Title: Durability of physiological and biomechanical variables during a marathon.

Running title: Changes to biomechanics during a marathon.

Authors: Ben Hunter[1], Aldo Lena[1] & Daniel Muniz-Pumares[2]

Affiliations:

[1] School of Human Sciences, London Metropolitan University, London, United Kingdom

[2] School of Life and Medical Sciences, University of Hertfordshire, Hatfield, United Kingdom

Corresponding author: DMP

Abstract

Durability is the ability to withstand the deterioration of physiological parameters and is associated with marathon performance. The aim of this study was to examine whether changes to biomechanical parameters are dependent on durability. Sixty-nine runners submitted data collected using a footworn accelerometer and heart rate (HR) recording device during a marathon (median finish time (IQR): 224.0 (60.4) mins). Biomechanical parameters (both speed-adjusted and absolute) including stiffness, duty factor, step frequency, step length and running speed, and HR were separated into eight 5 km segments. Decoupling was used to quantify durability, defined as ratio between HR and running speed. The magnitude of the decoupling was determined from the last full 5 km segment of the race (35-40 km) and expressed relative to the 5-10 km segment, and used to group the participants into high, moderate, and low decoupling groups. Greater biomechanical deterioration was observed in the high decoupling group, but this disappeared after adjusting for speed. More durable runners (i.e., low decoupling) exhibited distinct changes in speed-adjusted step frequency and step length across the marathon. These patterns may relate to fatigue resistance, though it remains unclear whether they reflect durability-enhancing adaptations or traits of inherently resilient runners.

Introduction

Marathons are of enduring interest and provide an opportunity to study fatigue-related phenomena in the field. Multiple factors have been studied in the field which account for marathon performance including footwear (Langley & Langley, 2024; Senefeld et al., 2021), weather (Vihma, 2010), and training characteristics (Haugen et al., 2022; Muniz-Pumares et al., 2024). Further to extrinsic factors, there are numerous intrinsic factors which contribute to marathon performance including, anthropometry (Legaz Arrese et al., 2006), and physiological characteristics including maximal oxygen uptake and utilisation ($\dot{V}O_{2max}$), running economy, and the maximal sustainable fractional utilisation of $\dot{V}O_{2max}$ (di Prampero et al., 1986; Jones et al., 2021; Joyner et al., 2008). These parameters, typically determined in a rested state, are subject to deterioration during prolonged endurance exercise (Jones, 2023), and the ability to preserve these has been termed durability (Maunder et al., 2021).

To assess durability in the field, changes to the ratio between internal work rate (e.g., heart rate) and external work rate (running speed) has been used (De Pauw et al., 2024; Hunter et al., 2025; Maunder et al., 2021; Smyth et al., 2022). This ratio can be expressed relative to baseline during the marathon, either over time (Maunder et al., 2021) or distance (Smyth et al., 2022). Briefly, decoupling represents an increase in HR for a given speed, a fall in speed for the same HR, or an increase or plateau in HR and decrease in speed. It has previously been shown that the magnitude of decoupling and its onset are associated with marathon performance, with faster runners experiencing less decoupling when compared to slower runners (Smyth et al., 2022). Similar findings have also been reported for a “backyard” ultramarathon, where less proficient runners (i.e., those that completed lower distances), exhibited significantly higher decoupling between HR and speed compared to more proficient runners (i.e., those that completed greater distances) in the final quarter of the event (De Pauw et al., 2024).

Further to physiological characteristics, biomechanical parameters have been implicated with marathon performance (Hoogkamer et al., 2017). Research has examined changes to several biomechanical aspects in response to marathon running, including foot strike patterns (Chan-Roper et al., 2012; Hanley et al., 2020; Larson et al., 2011), force production (Bertram et al., 2013; Nicol et al., 1991b; Petersen et al., 2007; Saldanha et al., 2008), joint kinematics (Chan-Roper et al., 2012; Kyröläinen et al., 2000; Nicol et al., 1991a; Reenalda et al., 2016), and muscle activity (Nicol et al., 1991a). Various methods have been used to analyse the manner in which these parameters change over time, including high-speed video cameras (Chan-Roper et al., 2012; Hanley et al., 2020; Larson et al., 2011), force plates installed at specific points on the course (Bertram et al., 2013; Nicol et al., 1991b), and isokinetic dynamometers (Petersen et al., 2007; Saldanha et al., 2008).

