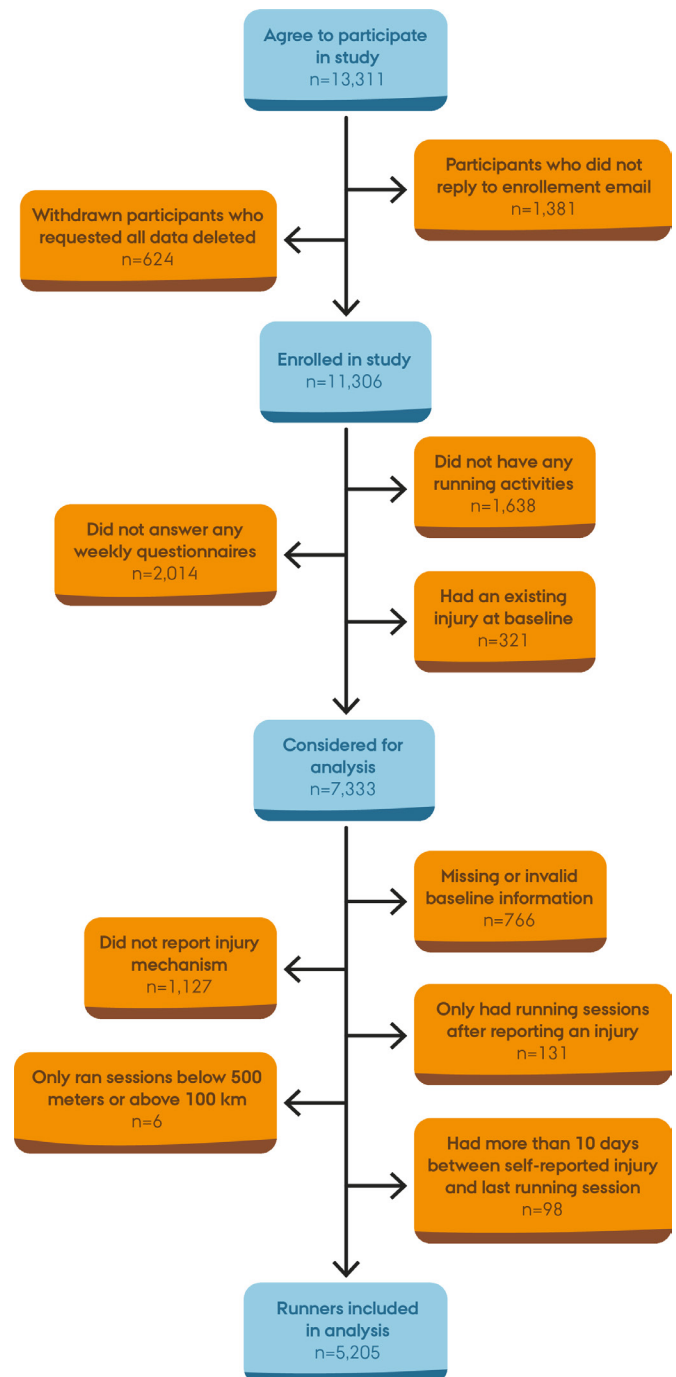


Figure 1 Flowchart visualising the inclusion of runners into the present study.

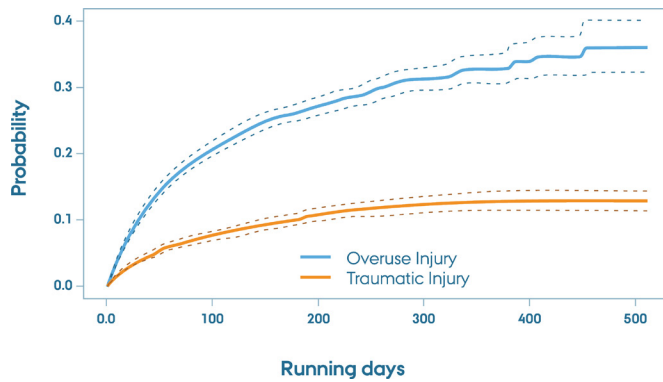


Figure 2 Aalen-Johansen plot visualising the probability of sustaining overuse and traumatic running-related injuries (y-axis) as a function of running sessions (x-axis). At 200 km, 30.5% (95% CI: 29.0% to 32.0%) reported an overuse injury and 12.0% (95% CI: 11.0% to 13.1%) had reported a traumatic injury.

