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The association between running velocity, cadence, and tibial acceleration in recreational runners in an outdoor environment

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ABSTRACT
Advances in wearable technology have improved the ability to measure spatiotemporal gait parameters and training metrics in real-world environments, providing greater insight into how runners accumulate mechanical load. While spatiotemporal parameters such as velocity and cadence are associated with tibial acceleration (TA), these relationships have typically been examined at fixed velocities under controlled conditions, and do not consider their potential interaction or reflect real-world running conditions. The purpose of this study was to investigate the association between running velocity, cadence and TA in an outdoor environment. One hundred recreational runners ran on an athletics track at five velocities, ranging from very slow to very fast, based on their self-selected training pace. The results showed a significant interaction effect between cadence and velocity for both axial ($p=0.002$) and resultant TA ($p<0.001$). The estimated increase in axial TA for every 1-step increase in cadence ranged from 0.017 g to 0.042 g across the five velocity bands. For resultant TA, the estimated increase ranged from 0.006 g to 0.082 g. These findings suggest that cadence had a larger effect on TA at faster velocities, highlighting the importance of monitoring cadence in conjunction with velocity to inform TA.

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KEYWORDS
Wearable sensors; load monitoring; running load; running kinematics

Introduction

Despite the numerous health benefits linked to running, it is associated with a mean prevalence of 37% for lower limb injuries (Dempster et al., 2021). Due to the repetitive nature of running, running-related injuries (RRI) are predominantly overuse in nature. Overuse injuries occur when tissues are subjected to repetitive stress, at magnitudes below the acute injury threshold, without sufficient recovery time between running bouts (Bertelsen et al., 2017). This can result in a cumulative load that exceeds the structure-specific load capacity, leading to tissue failure (Hreljac & Ferber, 2006). As such,

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workload is thought to contribute to the underlying mechanisms of overuse injury. While workload has not been clearly defined in the literature, it is likely a combination of impact loads, which refer to external forces such as ground reaction forces (GRFs) applied upon each foot strike, and training loads, which reflect the frequency and intensity with which impact loads are accumulated over time (Bertelsen et al., 2017; Staunton et al., 2021). Acute impact loads may be reduced by modifying running gait characteristics, such as stride rate or stride length (Sheerin et al., 2019), while cumulative training loads may be reduced by adjusting training habits, such as running frequency, duration or velocity (Anderson et al., 2022; Huang et al., 2019). The contribution of impact and training load to overall workload highlights the importance of monitoring GRF and training habits to inform an individual's susceptibility to overuse RRIs.

Developments in wearable technology and global positioning system (GPS) capabilities have enhanced the potential for workload monitoring in professional sports (Benson et al., 2020; Li et al., 2020). For runners, GPS smartwatches are now capable of calculating a range of spatiotemporal gait parameters and training metrics, such as velocity, cadence and stride length, that provide insight into how runners accumulate training load (Clermont et al., 2020). While these metrics can offer general insights into the frequency and intensity of training load accumulation, they cannot provide direct information on biomechanical or impact load itself. Workload monitoring strategies that integrate smartwatch-derived data alongside acceleration or GRF measurements offer valuable insights into acute impact loading during a running session and the subsequent accumulation of workload over time (Rasmussen et al., 2023).

Advancements in wearable inertial measurement units (IMUs) enable real-world measurement of tibial acceleration (TA), which have been used as a surrogate measure of how GRFs are experienced in the lower limb during running (Greenhalgh et al., 2012; Mason et al., 2023; Tenforde et al., 2020). Considering gait patterns collected using controlled, in-laboratory measures do not always reflect those observed in real-world running, using IMUs may offer a more accurate reflection of how runners experience mechanical load as part of their typical training (Bruneau et al., 2025; Davis et al., 2024). For kinematic analyses, multiple IMUs can be attached at various anatomical sites, including the foot, tibia, thigh, and pelvis (Zandbergen, Buurke et al., 2023), whereas assessments of impact loading using TA typically involve a single IMU placed at the distal tibia (Sheerin et al., 2019). While axial TA has been observed to be higher in injured and previously injured runners compared to uninjured runners (Milner et al., 2006; Tenforde et al., 2020), resultant TA provides a more complete measure of acceleration passing through the tibia as it incorporates all three axes of acceleration and should also be monitored in relation to impact loads and RRI (Sheerin et al., 2019). However, while TA provides insight into the impact forces at the tibia, it does not capture the full complexity of tibial bone loading, which is caused by both external GRFs and internal muscle compressive forces (Zandbergen, Ter Wengel et al., 2023). Accordingly, TA should be interpreted as one of several contributors to tibial loading and RRI risk. Although internal forces are difficult to measure in real-world settings, TA can be measured using wearable IMUs, offering a practical means of monitoring external impact loading. This may contribute to a broader understanding of how impact forces interact with individual running biomechanics and training habits to inform cumulative loading. As research-grade IMUs are not widely accessible to the recreational runner, smartwatch-derived metrics could offer a viable alternative for everyday load monitoring.