Accelerometers offer the advantage of continuous, high-frequency sampling of biomechanical data during the marathon (Clermont et al., 2019; Hunter et al., 2021; Meyer et al., 2021). Studies examining the validity and reliability of footworn accelerometers, commonly known as foot pods (e.g., Stryd), have demonstrated conflicting findings (Cartón-Llorente et al., 2021; Cerezuela-Espejo et al., 2021; García-Pinillos et al., 2021; Imbach et al., 2020). For example, when compared to the OptoGait System, Stryd has been shown to underestimate ground contact time and overestimate flight time (García-Pinillos et al., 2021; Rodríguez-Barbero et al., 2024). However, the Stryd system has demonstrated valid measures of ground contact time and leg stiffness when compared to 3D motion analysis and force plate (Imbach et al., 2020). Research has demonstrated good reliability of Stryd, making it useful for repeated measures design studies (Cartón-Llorente et al., 2021; Cerezuela-Espejo et al., 2021; García-Pinillos et al., 2021; Imbach et al., 2020).

Limited research has been focussed on continuous measurement of biomechanical parameters during marathon races (Clermont et al., 2019; Hunter, Karsten, et al., 2021; Meyer et al., 2021; Zandbergen et al., 2023). Clermont and colleagues (2019) used a waist-mounted inertial measurement unit to derive a composite index calculated from the mean and standard deviation of step frequency, braking, vertical oscillation, pelvic rotation, pelvic drop, and ground contact time during a marathon race. This approach successfully clustered 27 runners into two groups of differing age-grade performance, with the more successful cluster exhibiting greater consistency in running patterns throughout the race. Meyer et al. (2021) subsequently examined individual biomechanical parameters using footworn sensors during the Geneva marathon, and demonstrated progressive alterations to spatiotemporal parameters, maximal ground reaction force, vertical stiffness, leg stiffness, and foot strike angle during the race. Notably, their findings revealed significant changes in gait patterns around the 25 km and 35 km marks, likely influenced by factors such as reduced substrate availability and neuromuscular fatigue, both of which are believed to affect durability (Brownstein, Pastor, et al., 2022; Spragg et al., 2023). However, in a study by Hunter and Smith (2007) the increase in $\dot{V}O_2$ observed during a 1-hour treadmill run was not associated with changes in step frequency or stiffness. The discrepancy in findings might be due to the shorter distance covered (~14 km) in the treadmill run when compared to marathon races (Clermont et al., 2019; Meyer et al., 2021). In longer distances, such as a half marathon, shifts in biomechanical parameters have been linked to increased HR, with authors suggesting neuromuscular fatigue as a contributing factor (Prigent et al., 2022).

Despite a growing interest in durability and its effects on endurance performance, little attention has been paid to how this affects, or is affected by, biomechanical parameters. Therefore, the aim of this study was to examine whether changes to biomechanical parameters are dependent on the magnitude of decoupling. Previously, it has been shown that biomechanical and neuromuscular parameters are affected by the exercise intensity domain in which running is performed (Apte et al., 2021; Brownstein et al., 2021; Hunter, Greenhalgh, et al., 2021). If a greater magnitude of decoupling represents a greater deterioration of physiological function, it follows that greater decoupling would be associated with greater changes to biomechanical parameters. Therefore, it was hypothesised that runners with lower durability, i.e., greater decoupling, would exhibit larger changes to biomechanical parameters over the course of the marathon, and that this would follow the onset of decoupling. A further hypothesis was that faster runners would exhibit less decoupling, consistent with previous work examining decoupling and marathon performance (Smyth et al., 2023).

Methods

Recruitment

Following ethical approval by the [redacted], participants were recruited online through advertising on social media by non-probability sampling. Inclusion criteria required participants to be uninjured adult runners who were either registered for, or had completed within the past two weeks, an officially recognized marathon. Participants also needed to own a Stryd footpod and a device capable of measuring heart rate. Eligible race courses had to be certified by the Association for International Marathons and Distance Races (AIMS) or by the national governing body for distance running in the country where the race was held. Self-guided, trail, or virtual marathons were excluded. These conditions were verified through visual inspection of submitted data files and confirmation that the course met the criteria. No exclusion criteria for age, gender, or finish time were applied to permit the examination of a potentially wide variety of durability profiles. Participants were invited to complete an electronic informed consent form outlining the nature of the study and their right to withdraw at any time without consequence. Those who consented received online instructions detailing how to complete the study. All methods were conducted in line with the Code of Ethics of the World Medical Association and Declaration of Helsinki, except for pre-registration.