Sweden, Australia, Luxembourg), bringing multiple perspectives to the research. The study aimed to recruit a diverse participant population from 87 countries, ensuring representation across sex, ages and BMI. Efforts were made to include all types of runners, including those with comorbidities, to enhance the diversity of the study sample. We acknowledge that while running is a relatively affordable sport allowing everybody to participate, the requirement for participants to use a Garmin watch may limit inclusivity for some socioeconomic groups.

RESULTS

A total of 5205 runners, predominantly from Europe and North America, were included in the analysis. Of these, 4053 (77.9%) were male and 1152 (22.1%) were female. The mean age of the participants was 45.8 years (SD=10.4), with a BMI of 24.2 kg/m² (SD=3.6). The median running experience was 9.5 years (IQR: 4–20 years). The median time at risk was 80.0 (IQR: 31–161) running sessions with a total of 588 071 sessions. Figure 1 depicts a flow chart of runners at each stage from consideration until inclusion.

Of the 5205 runners, a total of 1820 (35.0%) reported a running-related injury, of which 1311 (72.0%) were classified as overuse injuries (main outcome), and 509 (28.0%)

as traumatic injuries (competing risk). Most of these injuries were reported on the same day as the running session or the following 1–2 days after the running session (online supplemental S3). An Aalen-Johansen plot visualising the proportion of runners sustaining overuse and traumatic injuries as a function of running sessions is presented in figure 2. At 200 sessions, 30.5% (95% CI: 29.0% to 32.0%) had reported an overuse injury and 12.0% (95% CI: 11.0% to 13.1%) had reported a traumatic injury.

The main results are presented in table 1. Relative to running less than the longest run or a progression ≤10% (the reference), significantly increased rates were identified for small spikes (hazard rate ratio (HRR)=1.64 (95% CI: 1.31 to 2.05, p=0.01)), moderate spikes (HRR=1.52 (95% CI: 1.16 to 2.00, p<0.01)) and large spikes (HRR=2.28 (95% CI: 1.50 to 3.48, p<0.01)) in kilometres in a single running session for the 1311 overuse running-related injuries. Conversely, the point estimates and CIs in table 2 revealed that small, moderate and large spikes in weekly running dose were associated with a significantly decreased rate of injury if the calculation of change in running distance was based on the ACWR. In contrast, no significant relationship was identified for the week-to-week ratio (table 3). Figure 3 visualises the development of the HRR for overuse injuries as a function of change in single-session running distance change, of change in the uncoupled ACWR, and for change in the week-to-week ratio, respectively. In online supplemental S4–S8, sensitivity analyses are presented using other outcome definitions and/or cut-offs. Collectively, these results revealed an increased rate for all running-related injuries and certain types of these injuries with an increase in single session running distance (online supplemental S4–S6 and S8). In addition, changing cut-offs from 10% to 1% revealed an increase in distance from 1% to 10% to be associated with an increased injury rate (online supplemental S7).

DISCUSSION

Training errors are considered the main contributor to overuse injury development in runners.¹³ The present study identified a dose-response relationship between a spike in the number of kilometres run during a single running session and running injury development (table 1). Increased hazards of 64%, 52% and 128% for small (>10% to 30%), moderate (>30% to

Table 1 Changes in session-specific running distance and hazards of sustaining running-related injuries

Exposure groups	n	Label	HRR _{Crude}	95% CI	P value	HRR _{Adjusted}	95% CI	P value
Overuse injuries								
Change from 0 to 1.1	1117	Regression or progression to 10%	1 (ref)	(-)	–	1 (ref)	(-)	–
Change from>1.1 to 1.3	81	Minor spike from>10% to 30%	1.64	(1.31 to 2.06)	<0.01	1.64	(1.31 to 2.05)	<0.01
Change from>1.3 to 2.0	56	Medium spike from>30% to 100%	1.51	(1.15 to 1.99)	<0.01	1.52	(1.16 to 2.00)	<0.01
Change above 2.0	24	Large spike more than 100%	2.27	(1.49 to 3.46)	<0.01	2.28	(1.50 to 3.48)	<0.01
N/P	33	Not possible to calculate a change	0.80	(0.40 to 1.60)	0.52	0.80	(0.40 to 1.61)	0.54
Traumatic injuries								
Change from 0 to 1.1	430	Regression or progression to 10%	1 (ref)	(-)	–	1 (ref)	(-)	–
Change from>1.1 to 1.3	30	Minor spike from>10% to 30%	1.54	(1.06 to 2.24)	0.02	1.56	(1.07 to 2.26)	0.02
Change from>1.3 to 2.0	24	Medium spike from>30% to 100%	1.60	(1.05 to 2.45)	0.03	1.63	(1.06 to 2.49)	0.03
Change above 2.0	8	Large spike more than 100%	1.74	(0.82 to 3.70)	0.15	1.79	(0.84 to 3.80)	0.13
N/P	17	Not possible to calculate a change	1.27	(0.52 to 3.10)	0.59	1.36	(0.56 to 3.31)	0.50

Results are presented for overuse injuries (main result highlighted with bold) and traumatic injuries, respectively, among the 5205 runners included in the analyses.