Evidence indicates that peak axial and resultant TA tend to increase with faster velocities, suggesting that runners may experience greater impact load magnitudes at higher velocities (Boey et al., 2017; Sheerin et al., 2020). Furthermore, cadence has also been observed to increase with velocity, which may also contribute to changes in TA through increased step frequency and loading cycles, although the extent to which cadence influences TA across different velocities is not well understood (Doyle et al., 2023). While there is also evidence suggesting that increasing cadence at a given velocity may reduce impact loading, this research has been conducted at fixed velocities under controlled conditions and does not consider the possible interaction between spatiotemporal parameters at different velocities and their effects on TA (Clarke et al., 1985; Hamill et al., 1995). Importantly, TA measured during treadmill running differs from overground running, where variances in velocity, running surface and other environmental factors may influence impact dynamics (Bruneau et al., 2025; Davis et al., 2024). Zandbergen, Buurke et al. (2023) examined overground running during a marathon, reporting that velocity and cadence explained 20–30% of the variance in peak TA. However, while velocity and cadence were corrected for, their interaction across discrete running velocities were not directly investigated. Additionally, fatigue was not corrected for, despite its likely influence on TA as the marathon progressed. Therefore, there remains a need to understand the underlying relationship between spatiotemporal gait parameters and TA, with consideration of runners' preferred running velocities. Improved understanding of this relationship may enhance load monitoring and insight into individuals respond to mechanical load based on their specific training habits.

The primary aim of this study was to investigate the association between running velocity, cadence and TA in an outdoor environment. By using each runner's preferred training velocities, this study explored how spatiotemporal variables measured by a GPS smartwatch could potentially enhance the understanding of impact loading and inform individualised training load monitoring strategies. We hypothesised that increases in running velocity and cadence would be associated with increased axial and resultant TA.

Materials and methods

Participants

The participants in this study were part of an ongoing prospective investigation of running overuse injuries in recreational runners. One hundred recreational runners (65 male; 35 female) were recruited through running groups and relevant social media groups. Participants were included if they were aged between 20–65 years, ran at least 30 km, over three or more days per week, and had been running regularly for at least one year (Winter et al., 2020). Participants needed to have the intention of continuing their running for the next six months, and were required to be injury-free at the time of starting data collection. Specifically, they needed to be free of any physical complaints that affected the way they ran, or that caused them to reduce their training volume and intensity from their normal levels, for at least seven days before starting data collection (Yamato et al., 2015). Ethical approval was obtained from the Auckland University of Technology Ethics Committee (AUTEC 22/120), and all participants provided written informed consent.

Study procedure

Participants wore their own running shoes and were provided with a GPS smartwatch (Garmin Forerunner 235, Garmin, Kansas, USA) to monitor and record their running velocity during the session. Tibial acceleration was collected using two tri-axial IMUs (Blue Trident, Vicon, Oxford, UK) with a built-in high-g accelerometer (±200 g, 1600 Hz, 13-bit). IMUs were attached to the distal antero-medial aspect of each tibia, 2 cm above the medial malleolus, with the vertical axis aligned with the long axis of the tibia, using double-sided tape and secured using an elastic adhesive bandage.