Study Design

Participants were asked to record during their respective marathons using their own Stryd Power Meter (Stryd Inc., Boulder CO, USA) and HR monitor (i.e., smart watch, optical HR monitor, or chest strap HR monitor). Following this, the participants were asked to upload the data to their own online training platform, i.e., Stryd Powercenter (Stryd Inc., Boulder CO, USA). No guidance was given regarding pacing strategy, and participants were blinded to the hypotheses of the study.

Data collection

Running speed and biomechanical parameters were recorded during respective marathons with a foot pod power meter (Stryd Inc., Boulder, CO, USA). Briefly, the foot pod attaches to the shoe at the midfoot, weighing 9.1 g. Based on a 6-axis inertial motion sensor (3-axis gyroscope, 3-axis accelerometer), the device provides metrics to quantify performance: speed, distance, elevation, power, ground contact time, vertical oscillation, leg stiffness, and cadence. Power (given in $W \cdot kg^{-1}$) in this instance, is the work rate required to propel the body forwards and is calculated by proprietary algorithms developed by Stryd Inc. (Boulder, CO, USA). These algorithms estimate the forces generated based on triaxial accelerometery, with inclusion of the runner's body mass, wind resistance, and gradient (Austin et al., 2018). Previous studies have evidenced good reliability for spatiotemporal running characteristics (García-Pinillos et al., 2021) and power output (Cartón-Llorente et al., 2021). Participants were instructed to calibrate the foot pod and attach the foot pod to their shoe in line with manufacturer's instructions. HR was recorded using the participant's own smart watch, optical HR monitor, or chest strap HR monitor. Participants completed an online form within two weeks of their respective marathons. The form collected details on running volume and experience prior to the marathon, the version of the foot pod used, the instrument used to measure heart rate, and the footwear worn during the marathon (see Supplemental File 1). Once both the form and the marathon were completed, participants downloaded their data from Stryd PowerCenter as .fit and .csv files and emailed them to the research team at their earliest convenience. Forms or marathons completed outside the two-week window of the marathon were excluded from further analysis.

Data analysis

All data analyses were carried out using MATLAB (2023b, Mathworks). Once marathon files were exported, data including speed, distance, elevation, running power, form power, step length, step frequency, ground contact time, vertical oscillation, leg stiffness, and HR were extracted for each participant. Speed was grade-adjusted using methods that have previously been described (Minetti et al., 2002). In brief, this accounts for the dissociation between measured speed and metabolic intensity observed during uphill and downhill running. Duty factor was calculated as the ratio between ground contact time and total stride time. Some participants walked due to fatigue or fluid intake. Due to the differences in walking and running in most biomechanical parameters (Ounpuu, 1994), strides corresponding to less than 2.016 $m \cdot s^{-1}$ were removed (Rotstein et al., 2005). Each of the biomechanical parameters were averaged for each 1-km segment.

To assess durability, the ratio between internal-to-external work rate was calculated for each segment. Internal work rate was determined as a percentage of the age-predicted maximum HR (Inbar et al., 1994). The external work rate was determined as the grade-adjusted speed. The decoupling observed in the last 5 km segment of the race (35–40 km) was used to determine the overall magnitude of the decoupling experienced by each athlete and expressed relative to the 5–10 km segment (Smyth et al., 2023). Runners experiencing a decoupling < 1.1 in the last segment of the race were classified as low decoupling, a decoupling ≥ 1.1 but < 1.2 was considered as moderate, and if decoupling was ≥ 1.2 it was deemed as high decoupling (Maunder et al., 2021; Smyth et al., 2022). The onset of decoupling was calculated by indexing the distance (km) at which decoupling exceeded, and remained above, 1.025, i.e., 2.5%. If decoupling did not exceed 2.5%, the onset of decoupling was given as 42.195 km. A similar approach was used to identify when biomechanical changes began in each parameter for each participant, given as the distance (km) at which a 2.5% deviation from baseline (5–10 km) was observed and sustained for the rest of the race. If this threshold was not exceeded, the value was given as 42.195 km.