The adjusted results were adjusted for age, BMI, sex, previous problems and running experience.

BMI, body mass index; HRR, hazard rate ratio; n, number of injuries in the corresponding state; N/P, not possible to calculate a change; ref, reference.

Table 2 Acute:chronic workload ratio running distance and hazards of sustaining running-related injuries

Exposure groups	n	Label	HRR _{Crude}	95% CI	P value	HRR _{Adjusted}	95% CI	P value
Overuse injuries								
Change from 0 to 1.1	432	Regression or progression to 10%	1 (ref)	(-)	–	1 (ref)	(-)	–
Change from >1.1 to 1.3	174	Minor spike from >10% to 30%	0.94	(0.79 to 1.12)	0.47	0.94	(0.79 to 1.12)	0.47
Change from >1.3 to 2.0	275	Medium spike from >30% to 100%	0.87	(0.75 to 1.02)	0.08	0.87	(0.75 to 1.02)	0.08
Change above 2.0	79	Large spike more than 100%	0.76	(0.60 to 0.96)	0.02	0.75	(0.59 to 0.96)	0.02
N/P	352	Not possible to calculate a change	0.59	(0.50 to 0.71)	<0.01	0.59	(0.50 to 0.71)	<0.01
Traumatic injuries								
Change from 0 to 1.1	157	Regression or progression to 10%	1 (ref)	(-)	–	1 (ref)	(-)	–
Change from >1.1 to 1.3	48	Minor spike from >10% to 30%	0.69	(0.50 to 0.95)	0.02	0.68	(0.49 to 0.95)	0.02
Change from >1.3 to 2.0	89	Medium spike from >30% to 100%	0.78	(0.60 to 1.01)	0.06	0.78	(0.60 to 1.01)	0.06
Change above 2.0	39	Large spike more than 100%	1.08	(0.76 to 1.53)	0.69	1.08	(0.76 to 1.54)	0.66
N/P	176	Not possible to calculate a change	0.88	(0.67 to 1.15)	0.34	0.9	(0.68 to 1.17)	0.42

Results are presented for overuse injuries (main result highlighted with bold) and traumatic injuries, respectively, among the 5205 runners included in the analyses.

The adjusted results were adjusted for age, BMI, sex, previous problems and running experience.

BMI, body mass index; HRR, hazard rate ratio; n, number of injuries in the corresponding state; N/P, not possible to calculate a change; ref, reference.

100%) and large spikes (>100%) were found, respectively. In contrast, significant decreases in injury rates were identified for spikes above 10% using the ACWR (table 2). Although the ACWR is widely used in research within a team-sport setting, there is a paucity of knowledge on the association between ACWR and running-related injury.^{17 38} To the best of our knowledge, only one 435-runner cohort study has previously examined the link between ACWR and running-related injury.³⁹ That study reported findings that closely align with those of the present analysis, suggesting that a higher ACWR is associated with a lower risk of running-related injury.³⁹ No significant differences were present for week-to-week ratio (table 3 and figure 3). This finding also corroborates results in an 874-person cohort of novice runners and a study on 434 youth cross-country runners.^{18 40} Collectively, these findings suggest a paradigm shift in understanding running-related injuries, indicating that most injuries occur due to an excessive training load in a single session, rather than gradual increases over time.

This study challenges the use of traditional load monitoring approaches, including the ACWR in the context of running-related injury occurrence. The single-session paradigm is therefore suggested as a novel approach to detecting deleterious spikes in running distance. Runners should avoid running

a distance in their current session that exceeds 10% of the longest distance covered in the previous 30 days. However, progressions up to 10% are not necessarily safe either and carry a degree of risk. Although not statistically significant, a progression between 1% and 10% translated into an increased rate of 19% (95% CI: –10% to 57%, p=0.22) compared with regression or progression up to 1% (results not shown in table 1). This is confirmed in figure 3 where progressions up to 10% appear to slightly increase the risk of injury. The current findings apply to a single running session and do not account for continuous progression over multiple sessions. For example, if the longest distance covered by a runner in the past 30 days was 10 km, then running 11 km, 12.1 km and 13.3 km in subsequent sessions within the same week, despite each reflecting a 10% increase, may still be considered excessive due to insufficient recovery time. Therefore, determining a safe progression in kilometres involves considering various factors beyond only the longest distance covered in the past 30 days.