Following a 5-minute warm-up, participants were required to complete runs across five different velocity bands, which were established based on running velocities typically used in running biomechanics research (Sheerin et al., 2020). Participants' self-selected training pace was first established using a treadmill (Bertec, Ohio, USA). Participants were instructed to find a running velocity approximating their normal training pace. Specifically, the researcher increased running velocity every 30 s until reaching a velocity participants could comfortably maintain for at least 20 minutes (Strongman & Morrison, 2021). Participants were then assigned a baseline 'normal' velocity band based on their self-selected comfortable training velocity, with two bands below (slow and very slow), and two bands above (fast and very fast). Each subsequent velocity band increased by 0.3 m/s (Sheerin et al., 2020). This range ensured that participants ran at velocities typical of their training routines, minimising any potential impact of unfamiliar velocities on their running technique or TA. The lowest velocity band was set between 1.9–2.1 m/s, which is considered the preferred walk-to-run transition velocity (Chase et al., 2023; Tseh et al., 2002). Participants with a velocity band slower than 1.9–2.1 m/s were excluded from the study, as this would likely have resulted in walking rather than running. Overground running data were collected over a 120 m length outdoor athletics track. Each participant completed two trials in each velocity band. Velocity was self-monitored using the provided GPS smartwatch, and trials were considered successful if the average velocity was within the target range.

Data processing

IMU data were recorded continuously across each velocity band, with at least two runs completed per band. To align IMU and GPS data, participants performed a jump at the start and end of each run while simultaneously starting and stopping the GPS smartwatch. These jumps produced distinct spikes in the IMU signal, which were used to identify and segment the corresponding intervals and align them with the GPS smartwatch data. Smartwatch data were extracted using the Garmin Connect portal and manually trimmed to determine a window aligning within the target velocity band. To better reflect a normal running environment, running velocity was not actively controlled; therefore, to accommodate the variance in running velocity the trimmed clips ranged between 15–38 s.

Acceleration data were processed using a custom Matlab script (R2024a, Mathworks, Massachusetts, USA) to align the accelerometry data to the GPS-determined velocity for each trial, and filtered using a fourth-order, 70 Hz Butterworth low-pass filter with zero phase lag. Trials with irregular acceleration signals, such as unclear or attenuated peaks, in any of the vertical, anterior-posterior, or medial-lateral axes were excluded from further analysis (Supplementary Figure 1). Resultant tibial acceleration (a_r) was calculated based on the relationship

$a_r = \sqrt{(a_x{}^2 + a_y{}^2 + a_z{}^2)}$

where a_x, a_y and a_z represent accelerations in the vertical, anterior-posterior, and medial-lateral axes, respectively.

Statistical analysis

All statistical analyses were conducted in R (v4.3.1, R Core Team, Vienna, Austria), using (primarily) the *Tidyverse* (Wickham et al., 2019), *robustlmm* (Koller, 2016), *easystats* (Lüdecke et al., 2025), *sjPlot* and *ggeffects* (Lüdecke, 2018; Lüdecke et al., 2024). Descriptive statistics are reported for the primary variables of interest, separated by velocity bands as mean and standard deviation. To address our aim and investigate associations between running velocity, cadence and TA, we adopted linear mixed effects models. Specifically, for each outcome (axial and resultant TA), two blocks of models were built: main-effects-only models with relative velocity band and cadence as independent predictors, and 'complete' models, which included their interaction. Both featured random intercepts for participant and random slopes for limb. Model assumptions were checked using diagnostic plots (leveraging various checks from *easystats*, notably '*check_model*'). Collinearity was evaluated using variance inflation factors (VIFs) and tolerance statistics for the main-effects-only models (i.e., excluding the interaction term, as interaction terms can mechanically inflate VIFs). VIFs were 2.12–2.13 for both cadence and relative velocity band (95% CI: 1.93–2.35), with tolerances of 0.47 (95% CI: 0.42–0.52), indicating low-to-moderate collinearity. Model residuals were non-normal and exhibited heavy tails (confirmed via Shapiro-Wilk tests of the studentised residuals, $p < 0.001$). Subsequently, we tested the sensitivity of these violations using robust mixed effects models. Although coefficients and substantive interpretations were stable across conventional and robust models, we retained the robust models for primary reporting since they are less sensitive to departures from distributional assumptions. Overall model fit was interpreted using conditional and marginal R^2. Raw coefficients (b) and 95% confidence intervals were reported for each predictor, with standardised coefficients (β) derived from refitted models (note, all inferences were based on the original, unstandardised models). Following the identification of an interaction effect from the complete model, we estimated slopes to characterise the shifting effect of cadence on axial and resultant TA at each velocity band. The alpha value for all tests was set at 0.05.

