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Interactions Between Running Volume and Running Pace and Injury Occurrence in Recreational Runners: A Secondary Analysis

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Context: The combination of excessive increases in running pace and volume is essential to consider when investigating associations between running and running-related injury.

Objectives: To complete a secondary analysis, using a dataset from a randomized trial, to evaluate the interactions between relative or absolute weekly changes in running volume and running pace on the occurrence of running injuries among a cohort of injury-free recreational runners in Denmark.

Design: Prospective cohort study.

Setting: Running volume and pace were collected during a 24-week follow-up using global positioning systems data. Training data were used to calculate relative and absolute weekly changes in running volume and pace.

Patients or Other Participants: A total of 586 recreational runners were included in the analysis. All participants were injury free at baseline.

Main Outcome Measure(s): Running-related injury was the outcome. Injury data were collected weekly using a modified version of the Oslo Sports Trauma Research Centre questionnaire. Risk difference (RD) was the measure of injury risk.

Results: A total of 133 runners sustained running-related injuries. A relative weekly change of progression $>$10% in running volume and progression in running pace (RD = 8.1%, 95% CI = –9.3%, 25.6%) and an absolute weekly change of progression $>$5 km in running volume and progression in running pace (RD = 5.2%, 95% CI = –12.0%, 22.5%) were not associated with a statistically significant positive interaction.

Conclusions: Given that coaches, clinicians, and athletes may agree that excessive increases in running pace and running volume are important contributors to injury development, we analyzed the interaction between them. Although we did not identify a statistically significant positive interaction on an additive scale in runners who progressed both running pace and running volume, readers should be aware that an interaction is an important analytical approach that could be applied to other datasets in future publications.

Key Words: training load, running-related injury, interaction analysis, observational study, etiology

Key Points

- Coaches, athletes, and clinicians may consider the following question: Is the combination of excessive increases in running pace and running volume more injurious than an excessive increase in one of these factors?
- This study is the first interaction analysis in running-related injury research. Researchers can apply this analysis to help coaches, athletes, and clinicians answer the question in the first key point.
- Although our results were nonsignificant, we highlighted an analytical approach that is equally important as other well-known analytical methods, such as confounding.

In recent years, the field of running-related injury (RRI) research has witnessed an increase in the scientific literature investigating the association between training load and RRI.[1] The training load in studies involving runners is often quantified using variables such as volume (eg, kilometers or hours run), pace, or frequency.[1,2] However, the authors[1,3] of reviews concluded that limited evidence existed regarding the role of training load in the etiology of RRI, regardless of which training variable was used as the primary exposure. The reason for this may be that the nature of running participation is both multifactorial and complex.[4] Characteristics of this complex nature include the relationships between different training variables during running and the changes over time in these training variables.[5,6] Furthermore, the load tolerance of the musculoskeletal system may be especially challenged by sudden changes in training load.[7] Weekly changes in training variables may therefore be of particular relevance.[3,8]

To accomplish this, one may first consider the interrelation between time and variation in a training variable. This can be done by quantifying running participation and including it in an analysis as a *time-varying exposure* (a variable that changes over time).[5] Second, any separate analysis of an association between, for example, changes in running volume and the risk of injury, assumes that other training variables, such as running pace, are constant over time, which is not very plausible. Hence, considering the interaction of time-varying training variables is necessary because it may be more plausible to assume that the effects of the 2 factors exceed the effect of each individually.[9] No previous RRI research has accounted for the time-varying nature of training load and included the interaction between multiple training load variables while examining injury occurrence.[1–3]

To date, investigators[3] of changes in training variables and RRI have used relative changes as the primary exposure. Yet no consensus exists on what defines a change and what magnitude of sudden changes is relevant to injury risk[3]; sudden changes could also be quantified as absolute measures. Therefore, future researchers should also consider assessing absolute changes in training variables as exposures of interest. Evaluating absolute or relative changes in training variables and the interaction of these training variables while accounting for the time-varying nature of changes in running volume and running pace may shed new light on the role of training load in the etiology of RRIs.[5]

Thus, the purpose of our study was to complete a secondary analysis, using a dataset from a randomized trial, to investigate the interactions between relative or absolute weekly changes in running volume and weekly changes in running pace and the occurrence of running injuries among a cohort of recreational runners in Denmark who were injury free at baseline. We hypothesized that a significant positive interaction on an additive scale would exist if runners progressed both running pace and running volume.