The strengths of the present study include its considerably large sample size of 5205 runners, or approximately five times larger than the largest sample reported in previous prospective cohort studies, which have typically ranged from 100 to 1000 participants.^{18 39 41–44} Further strengths include the

Table 3 Week-to-week change in running distance and hazards of sustaining running-related injuries

Exposure groups	n	Label	HRR _{Crude}	95% CI	P value	HRR _{Adjusted}	95% CI	P value
Overuse injuries								
Change from 0 to 1.1	520	Regression or progression to 10%	1 (ref)	(-)	–	1 (ref)	(-)	–
Change from >1.1 to 1.3	158	Minor spike from >10% to 30%	0.97	(0.81 to 1.16)	0.75	0.97	(0.81 to 1.16)	0.75
Change from >1.3 to 2.0	262	Medium spike from >30% to 100%	0.88	(0.76 to 1.02)	0.11	0.88	(0.76 to 1.02)	0.11
Change above 2.0	217	Large spike more than 100%	0.91	(0.77 to 1.07)	0.29	0.91	(0.78 to 1.07)	0.29
N/P	155	Not possible to calculate a change	0.7	(0.56 to 0.88)	<0.01	0.7	(0.56 to 0.88)	<0.01
Traumatic injuries								
Change from 0 to 1.1	187	Regression or progression to 10%	1 (ref)	(-)	–	1 (ref)	(-)	–
Change from >1.1 to 1.3	51	Minor spike from >10% to 30%	0.86	(0.64 to 1.18)	0.33	0.86	(0.63 to 1.17)	0.33
Change from >1.3 to 2.0	112	Medium spike from >30% to 100%	1.05	(0.83 to 1.33)	0.71	1.05	(0.83 to 1.32)	0.72
Change above 2.0	88	Large spike more than 100%	1	(0.77 to 1.29)	0.99	1	(0.77 to 1.30)	0.99
N/P	71	Not possible to calculate a change	0.82	(0.56 to 1.19)	0.33	0.84	(0.57 to 1.22)	0.33

Results are presented for overuse (main result highlighted with bold) and traumatic injuries, respectively, amongst the 5205 runners included in the analyses.

The adjusted results were adjusted for age, BMI, sex, previous problems and running experience.

BMI, body mass index; HRR, HR ratio; n, number of injuries in the corresponding state; N/P, not possible to calculate a change; ref, reference.