Results

Data were analysed from 94 out of 100 runners. One runner was excluded due to their normal training velocity being too low, resulting in a velocity band below the lowest defined velocity band. A further five runners were excluded due to irregular acceleration signals. Descriptive data of running pace, cadence, and TA for each relative velocity band are presented in (Table 1).

The main-effects-only and complete models achieved an overall good fit (conditional R^2: axial TA = 0.929 – 0.930; resultant TA = 0.924 – 0.930), although a relatively small

Table 1. Spatiotemporal variables and tibial acceleration measures for each relative velocity band (mean ± standard deviation).

Relative velocity band	Pace (min/km)	Cadence (steps/minute)	Axial TA (g)	Resultant TA (g)
Very slow	6.73 ± 0.86	164.6 ± 9.0	6.91 ± 2.54	10.69 ± 4.27
Slow	6.02 ± 0.68	166.8 ± 8.6	7.75 ± 2.71	11.82 ± 4.52
Normal	5.44 ± 0.56	169.9 ± 8.5	8.64 ± 2.81	13.05 ± 4.59
Fast	4.97 ± 0.45	172.7 ± 9.2	9.60 ± 3.01	14.43 ± 4.84
Very fast	4.55 ± 0.41	175.7 ± 9.6	10.24 ± 3.11	15.79 ± 5.36

Note: TA, tibial acceleration.

proportion of the variance appears due to the fixed effects in the models (marginal R^2: axial TA = 0.158 – 0.160; resultant TA = 0.142 – 0.145). The main-effects models showed statistically significant relationships for both cadence (axial TA: $b = 0.03$ [95% CI: 0.02–0.04], $p < 0.001$, $\beta = 0.10$; resultant TA: $b = 0.05$ [95% CI: 0.02–0.07], $p < 0.001$, $\beta = 0.09$) and relative velocity band (axial TA: $b = 0.72$ [95% CI: 0.67–0.77], $p < 0.001$, $\beta = 0.33$; resultant TA: $b = 1.07$ [95% CI: 0.98–1.15], $p < 0.001$, $\beta = 0.30$). However, in both complete models, the interaction term was significant (axial TA: $p = 0.002$; resultant TA: $p < 0.001$) (Table 2). Accordingly, in these models, the main effects tended to be no longer statistically significant ($p = 0.236$ – 0.365), except for relative velocity for resultant TA ($p < 0.001$), although our focus is on the presence of the interaction effect and estimated values from the model.

Estimated slopes between cadence and TA for each velocity band were positive and tended to be progressively steeper with increasing velocity (Figure 1) for both axial and resultant TA, though more pronounced at higher velocities for resultant TA. The estimated increase in axial TA for every 1-step increase in cadence ranged from 0.017 g at the very slow velocity band, to 0.042 g at the very fast velocity band (Table 3). For resultant TA, the estimated increase ranged from 0.006 g to 0.082 g across the same velocity bands.

Discussion

This study investigated the association between running velocity, cadence and TA in an outdoor environment relative to runners' self-selected training velocities. In line with our hypothesis, positive relationships were observed between cadence, relative velocity band,

Table 2. Relationships between cadence, velocity, and tibial acceleration components (complete model).

	Linear mixed effects model			
Predictors	*b*	95% CI	*p*	*β*
Axial TA				
(Intercept)	4.44	1.35–7.53	0.005	−0.04
Cadence	0.01	−0.01 – 0.03	0.236	0.10
Relative velocity band	−0.33	−0.99 – 0.32	0.315	0.33
Cadence × relative velocity band	0.01	0.00–0.01	0.002	0.03
Resultant TA				
(Intercept)	11.63	6.70–16.56	<0.001	−0.12
Cadence	−0.01	−0.04 – 0.02	0.365	0.09
Relative velocity band	−2.19	−3.22 – −1.16	<0.001	0.30
Cadence × relative velocity band	0.02	0.01–0.03	<0.001	0.05

Note: TA, tibial acceleration; *b*, unstandardised coefficients, in *g*; 95% CI, 95% confidence intervals; *p*, *p*-value; *β*, standardised coefficients, based on fully refitted models; Note: Model includes random intercepts for participant, and random slopes for limb.