METHODS

Data collection during the Run Clever trial ran from April 2015 through March 2016. The Run Clever trial was registered on Clinicaltrials.gov (January 23, 2015; NCT02349373), and a protocol article was published online on April 23, 2016 (submitted March 14, 2015).[10] The Ethics Committee Northern Denmark Region reviewed the study protocol and provided ethics approval (N-20140069). All included participants provided oral and written informed consent. The Run Clever trial randomly allocated recreational runners to a running schedule focused on increasing either the average weekly volume (km/wk) or the average weekly pace (min/km). The follow-up lasted 24 weeks, divided into an 8-week preconditioning period and a 16-week intervention training period. Randomization was performed after the 8 weeks of preconditioning. A detailed description of the original intervention was presented in the published protocol article.[10] We have reported the present study following the Strengthening the Reporting of Observational Studies in Epidemiology statement.[11]

Our 24-week cohort study was based on participants in the original Run Clever trial.[12] A call for study participants was distributed by contacting large companies and organizations, asking for permission to distribute information about the study through their internal communication platforms, using videos on social media, and advertising in running magazines and shops selling running gear.

The population of interest was recreational runners. A *recreational runner* was defined as a person who averaged 1 to 3 weekly running sessions during the past 6 months. Persons conforming to the definition of a recreational runner were considered for eligibility. The eligibility criteria were healthy persons between 18 and 65 years who owned a Garmin global positioning system (GPS) watch (Garmin International, Inc) or an iOS (Apple Inc)- or Android-based smartphone. Persons otherwise eligible for inclusion were excluded if they met ≥ 1 of the following criteria: injured within the past 6 months, pregnant, or vigorous physical activity contraindicated.[13] At inclusion, the following baseline information was collected via a questionnaire: sex, age, height, weight, running experience in years, and previous injury.

The exposure of interest was the relative or absolute changes in running volume and running pace between the weeks (weekly changes). The change was defined as either a regression or progression. Running volume was measured in kilometers and running pace in minutes per kilometer (min/km). Weekly running volume was calculated in the following manner: the number of kilometers completed during a running session was added to the sum of the kilometers covered during running sessions in the past 6 days, resulting in the continuous variable *cumulated volume over the last 7 days*.[8] Weekly running pace was calculated in a similar manner, resulting in a continuous variable reflecting the cumulative running time. By dividing the cumulative volume variable by the cumulative time variable, a continuous variable, *average pace over the last 7 days*, was calculated. Weekly changes could not be calculated for the first 2 weeks of follow-up.

Relative changes in both running volume and running pace were the ratios between 2 weeks expressed as percentage changes. Absolute changes in both running volume and running pace were the differences between the 2 weeks expressed in kilometers (min/km). Because such changes were not fixed in time but varied, they were treated as time-varying covariates (equivalent to states). After calculating weekly relative and absolute changes for both training variables, we categorized changes in the following exposure states:

- relative changes in pace (regression or progression pace), relative changes in volume (regression $>$ 10%; regression = 10%–0%; progression = 0%–10%; progression $>$ 10%).
- absolute changes in pace (regression or progression pace), absolute changes in volume (regression $>$ 5 km; regression = 0–5 km; progression = 0–5 km; progression $>$ 5 km).

The outcome was *RRI*, defined using a time-loss definition: "An injury sustained to muscles, joints, tendons and/or bones during or after running and attributed to running. The injury must have caused a training reduction (eg, reduced distance, intensity, frequency) for $\geq$7 days."[14(p2)] The diagnosis of time-loss RRI was based on a standardized clinical examination carried out by $\geq$1 physiotherapists. A total of 33 physiotherapists from 18 clinics constituted the diagnostic team and conducted clinical examinations of all injured runners. A consultation from an investigator to the physiotherapists in the individual clinics introduced them to the standardized examination schedule and accompanying diagnostic criteria to be used in the clinical examinations. The examination schedule and accompanying diagnostic criteria have previously been used in a prospective cohort study on novice runners.[15]

All data collected during the study were stored in a secured back-end system accessible only to the investigators. On a weekly basis, study participants answered online questionnaires on RRIs using a modified version of the Oslo Sports Trauma Research Centre questionnaire.[16] The modification consisted of a fifth possible answer, *cannot participate due to pain*, in addition to the existing possibilities in question 4. The questionnaire was distributed by email every Sunday during the follow-up period. Reminder emails were sent the following Monday if the questionnaire was not answered on Sunday. All participants who reported pain and time loss related to running received formal instructions concerning clinical examination by a physiotherapist.