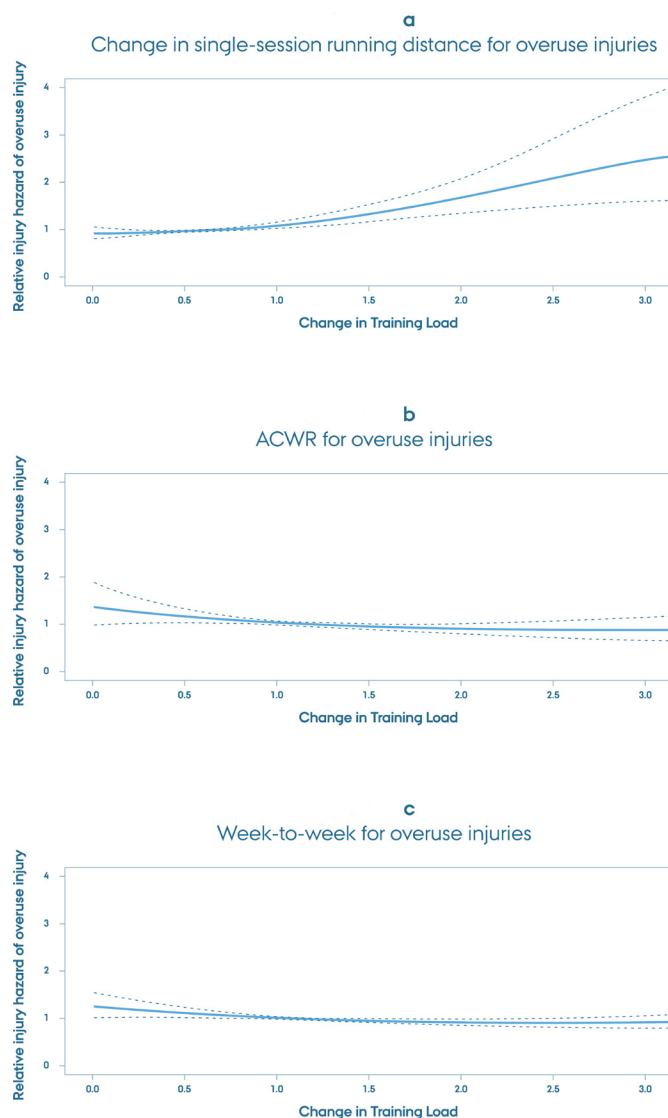


Figure 3 Plot of overuse injury HRs as a function of change in (a) single-session change in running distance; (b) acute:chronic workload ratio (ACWR); and (c) week-to-week ratio. On the x-axis, a value of 1 represents no change, a value below 1 represents regression and a value above 1 represents progression in kilometres.

following: (1) the prospective study design, which includes an up to 18-month follow-up period allowing for the assessment of exposure information prior to outcome data; (2) the inclusion of objectively-measured time-varying exposure rather than averaged information on running data; and (3) recruitment of English-speaking runners from more than 87 different countries facilitated via a productive partnership with Garmin.²²

Limitations

The following limitations are noted: (1) validity of the self-reported injury outcomes; (2) use of running distance as an exposure and the use of 'binned' exposure states; (3) the analytical approach including generalisability; and (4) causal assumptions. Injury assessment, origin (overuse vs traumatic) and location were self-reported, which carries information bias⁴⁵ though the validity of self-reported injury locations is found to be high.⁴⁶ Self-reporting running-related injuries depends on the injury definition used, which in this case did not require complete

stoppage. Further, runners may struggle to classify injuries as overuse or traumatic, possibly inflating the number of traumatic injuries.

The use of running distance to calculate changes in running load should be considered, although GPS-measured distance is superior to self-reported running distance.^{25 26 47} While running distance is a widely understood metric, especially among runners, it may not be the optimal measure of load. Another consideration is the approach used to analyse data. Other risk factors beyond changes in training load, such as previous injury, absolute running distance (eg, weekly mileage), age, diseases/musculoskeletal conditions and BMI were not included as effect measure modifiers as recommended due to low injury numbers, raising the risk of sparse data bias.⁴⁸ Therefore, it was not possible to provide specific advice for different subgroups of runners. Finally, the causal assumptions underpinning the study should be carefully considered. While confounders such as sex, BMI and prior injuries were included, the cause of running-related injury is multifactorial involving various exposures.^{23 25} The observational nature of the study design limits the robustness of the causal claims regarding injury prevention. To evidence-base the preventive effect of recommending runners to stay below a 10%-spike threshold to reduce injury risk, randomised trials or novel approaches such as target trial emulation should be pursued in future work.⁴⁹

CONCLUSION

This study has revealed that a significant dose-response relationship exists between changes in single-session distance and running-related injuries in a cohort of 5205 adult runners, predominantly males from Europe and North America. Notably, a spike >10% in single-session running distance significantly increased the rate of overuse running-related injuries, with the risk sharply rising when the distance more than doubled. Spikes in the ACWR, traditionally used in research and by industry, and spikes in the week-to-week ratio approach were not associated with an increased injury rate. Coaches and healthcare professionals, including primary care physicians, allied health services and orthopaedic specialists may consider using a session-specific cut-off below 10% to ensure the health and safety of runners and patients.

Author affiliations

¹Big Data Centre for Environment and Health, Aarhus University, Aarhus, Denmark

²Southern Queensland Rural Health, Faculty of Health, Medicine and Behavioural Sciences, The University of Queensland, Brisbane, Queensland, Australia

³Thompson Institute, University of the Sunshine Coast, Sunshine Coast, Queensland, Australia

⁴Department of Public Health, Aarhus University, Aarhus, Denmark

⁵Department of Sports Science and Clinical Biomechanics, The Faculty of Health Sciences, University of Southern Denmark, Odense, Denmark

⁶Oslo Sports Trauma Research Center, Department of Sports Medicine, Norwegian School of Sport Sciences, Oslo, Norway

⁷General Practice/Family Medicine, School of Public Health and Community Medicine, Institute of Medicine, Sahlgrenska Academy, University of Gothenburg, Gothenburg, Sweden

⁸Research, Education, Development and Innovation, Primary Health Care, Region Västra Götaland, Gothenburg, Sweden

⁹Orthopaedic Research Unit, Sahlgrenska University Hospital, Gothenburg, Sweden

¹⁰Department of Health and Rehabilitation, University of Gothenburg Institute of Neuroscience and Physiology, Gothenburg, Sweden