Statistical Analysis

Normally distributed data are presented as mean ± SD, whereas non normally distributed data are presented as median (interquartile range [IQR]). Kolmogorov–Smirnov tests for normality were conducted on the data. The assumption of sphericity was tested using Mauchly's test, with Huynh-Feldt corrections made for violations ($P < 0.05$). Decoupling magnitude, onset of decoupling, and finishing time violated tests of normality. Thus, Kruskal-Wallis one-way analysis of variance (ANOVA) was performed to test the effects of group on decoupling magnitude, onset of decoupling, and finishing time, with a one-way Welch's ANOVA to test the effects of group on average speed. Post hoc comparisons were conducted using Dwass-Steel-Critchlow-Fligner and Games-Howell pairwise comparisons for not normally distributed and normally distributed data, respectively.

Due to the relationship between running speed and biomechanical parameters, variables including leg stiffness, vertical oscillation, duty factor, contact time, step frequency, step length, and power were adjusted to account for runner-specific changes in speed, which could otherwise mask fatigue-related changes throughout the marathon (Zandbergen et al., 2023). Mean speed and the mean of each biomechanical parameters for each 1-km segment from 6-40 km were used to create runner-specific linear regression models. Intercepts and coefficients for each runner were then used to correct biomechanical parameters by subtracting the individual coefficients for speed multiplied with the deviation from the individual mean speed for all 1-km segments during the marathon. Each of the biomechanical parameters (speed-adjusted and absolute) were subsequently mean-averaged for each 5-km segment, plus the final 2.195 km. Two-way repeated measures ANCOVAs (group x segment) were then used to compare differences in absolute leg stiffness, vertical oscillation, duty factor, contact time, step frequency, step length, and power with average race speed as a covariate. As speed had been used to adjust biomechanical parameters, two-way repeated measures ANOVAs (group x segment) were used to compare differences in speed-corrected leg stiffness, vertical oscillation, duty factor, contact time, step frequency, step length, and power.

Repeated measures ANOVAs (group x segment) were used to test for differences in decoupling, grade-adjusted speed, and HR. For all ANCOVA and ANOVA tests, the first (0–5 km) and last (40–42.195 km) segments of the race were excluded to avoid possible artefacts caused by sudden changes in pace in the first and last few kms of the race, respectively. Pairwise comparisons were conducted using Bonferroni adjustments where main effects and interactions were significant ($P < 0.05$). Partial eta-squared (η^2p) was used as a measure of effect size, and interpreted as small (0.01, medium (0.06) and large (0.14) and Hedge's g was used to measure effect sizes between groups and interpreted as small (0.2), medium (0.5) and large (0.8).

The relationship between the magnitude of decoupling and the fractional change in biomechanical variables between 5-10 km and 35-40 km segments was determined using Pearson's product correlations. Results were deemed statistically significant when $P < 0.05$. A Bland-Altman analysis was used to quantify the bias and 95% confidence intervals between decoupling onset and onset of changes to each biomechanical parameter. All statistical analyses were performed using Jamovi Software (Version 2.3.28.0) and figures drawn in GraphPad Prism (Version 10.1.2).

Results

A total of 122 participants filled out the online survey and were invited to submit race files. Of these, sixty-nine runners (four females, group mean ± standard deviation age: 44.4 ± 10.5 yrs; stature: 1.78 ± 0.08 m; mass: 73.3 ± 10.8 kg; running experience: 12.1 ± 9.6 yrs submitted self-measured data successfully. The level of performance of the participants in the study fell under Tiers 1, 2, and 3 based on the framework outlined by McKay et al., (2021). Reasons for participants not being included in the final analysis included: submitting incorrect file types (n = 11), submitting files of previous marathons (> 2 weeks; n = 3), no race files being submitted despite follow up communication (n = 35), submitting files which did not meet the requisite distance (42.195 km; n = 2). Two participants were excluded as both exhibited a run-walk strategy throughout the marathon. Included participants completed the marathon in a median finish time (IQR) of 222.5 (60.4) mins. Table 1 summarises the marathon performance and decoupling characteristics of the participants.