All data on running participation were collected using GPS watches or iOS- (Apple Inc) or Android-based smartphones by the Help2Run application.[17,18] All running data were uploaded by the participants to the secure back-end system via a personalized internet-based training diary.

We performed the original power calculation before these data were collected relative to the primary hypothesis of the Run Clever trial, which was presented elsewhere.[12] Therefore, neither sample size nor power was calculated.

A time-to-event model (generalized linear regression using the pseudo-observation method) was used to calculate the cumulative injury risk difference (RD), which was the measure of association.[19] The duration (time) scale was kilometers of running during follow-up with the main analysis conducted at 150 km.[20] The interactions on an additive scale between relative or absolute weekly changes of running volume and running pace were calculated using an interaction term in the generalized linear regression (pseudo-observation method).[9,19] Interactions with a positive interaction term were considered positive, and interactions with a negative interaction term were considered negative. The reference group in the analysis of relative weekly changes was the regression pace plus regression of 10% to 0% volume. The reference group in the analysis of absolute weekly changes was regression pace plus regression of 0 to 5 km. Estimates are presented with 95% CIs and *P* values, with $P < .05$ considered statistically significant.[21]

A minimum of 10 events per variable (EVP) was considered necessary in the regression analysis.[22] In addition, 5 injuries per state was chosen as the minimum to reduce the risk of sparse data bias.[23] Running-related injuries and withdrawals from the study in the first 2 weeks were excluded from the analysis because it was impossible to calculate weekly changes over time among these runners. Included participants were right censored in case of pregnancy, illness, nonsport accidents causing a permanent end of running, lack of motivation to continue participation, > 10% manual upload of performed running, or the end of follow-up. Non–running-related injuries causing a permanent end of running were considered a competing risk.[24] All analyses were performed using STATA/SE (version 13; StataCorp LP).

RESULTS

From the original eligible Run Clever sample of 839 participants, a total of 253 were excluded due to RRI or withdrawal from the study in the first 2 weeks. The final sample of 586 participants performed a total running volume of 136 647 km, with an average volume per participant of 233 km. Data on running participation were collected using the GPS unit in an iPhone (77%, n = 451; Apple Inc), a Garmin GPS watch (7%, n = 41), an HTC smartphone (2%, n = 12), a Samsung smartphone (11%, n = 65), or a Nokia smartphone (2%, n = 12); the device was not reported by 1% (n = 6). Of the 586 participants, a total of 133 (23%) sustained an RRI (Figure). Baseline characteristics of all participants and separately for uninjured and injured individuals are presented in Table 1.

The RDs associated with combinations of different relative changes in running volume and changes in running pace are provided in Table 2. Measures of the interaction of relative changes in running volume and running pace on an additive scale for (1) a regression in running volume > 10% and (2) a progression in running pace and a progression in running volume < 10% and a progression in running pace were, respectively, –10.4% (95% CI = –30.1, 9.2; *P* = .30) and –19.4% (95% CI = –87.6, 48.9; *P* = .58). Hence, a nonstatistically significant negative interaction was associated with both changes, whereas nonstatistically significant positive interactions were observed for a progression >10% in running volume and a progression in running pace: 8.1% (95% CI = –9.3, 25.6; *P* = .36).

The RDs associated with combinations of different absolute changes in running volume and changes in running pace are shown in Table 2. Nonstatistically significant negative interactions of absolute changes in running volume and running pace on an additive scale were observed for a regression in running volume of > 5 km and a progression in running pace: –6.3% (95% CI = –27.3%, 14.6%; *P* = .55). Absolute changes consisting of a progression in running volume of 0 to 5 km and a progression in running pace (1.3%; 95% CI = –36.1%, 38.7%; *P* = .95), or a progression > 5 km in running volume and a progression in running pace (5.2%; 95% CI = –12.0%, 22.5%; *P* = .55) both revealed nonstatistically significant positive interactions.