¹¹Research Unit for General Practice, Aarhus, Denmark

¹²Research Centre for Care and Rehabilitation, Faculty of Health and Society, VIA University College, Aarhus, Denmark

¹³Department of Physiotherapy, University College of Northern Denmark, Aalborg, Denmark

¹⁴Department of Precision Health, Luxembourg Institute of Health, Strassen, Luxembourg

X Merete Møller @Merete_Moller, Laurent Malisoux @LaurentMalisoux and Rasmus Oestergaard Nielsen @RUNSAFE_Rasmus

Acknowledgements Garmin is greatly acknowledged for the assistance with recruiting study participants. Peter Lübben assisted with graphical layout of Figure 1, 2 and 3.

Contributors The study was designed in collaboration between all authors. Data collection was completed by NSS and RON. The analyses were carried out by JSBF, ETP and SS. The results were interpreted by all authors. RON, AH and JSBF wrote the first draft of the manuscript, which was subsequently revised for important intellectual content by the remaining authors. All authors approved the final version of the manuscript prior to submission. RON is the guarantor.

Funding The study is supported by unconditional grants from Aarhus University Research Foundation (grant number: AUFF-E-2015-FLS-9-9) and the Danish Rheumatism Association to RON (grant number: R160-A5157). The contribution made by AH was supported by an Australian Research Council DECRA Fellowship: DE240100095. Garmin and these funders had no role in the study design; in the collection, analysis, and interpretation of data; in the writing of the report; and in the decision to submit the paper for publication.

Competing interests None declared.

Patient and public involvement Patients and/or the public were not involved in the design, or conduct or reporting, or dissemination plans of this research. Viewpoints and opinions from runners published in the scientific literature, the authors' experience as runners and experienced running injury researchers, as well as the 10% rule, collectively served as inspiration for this work.

Patient consent for publication Not applicable.

Ethics approval Permission from research ethics committee was not required as per The Danish Act on Research of Health Projects, Section 14, no.2. The Danish Data Protection Agency approved the study (reference number 2015-57-0002).

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement According to the informed consent, no data can be shared outside Aarhus University.

Supplemental material This content has been supplied by the author(s). It has not been vetted by BMJ Publishing Group Limited (BMJ) and may not have been peer-reviewed. Any opinions or recommendations discussed are solely those of the author(s) and are not endorsed by BMJ. BMJ disclaims all liability and responsibility arising from any reliance placed on the content. Where the content includes any translated material, BMJ does not warrant the accuracy and reliability of the translations (including but not limited to local regulations, clinical guidelines, terminology, drug names and drug dosages), and is not responsible for any error and/or omissions arising from translation and adaptation or otherwise.

Open access This is an open access article distributed in accordance with the Creative Commons Attribution Non Commercial (CC BY-NC 4.0) license, which permits others to distribute, remix, adapt, build upon this work non-commercially, and license their derivative works on different terms, provided the original work is properly cited, appropriate credit is given, any changes made indicated, and the use is non-commercial. See: <http://creativecommons.org/licenses/by-nc/4.0/>.