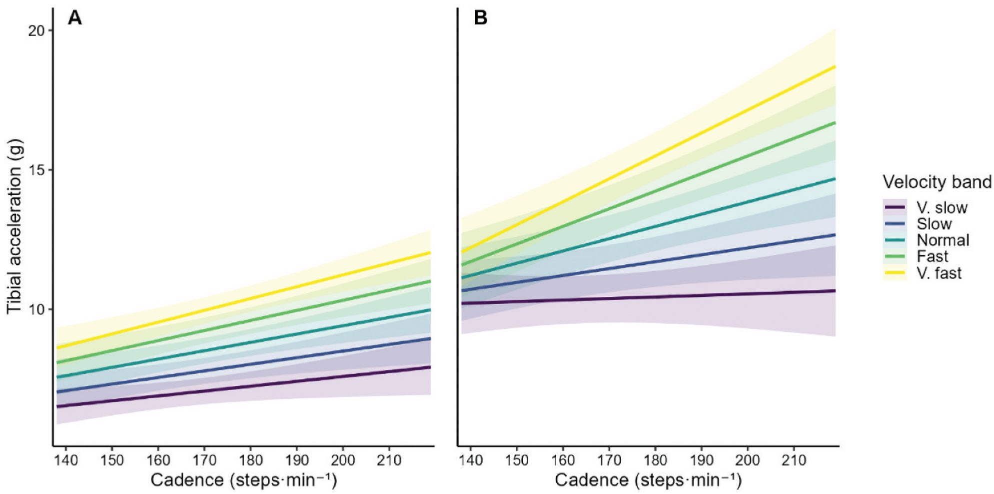

Figure 1. The interaction effect between cadence and relative velocity band on (A) axial and (B) resultant tibial acceleration. Shaded areas correspond to 95% confidence intervals.

Table 3. Estimated increase in axial and resultant tibial acceleration for a single-step increase in cadence.

Relative velocity band	Estimated slope (axial TA)	Estimated slope (resultant TA)
Very slow	0.017	0.006
Slow	0.023	0.025
Normal	0.030	0.044
Fast	0.036	0.063
Very fast	0.042	0.082

Note: TA, tibial acceleration.

and axial and resultant TA. However, a statistically significant interaction effect highlighted that the effect of cadence on axial and resultant TA varied depending on velocity. While the magnitude of interaction was modest, ultimately this suggests that considering both cadence and velocity together provides a more nuanced picture of TA than either factor alone. Measuring cadence and velocity during training could be meaningful when considering the cumulative effects on TA.

A key finding from this study was that the effect of cadence on axial and resultant TA was not uniform across velocities. Specifically, the statistically significant interaction effect indicated that cadence had a larger effect on TA at faster velocities. This was particularly notable for resultant TA, which is easily discerned in (Figure 1) with the steeper and more disparate slopes as velocity increases. By contrast, the same increase in cadence at lower velocities was associated with much smaller changes in TA, as reflected by the shallower slopes observed at the very slow and slow velocity bands. Although the absolute changes in TA per step may appear relatively small in isolation (notably for slower velocities), their cumulative effect over prolonged or repeated running exposures at faster velocities and higher cadences could be practically meaningful. For example, at the normal velocity band, a 10-step increase in cadence is estimated to increase axial TA by 0.30 g and resultant TA by 0.44 g per step. Whereas at the very fast velocity band, the same cadence increase is associated with an increase of 0.42 g axial TA and 0.82 g resultant TA per step. Higher cadences also increase the total number of steps accumulated per km, hence these per-step increases in TA could lead to greater cumulative loading during prolonged running bouts (Doyle et al., 2023).