DISCUSSION

Based on the notion that running volume and running pace are time-dependent variables that interact, we conducted an interaction analysis to investigate the association between weekly changes in running volume and running pace and running injury occurrence. Furthermore, separate analyses of each exposure were conducted because weekly changes in running pace and running volume could be quantified as both relative and absolute changes. The hypothesized positive interactions on an additive scale associated with relative or absolute progressions in both running pace and running volume were not supported by the results.

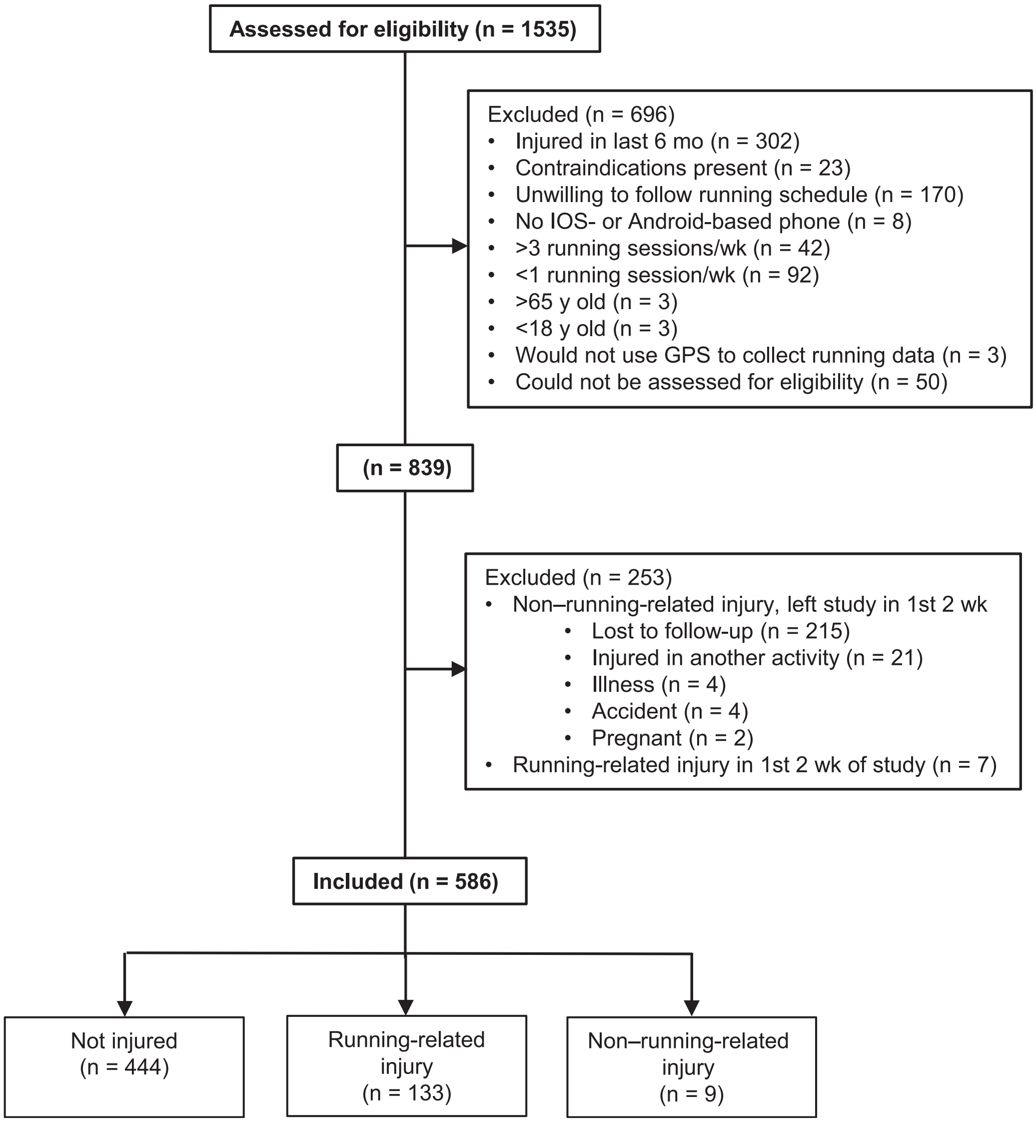

Figure. Flow of participants. Reasons for exclusion of participants from the original sample are listed. Running-related injuries are the number of events. Abbreviation: GPS, global positioning system. IOS, Apple Inc.