ORCID iDs

Merete Møller <http://orcid.org/0000-0001-7514-0399>

Ida Lindman <http://orcid.org/0000-0003-1450-4114>

Josefin Abrahamson <http://orcid.org/0000-0003-3949-0425>

Laurent Malisoux <http://orcid.org/0000-0002-6601-5630>

Rasmus Oestergaard Nielsen <http://orcid.org/0000-0001-5757-1806>

REFERENCES

- Hespanhol Junior LC, Pillay JD, van Mechelen W, et al. Meta-Analyses of the Effects of Habitual Running on Indices of Health in Physically Inactive Adults. *Sports Med* 2015;45:1455–68.
- Shipway R, Holloway I. Health and the running body: Notes from an ethnography. *Int Rev Sociol Sport* 2016;51:78–96.
- Scheerder J, Breedveld K, Borgers J. *Running across Europe: the rise and size of one of the largest sport markets*. Springer, 2015.
- Janssen M, Scheerder J, Thibaut E, et al. Who uses running apps and sports watches? Determinants and consumer profiles of event runners' usage of running-related smartphone applications and sports watches. *PLoS One* 2017;12:e0181167.
- Hollander K, Rahlff AL, Wilke J, et al. Sex-Specific Differences in Running Injuries: A Systematic Review with Meta-Analysis and Meta-Regression. *Sports Med* 2021;51:1011–39.
- Videbæk S, Bueno AM, Nielsen RO, et al. Incidence of Running-Related Injuries Per 1000 h of running in Different Types of Runners: A Systematic Review and Meta-Analysis. *Sports Med* 2015;45:1017–26.
- Fokkema T, Hartgens F, Kluitenberg B, et al. Reasons and predictors of discontinuation of running after a running program for novice runners. *J Sci Med Sport* 2019;22:106–11.
- Davis JJ, Gruber AH. Injured Runners Do Not Replace Lost Running Time with Other Physical Activity. *Med Sci Sports Exerc* 2020;52:1163–8.
- Menheere D, Janssen M, Funk M, et al. Runner's Perceptions of Reasons to Quit Running: Influence of Gender, Age and Running-Related Characteristics. *Int J Environ Res Public Health* 2020;17:6046.
- Saragiotto BT, Yamato TP, Lopes AD. What do recreational runners think about risk factors for running injuries? A descriptive study of their beliefs and opinions. *J Orthop Sports Phys Ther* 2014;44:733–8.
- Peterson B, Searle A, Spink M, et al. Going their own way-male recreational runners and running-related injuries: A qualitative thematic analysis. *PLoS One* 2022;17:e0273401.
- Linton L, Barr M, Valentin S. Prehabilitation for Recreational Runners: Motivators, Influencers, and Barriers to Injury Prevention Strategies for Running-Related Injury. *J Sport Rehabil* 2022;31:544–53.
- Bertelsen ML, Hulme A, Petersen J, et al. A framework for the etiology of running-related injuries. *Scand J Med Sci Sports* 2017;27:1170–80.
- Malisoux L, Nielsen RO, Urhausen A, et al. A step towards understanding the mechanisms of running-related injuries. *J Sci Med Sport* 2015;18:523–8.
- Soligard T, Schwelunus M, Alonso J-M, et al. How much is too much? (Part 1) International Olympic Committee consensus statement on load in sport and risk of injury. *Br J Sports Med* 2016;50:1030–41.
- Buist I, Bredeweg SW, van Mechelen W, et al. No effect of a graded training program on the number of running-related injuries in novice runners: a randomized controlled trial. *Am J Sports Med* 2008;36:33–9.
- Damsted C, Glad S, Nielsen RO, et al. IS THERE EVIDENCE FOR AN ASSOCIATION BETWEEN CHANGES IN TRAINING LOAD AND RUNNING-RELATED INJURIES? A SYSTEMATIC REVIEW. *Int J Sports Phys Ther* 2018;13:931–42.
- Nielsen RO, Parner ET, Nohr EA, et al. Excessive progression in weekly running distance and risk of running-related injuries: an association which varies according to type of injury. *J Orthop Sports Phys Ther* 2014;44:739–47.
- Gabbett TJ. The training-injury prevention paradox: should athletes be training smarter and harder? *Br J Sports Med* 2016;50:273–80.
- Running: How to Safely Increase Your Mileage. *Journal of Orthopaedic & Sports Physical Therapy* 2014;44:748.
- Bourdon PC, Cardinale M, Murray A, et al. Monitoring Athlete Training Loads: Consensus Statement. *Int J Sports Physiol Perform* 2017;12:S2161–70.
- Frandsen JSB, Simonsen NS, Hulme A, et al. A Paradigm Shift in Understanding Overuse Running-Related Injuries: Findings From the Garmin-RUNSAFE Study Point to a Sudden Not Gradual Onset. *JOSPT Open* 2025;3:85–92.
- Nielsen RO, Bertelsen ML, Ramskov D, et al. The Garmin-RUNSAFE Running Health Study on the aetiology of running-related injuries: rationale and design of an 18-month prospective cohort study including runners worldwide. *BMJ Open* 2019;9:e032627.
- Mansournia MA, Collins GS, Nielsen RO, et al. Checklist for statistical Assessment of Medical Papers: the CHAMP statement. *Br J Sports Med* 2021;55:1002–3.
- Dideriksen M, Soegaard C, Nielsen RO. Validity of Self-Reported Running Distance. *J Strength Cond Res* 2016;30:1592–6.
- Nielsen RO, Cederholm P, Buist I, et al. Can GPS be used to detect deleterious progression in training volume among runners? *J Strength Cond Res* 2013;27:1471–8.
- Taunton JE, Lloyd-Smith DR, et al. Preventing running injuries. Practical approach for family doctors. *Can Fam Physician Med Fam Can* 2003;49:1101–9.
- Gabbett TJ, Hulin B, Blanch P, et al. To Couple or not to Couple? For Acute/Chronic Workload Ratios and Injury Risk, Does it Really Matter? *Int J Sports Med* 2019;40:597–600.
- Clarsen B, Myklebust G, Bahr R. Development and validation of a new method for the registration of overuse injuries in sports injury epidemiology: the Oslo Sports Trauma Research Centre (OSTRC) overuse injury questionnaire. *Br J Sports Med* 2013;47:495–502.
- Yamato TP, Saragiotto BT, Lopes AD. A consensus definition of running-related injury in recreational runners: a modified Delphi approach. *J Orthop Sports Phys Ther* 2015;45:375–80.
- Hulme A, Nielsen RO, Timpka T, et al. Risk and Protective Factors for Middle- and Long-Distance Running-Related Injury. *Sports Med* 2017;47:869–86.
- van Poppel D, van der Worp M, Slabbekoorn A, et al. Risk factors for overuse injuries in short- and long-distance running: A systematic review. *J Sport Health Sci* 2021;10:14–28.
- van der Worp MP, ten Haaf DSM, van Cingel R, et al. Injuries in runners; a systematic review on risk factors and sex differences. *PLoS One* 2015;10:e0114937.
- Vittinghoff E, McCulloch CE. Relaxing the rule of ten events per variable in logistic and Cox regression. *Am J Epidemiol* 2007;165:710–8.
- Nielsen RO, Bertelsen ML, Ramskov D, et al. Time-to-event analysis for sports injury research part 1: time-varying exposures. *Br J Sports Med* 2019;53:61–8.
- Nielsen RO, Bertelsen ML, Ramskov D, et al. Time-to-event analysis for sports injury research part 2: time-varying outcomes. *Br J Sports Med* 2019;53:70–8.