*** Table 1 about here ***

The ratio between HR and speed exhibited differences between groups ($P < 0.001$; $\eta^2p = 0.499$), with interaction effects evident ($P < 0.001$; $\eta^2p = 0.472$), demonstrating decoupling throughout the marathon ($P < 0.001$; $\eta^2p = 0.593$; Figure 1). There was an increase in HR throughout the marathon across all groups ($P < 0.001$; $\eta^2p = 0.073$) with no differences between groups ($P = 0.977$; $\eta^2p = 0.001$). However, there were significant interaction effects evident ($P = 0.037$; $\eta^2p = 0.054$; Figure 1), with moderate and high decoupling groups exhibiting greater increases in HR earlier in the marathon. Despite no differences between groups for speed ($P = 0.140$, $\eta^2p = 0.058$), main effects for segment ($P < 0.001$; $\eta^2p = 0.494$), and interaction effects ($P < 0.001$; $\eta^2p = 0.308$) were shown, with speed reducing throughout the marathon, and more marked reductions shown in the high decoupling and moderate decoupling groups (Figure 1). Greater magnitudes of decoupling were associated with slower finish times ($r = 0.304$, $P = 0.011$) and lower average race speed ($-r = 0.306$, $P = 0.011$).

*** Figure 1 about here ***

The time course of biomechanical parameters during the marathon are shown in Figure 2. Average race speed was a significant covariate across all parameters ($P < 0.05$) apart from within-participants comparisons in duty factor ($P = 0.086$), step frequency ($P = 0.106$), step length ($P = 0.071$) and between groups in leg stiffness ($P = 0.500$). ANVOCA with speed as covariate revealed main effects of segment in duty factor ($P < 0.001$; $\eta^2p = 0.098$), leg stiffness ($P = 0.029$; $\eta^2p = 0.051$), and vertical oscillation ($P = 0.001$; $\eta^2p = 0.102$), but not in step frequency ($P = 0.310$; $\eta^2p = 0.018$), power ($P = 0.064$; $\eta^2p = 0.042$), or step length ($P = 0.314$;

η^2p = 0.018). No differences were found between groups ($P > 0.05$) in any biomechanical parameters. Significant segment x group interaction effects were evident in power ($P < 0.001$; η^2p = 0.314), duty factor ($P < 0.001$; η^2p = 0.191), step frequency ($P < 0.001$; η^2p = 0.236), step length ($P < 0.001$; η^2p = 0.900), but not stiffness (P = 0.291, η^2p = 0.037), or vertical oscillation (P = 0.821, η^2p = 0.011). Where interaction effects were evident, changes to biomechanical parameters over time were more pronounced in moderate and high decoupling groups (Figure 2).

The variance explained (R^2) by runner-specific linear regression equations are given in Table 2. When used to correct for speed throughout the marathon (Figure 3), significant effects were noted between segments for power ($P < 0.001$, η^2p = 0.194), duty factor ($P < 0.001$, η^2p = 0.133), step frequency ($P < 0.001$, η^2p = 0.080), stiffness (P = 0.014, η^2p = 0.054), step length ($P < 0.001$, η^2p = 0.069), and vertical oscillation ($P < 0.001$, η^2p = 0.131). Significant differences between groups were noted only for speed-adjusted step frequency (P = 0.027, η^2p = 0.103), where step frequency was greater in the low decoupling group compared to the high decoupling group (P = 0.042). Segment x group interactions were evident in speed-adjusted step frequency (P = 0.042, η^2p = 0.063) and speed-adjusted step length (P = 0.023, η^2p = 0.073), with the low decoupling group increasing step frequency, but decreasing step length as the marathon progressed. Similarly, segment x group interactions were shown for speed-adjusted vertical oscillation (P = 0.046, η^2p = 0.052), where the low decoupling group exhibited lower vertical oscillation towards the end of the marathon.

*** Table 2 about here ***

*** Figure 2 about here ***

*** Figure 3 about here ***

Table 3 shows the onset of biomechanical changes during the marathon across all groups, and the relative distance from the HR-to-speed decoupling onset. The onset of all biomechanical changes occurred after the decoupling onset. Group effects were evident for the distance at which power ($P < 0.001$), speed ($P < 0.001$), step frequency ($P < 0.001$), duty factor ($P < 0.001$), and step length ($P < 0.001$) exhibited change from baseline. No differences in the onset of change in stiffness or vertical oscillation were evident ($P = 0.130$). Once correcting for speed-adjustments, group effects were only evident for step length ($P = 0.023$), but no significant changes were evident following Bonferroni corrections. Table 4 shows the association between the magnitude of decoupling and the change in biomechanical parameters from the 5-10 km segment.