Previously, Nielsen et al[8] and Kluitenberg et al[25] performed individual analyses to assess running volume as a time-dependent exposure, and Kluitenberg et al[25] also evaluated the rate of perceived exertion as a time-dependent exposure in an individual analysis. We analyzed volume and pace as interacting training variables that change status over time. To the best of our knowledge, this is the first study to measure the combined effects of both training variables on RRI occurrence. This approach has practical implications when the aim is to advise runners on training-load management.

Consider a runner with a weekly progression in running volume > 10% and a weekly progression in running pace. The observed RD estimate tells us that this is 12.4% more injurious than for a runner with a weekly regression in running volume of 0% to 10% and a weekly regression in pace, although the observed interaction estimate indicates that a weekly change would be 8.1% more injurious if both running volume (>10%) and running pace were progressed versus a progression > 10% in volume and regression in pace or a progression of 0% to 10% in volume and a progression in pace. For advising runners on training-load management, the estimated interaction is therefore of particular importance. We examined injury risk. Notably, the analytical approach can also be applied if the aim is to investigate performance improvements.

Table 1. Baseline Characteristics of Participants

Characteristic	All (N = 586)	Uninjured (n = 453)	Injured (n = 133)
Sex, n (%)			
Female	365 (62.3)	269 (59.4)	96 (72.2)
Male	221 (37.7)	184 (40.6)	37 (27.8)
Age, y, mean ± SD	39.2 ± 10.0	38.8 ± 9.8	40.6 ± 10.2
Body mass index, kg/m^2, mean ± SD	24.3 ± 3.1	24.2 ± 3.0	24.4 ± 3.2
Running experience, y, median (interquartile range)	6 (3–12)	6 (3–13)	6 (2–10)
Previous injury? No. (%)			
No	278 (47.4)	231 (51.0)	47 (35.3)
Yes	308 (52.6)	222 (49.0)	86 (64.7)

Table 2. Risk Differences Associated With Weekly Relative Changes in Running Pace and Running Volume[a,b]

Relative	Reg >10% Volume				Reference				Prog = 0%–10% Volume				Prog >10% Volume			
Changes	Sessions	RD[c]	95% CI	*P* Value	Sessions	RD[c]	95% CI	*P* Value	Sessions	RD[c]	95% CI	*P* Value	Sessions	RD[c]	95% CI	*P* Value
Reg pace	21/2920	9.8	−7.3, 27.0	.26	19/2510	Reference group[d]			8/1279	28.6	−37.6, 94.8	.40	22/3863	1.4	−10.6, 13.5	.84
Prog pace	13/2805	2.3	−9.3, 13.9	.70	14/1664	2.9	−10.1, 15.9	.66	10/1286	12.1	−5.6, 29.9	.18	26/3649	12.4	−1.8, 26.7	.09
Interaction		**−10.4**	−30.1, 9.2	.30						**−19.4**	−87.6, 48.9	.58		**−8.1**	−9.3, 25.6	.36

Abbreviations: Prog, progression; RD, risk difference; Reg, regression.

[a] Interaction estimates are presented in bold.

[b] Results are presented as participant sessions in exposure group counts (injury registered in session/no injury registered in session), RD, 95% CI, significance level (*P*).

[c] Risk differences between percentage changes and absolute changes of weekly Prog and Reg in running pace (min/km) and running volume (km). Values are absolute percentage points.

[d] Reference cumulative incidence proportion 10.0% (relative changes).