- 37 Nielsen RØ, Malisoux L, Møller M, *et al.* Shedding Light on the Etiology of Sports Injuries: A Look Behind the Scenes of Time-to-Event Analyses. *J Orthop Sports Phys Ther* 2016;46:300–11.
- 38 Maupin D, Schram B, Canetti E, *et al.* The Relationship Between Acute: Chronic Workload Ratios and Injury Risk in Sports: A Systematic Review. *Open Access J Sports Med* 2020;11:51–75.
- 39 Nakaoka G, Barboza SD, Verhagen E, *et al.* The Association Between the Acute:Chronic Workload Ratio and Running-Related Injuries in Dutch Runners: A Prospective Cohort Study. *Sports Med* 2021;51:2437–47.
- 40 Joachim MR, Heiderscheit BC, Kliethermes SA. Week-to-week changes in training were not prospectively associated with injuries among Wisconsin high school cross-country runners. *Inj Prev* 2024;ip–2024.
- 41 Ramskov D, Rasmussen S, Sørensen H, *et al.* Run Clever - No difference in risk of injury when comparing progression in running volume and running intensity in recreational runners: A randomised trial. *BMJ Open Sport Exerc Med* 2018;4:e000333.
- 42 Fokkema T, Burggraaff R, Hartgens F, *et al.* Prognosis and prognostic factors of running-related injuries in novice runners: A prospective cohort study. *J Sci Med Sport* 2019;22:259–63.
- 43 Toresdahl BG, Metz J, Kinderknecht J, *et al.* Training patterns associated with injury in New York City Marathon runners. *Br J Sports Med* 2023;57:146–52.
- 44 Fokkema T, van Damme AADN, Fornerod MWJ, *et al.* Training for a (half-)marathon: Training volume and longest endurance run related to performance and running injuries. *Scand J Med Sci Sports* 2020;30:1692–704.
- 45 Lacey A, Whyte E, Dillon S, *et al.* Definitions and surveillance methods of running-related injuries: A scoping review. *Eur J Sport Sci* 2024;24:950–63.
- 46 Smits D-W, Backx F, Van Der Worp H, *et al.* Validity of injury self-reports by novice runners: comparison with reports by sports medicine physicians. *Res Sports Med* 2019;27:72–87.
- 47 Cloosterman KLA, Fokkema T, de Vos R-J, *et al.* Feasibility and usability of GPS data in exploring associations between training load and running-related knee injuries in recreational runners. *BMC Sports Sci Med Rehabil* 2022;14:78.
- 48 Nielsen RO, Bertelsen ML, Møller M, *et al.* Methods matter: exploring the “too much, too soon” theory, part 1: causal questions in sports injury research. *Br J Sports Med* 2020;54:1119–22.
- 49 Hernán MA, Wang W, Leaf DE. Target Trial Emulation: A Framework for Causal Inference From Observational Data. *JAMA* 2022;328:2446–7.