*** Table 3 about here ***

*** Table 4 about here ***

Discussion

The primary aim of this study was to examine whether previously observed deterioration in biomechanical parameters during marathon running was associated with physiological durability. To our knowledge, this is the first study to explore changes in running biomechanics alongside measures of durability in a marathon context. Our findings suggest that runners with lower decoupling (i.e., greater durability) tended to preserve “fresh” gait mechanics more effectively than those with higher decoupling. However, these group differences largely disappeared after applying runner-specific speed adjustments, indicating that much of the observed biomechanical variation may be attributable to differences in running speed. Interestingly, only the low decoupling group exhibited changes in speed-adjusted biomechanical parameters over the course of the marathon. Although several biomechanical variables were associated with decoupling magnitude, only two remained significant after speed adjustment (Table 4). Notably, biomechanical changes consistently occurred after the onset of decoupling (Table 3), suggesting a temporal relationship between physiological strain and gait alterations.

Despite no differences between groups for HR or speed, and consistent with previous literature examining decoupling during marathons (Smyth et al., 2022), on average runners experienced a mean ~1.15 decoupling between HR and speed, which occurred after ~ 25 km, and there was substantial inter-individual variability in these variables (Figure 1). Runners were subsequently grouped into low, moderate, and high decoupling groups. The differences observed in decoupling were due to both a downward shift in the grade adjusted speed and an increase in HR over time. A similar pattern to speed was evident for absolute power across segments, indicating a potentially diminished ability to produce force during the latter part of the marathon, which was exacerbated in runners with worse durability. However, once corrected for speed, the decrease in power was evident across all groups, with speed-adjusted power decreasing from 30 km onwards. Diminished force production following prolonged running has previously been noted consistently (Brownstein et al., 2021). Contrary to the secondary hypothesis, no significant differences were shown between groups in marathon finish time or average running speed, despite effect sizes similar to those of Smyth et al. (2022). This may be due to the differences in sample size between the studies, whereby the >80,000 runners examined by Smyth et al. (2022) would demonstrate significant differences even with more modest effect sizes. However, when employing correlational analysis, greater magnitudes of decoupling were associated with poorer performance, indicated by greater finish times and lower average speed. Although some conjecture exists (e.g., (Billat et al., 2022), the findings presented herein, together with those of Smyth et al. (2022) and De Pauw et al. (2024) suggest that decoupling, and by inference durability, are important considerations when profiling endurance performance.

It has been suggested that changes in gait patterns during marathon running may increase the internal work rate required to maintain a given running speed (Smyth et al., 2022). Table 4 demonstrates correlations between decoupling and biomechanical variables. However, debate persists on whether these alterations in running mechanics are a cause or a consequence of the elevated internal work rate (Jones, 2023). Findings from the present study seem to refute the notion that changes in running mechanics are a consequence of rising internal work rate. Although more pronounced changes in biomechanics occurred in the high decoupling group, these did not persist once employing runner-specific linear regressions to account for changes in speed. Prior research has shown a progressive deterioration in running mechanics over the course of a marathon, with biomechanical breakpoints typically occurring between 20-30 km (Clermont et al., 2019; Meyer et al., 2021; Nicol et al., 1991b). Using a biomechanical index, Clermont et al. (2019) demonstrated significant differences between higher and lower age-grade performance scores at 20 to 22 km, indicating fatigue induced changes in biomechanics. Changes to running biomechanics in the high age-grade performance cluster were less pronounced. Furthermore, foot contact time, duty factor, step length, and step period have been shown to change more in slower runners compared to faster runners (Bertram et al., 2013). However, both studies did not account for changes in speed, which is likely to impact running biomechanics. When accounting for changes to speed across the marathon, the current study has shown that more durable athletes, i.e., runners with low decoupling, exhibited changes in speed-adjusted gait parameters, such as increased step frequency and reduced step length, over the course of the marathon. While these changes may appear consistent with fatigue-mitigation strategies, we cannot determine whether they reflect intentional adaptations, biomechanical constraints, or byproducts of other factors such as fitness, pacing, or neuromuscular control. Therefore, while this finding suggests a relationship between durability and gait changes, we caution against interpreting these as deliberate strategies to offset fatigue.