Table 3. Risk Differences Associated With Weekly Absolute Changes in Running Pace and Running Volume[a,b]

Absolute	Regression >5 km Volume				Reference				Progresssion = 0–5 km Volume				Progression > 5 km Volume			
Changes	Sessions	RD[c]	95% CI	*P* Value	Sessions	RD[c]	95% CI	*P* Value	Sessions	RD[c]	95% CI	*P* Value	Sessions	RD[c]	95% CI	*P* Value
Reg pace	14/2168	9.8	−9.1, 28.7	.31	18/2639	Reference group[d]			15/2584	14.5	−20.1, 49.2	.41	15/2527	3.0	−10.3, 16.2	.66
Prog pace	12/2031	5.1	−17.8, 18.0	.68	15/2410	1.6	−11.0, 14.2	.80	25/2724	17.5	1.0, 34.5	.04	19/2751	9.8	−4.6, 24.3	.18
Interaction		**−6.3**	−27.3, 14.6	.55						**1.3**	−36.1, 38.7	.95		**5.2**	−12.0, 22.5	.55

Abbreviation: RD, risk difference.

[a] Interaction estimates are presented in bold.

[b] Results are presented as participant sessions in exposure group counts (injuries registered in session/no injuries registered in session), RD, 95% CI, significance level (*P* value).

[c] Risk differences between percentage changes and absolute changes of weekly regression and progression in running pace (min/km) and running volume (km). Values are absolute percentage points.

[d] Reference cumulative incidence proportion = 9.2% (absolute change).

Several important methodologic implications of our study downgrade the relevance of the results to clinical practice. Instead, this work should be viewed as a methodologic contribution, to which athletic trainers and sports medicine providers can direct attention when discussing the importance of including multiple training variables in studies of RRI causation. Also, future RRI research can also benefit from the statistical methods we used. This was not our original perspective but a result of the available data at the end of the follow-up. However, we still consider it plausible that a weekly progression in 2 training variables simultaneously challenges the load tolerance of the musculoskeletal system.

The assumption of EPV is the overall reason for the methodologic implications. To comply with this assumption, the pseudo-observations related to RD estimates should not be based on < 10 EPVs and 5 injuries per state; otherwise, the validity of the estimates would be questionable.[22] Thus, the EPV challenge relates to the deviation in our work from hypothesis H4: "A positive excess risk due to interaction exists between running intensity and running volume, and the effect is more pronounced for pace-related injuries with greater changes in speed than volume, while the effect is more pronounced for distance-related injuries with greater changes in volume than speed."[10(p2)] Specifically, to investigate the original hypothesis, the 133 observed injuries should have been categorized as RRIs hypothesized to be associated with changes in running pace, RRIs hypothesized to be associated with changes in running volume, and RRIs hypothesized to be associated with other risk factors.[8,26] A consequence of this approach would be a further necessary reduction of included exposure states in accordance with the assumption of EPV.[6,22] However, the categories of both relative and absolute weekly changes in running volume and running pace need to be refined in order for future researchers to identify a threshold for sudden changes in training load above which the risk of RRI increases significantly.[3]

The approach underpinning the analysis should also be carefully considered when interpreting these results. Ours was a secondary analysis, and the original randomization may have influenced the findings. Furthermore, authors[27–29] have shown that measures of association between training load and RRI are modified by personal characteristics such as body mass index, running experience, and previous injury. Our analysis might have produced different estimates of RD if additional variables, and thus more events of interest, had been included. Specifically, relevant effect-measure modifiers are needed in the analysis of future studies to allow for the determination of causal inference.[30]

Therefore, when designing future studies, an important focus should be on complying with the EPV assumption and minimizing the risk of sparse data bias. More injuries (events) will allow for a more detailed categorization of the exposure variable into various groups. In addition, more injuries would allow for the adjustment of more confounders without violating the EPV assumption. Indeed, adding more variables to the analysis would strengthen its clinical relevance. Moreover, a larger sample would allow for the inclusion of relevant effect-measure modifiers, which, in the presence of a low risk of sparse data bias, would improve the understanding of which changes in training load are acceptable for certain runners under different circumstances.

CONCLUSIONS

Given that coaches, clinicians, and athletes may agree that excessive increases in running pace and running volume are important contributors to injury development, we analyzed the interaction between them. Although we did not identify a statistically significant positive interaction on an additive scale in runners who progressed both running pace and running volume, readers of scientific articles should be aware that interaction is an important analytical approach that could be applied to other datasets in future publications.

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