The interaction between cadence and velocity observed in this study may reflect changes in running kinematics as a natural response to increasing velocity, as both cadence and stride length have been shown to increase as running velocity increases (Doyle et al., 2023; Mercer et al., 2002). Additionally, increases in stride length have been suggested to alter lower limb geometry at impact, including hip, knee and ankle orientation, which could influence TA magnitude (Mercer et al., 2003; Sheerin et al., 2019). Although stride length was not measured as part of this study, the results underscore the importance of considering how running gait parameters interact to inform TA, especially as running velocity changes. This is further supported by the modest proportion of variance explained by cadence and velocity (marginal R^2: axial TA = 0.160; resultant TA = 0.145), indicating considerable variability in TA across individuals. Similarly, Sheerin et al. (2020) reported that velocity accounted for only 19% of the variance in peak resultant TA magnitude. This suggests that velocity and cadence alone are not sufficient to explain variation in TA, and that the interaction of additional biomechanical and spatiotemporal variables, such as stride length and joint kinematics, should be considered to better understand how TA responds to changes in running velocity. Accordingly, the results also highlight the importance of running technique, and accordingly, controlling cadence or stride length when transitioning to faster velocities, where small adjustments may lead to greater increases in TA. Additionally, the interaction effect was more pronounced for resultant TA. While resultant TA has not been linked to RRI, these results illustrate the importance of measuring resultant TA for load monitoring purposes, as it provides a more complete representation of acceleration passing through the tibia than axial TA (Sheerin et al., 2020).

Previous studies investigating the relationship between spatiotemporal parameters and TA have typically used a single fixed or self-selected velocity (Clarke et al., 1985; Derrick et al., 1998; Hamill et al., 1995). This may not accurately reflect real-world running conditions, where velocity can vary depending on factors such as running surface, environmental conditions, or specific training objectives. In contrast, this study examined the association between running velocity, cadence and TA using a range of velocities relative to self-selected normal training pace, better reflecting how individuals experience TA based on their specific training velocities. The effects of cadence adjustments on impact loading have also been explored in gait retraining studies, which report significant reductions in vertical average and instantaneous loading rates following a 7.5% increase in cadence at a single velocity (Futrell et al., 2020; Wang et al., 2020; Willy et al., 2016). By comparison, the results from this study suggest that cadence-related changes in TA are not consistent across different velocities, and that there may be a practical threshold beyond which the potential mechanical benefits of increasing cadence are offset by elevated TA. Further research is needed to understand both the acute and cumulative effects of changes in spatiotemporal parameters on TA across different velocities relative to an individual's preferred training velocity.

A strength of this study was the inclusion of five velocity bands relative to each participant's normal training pace, better reflecting how individuals experience TA at different velocities relative to their normal training velocity. However, only cadence and velocity were analysed in relation to TA. Considering the positive linear trend between axial TA and increased stride length (Sheerin et al., 2019), its inclusion in future research may provide a more comprehensive understanding of how spatiotemporal parameters collectively inform TA, particularly as velocity changes. Another limitation is the relatively short running segments, which do not represent how a runner would typically train, or reflect any changes in biomechanics and TA that may result from fatigue. Additionally, the results are limited to running on a tartan athletics track. Future research should consider longer duration running on different surfaces to further understand the interaction of spatiotemporal parameters and the practical implications of these interactions on how TA is accumulated during real-world training.

Conclusion

This study investigated the association between running velocity, cadence and TA relative to runners' self-selected training velocities in an outdoor environment. A significant interaction effect between cadence and relative velocity band was observed, indicating that cadence had a larger effect on TA at faster velocities. These findings emphasise the importance of monitoring cadence in conjunction with velocity, as their combined effect provides a more comprehensive explanation of TA. However, velocity and cadence only explained a modest proportion of the variance in axial and resultant TA, suggesting that additional factors contribute to variability in TA. Collectively, these findings highlight the importance of considering how spatiotemporal parameters interact at different velocities to inform TA.

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Author contributions

CRediT: **Jasper Wong:** Conceptualization, Data curation, Investigation, Methodology, Project administration, Visualization, Writing – original draft, Writing – review & editing; **Hannah E. Wyatt:** Conceptualization, Methodology, Writing – review & editing; **Chris Whatman:** Conceptualization, Methodology, Writing – review & editing; **Matt R. Cross:** Formal analysis, Visualization, Writing – review & editing; **Kelly Sheerin:** Conceptualization, Methodology, Writing – review & editing.

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