Consistent with previous investigations on half marathon (Prigent et al., 2022) and marathons (Chan-Roper et al., 2012; Meyer et al., 2021), both speed-corrected and absolute step frequency and step length decreased over time. More pronounced decreases in absolute step frequency over the course of the marathon were observed in high decoupling group, whereas decreases in absolute step length were observed in high and moderate decoupling groups. Neither were explained by the covariate of speed. However, step frequency and step length both seem to present consistent responses to acute fatigue during running (Apte et al., 2021). Reductions in step length are apparent during overground running (Chan-Roper et al., 2012; Meyer et al., 2021), but less so in treadmill running of comparable intensities (Riazati et al., 2020; Siler & Martin, 1991). Whereas the treadmill speeds adopted in these studies is fixed, reductions in speed during the race likely affect changes to stride characteristics. Nevertheless, when controlling for individual differences in speed throughout the marathon, changes in step frequency and step length across segments persisted. Contrary to our hypothesis, only the low decoupling group exhibited changes in speed-adjusted step frequency and step length, demonstrating an upward shift in step frequency whilst decreasing step length over time. Whether these changes represent intentional self-optimisation, biomechanical constraints, or byproducts of other unmeasured traits (e.g., fitness, pacing, or neuromuscular control) remains unclear. However, runners adopt a running style which minimises, or closely minimises oxygen cost (Moore, Ashford, Cross, Hope, Jones, & McCarthy-Ryan, 2019). It has previously been demonstrated that well-trained runners are able to self-optimise step frequency following a 1-hour treadmill run (Hunter & Smith, 2007). It could be posited that more durable runners owe their durability to an enhanced ability to self-optimise their running style. Indeed, experienced and novice runners differ in their capacity to self-select the most economical running pattern. (de Ruiter et al., 2014). Conjecture exists as to whether changes to step characteristics result in beneficial modulation of running economy following prolonged running (Hunter & Smith, 2007; Kyröläinen et al., 2000). Differences between runners of different performance levels have not been examined following prolonged exercise and thus warrants further investigation.

Concurrent with previous research (Apte et al., 2021; Bertram et al., 2013; Meyer et al., 2021; Prigent et al., 2022), absolute duty factor increased throughout the marathon and persisted following speed-correction. In the current study, the onset of a 2.5% increase in absolute duty factor (33.79 ± 8.16 km) was very similar to the onset of a 2.5% reduction in running speed (33.96 ± 8.67 km). However, when correcting for differences in speed within-participants, the increase in duty factor throughout the marathon persisted. Therefore, it is likely that beyond speed-mediated changes to duty factor, diminished force production following prolonged running also contributed to this adjustment. Changes to absolute and speed-adjusted duty factor may have been due to a diminished ability to utilise the stretch-shortening cycle, which has been posited previously (Chan-Roper et al., 2012). Duty factor may have also increased as a protective mechanism against injury, allowing for a longer distribution of impact forces (Strohrmann et al., 2012). However, changes to these parameters are most likely associated with a decline in contractile function, which has been noted previously following prolonged running (Brownstein, Metra, et al., 2022).

Absolute leg stiffness decreased throughout the marathon, consistent with previous literature (Dutto & Smith, 2002; García-Pinillos et al., 2020; Meyer et al., 2021), with no differences between groups. However, once applying runner-specific regressions to account for changes in speed, leg stiffness remained consistent throughout the marathon. While leg stiffness is generally less sensitive to speed variations than vertical stiffness (Struzik et al., 2021), it is not entirely independent of running speed, as small but measurable changes have been observed with shifts in speed (Arampatzis et al., 1999). Therefore, the progressive reduction in leg stiffness seen during the marathon may primarily be attributed to decreases in running speed. Similar to the current study, large inter-individual variations in the reduction of leg stiffness have been shown following prolonged running (Hunter & Smith, 2007). This variability may be due to runners adopting different biomechanical strategies to minimise the energetic cost of running - a strategy which has previously been demonstrated in “rested” conditions (Moore, Ashford, Cross, Hope, Jones, & Mccarthy-Ryan, 2019). It is therefore posited that runners prioritise the maintenance of a near-constant leg stiffness for a given speed to minimise energetic cost.

Vertical oscillation decreased throughout the marathon, with more pronounced decreases evident in the low decoupling group, and the magnitude of decoupling and changes to speed-adjusted vertical oscillation were correlated (Table 4). There have been conflicting findings regarding changes to vertical oscillation following fatigue (Meyer et al., 2021; Sanno et al., 2018; Strohrmann et al., 2012). This may be due to methodological differences in the definition of vertical oscillation between studies. In the current study, the Stryd footpod gives vertical oscillation as the vertical displacement of the runner's center of mass between steps. As such, the magnitude of vertical oscillation will depend on the ability to produce large vertical impulse during the push-off phase, as well as running speed. While reductions in vertical impulse have previously been associated with fatigue (Meyer et al., 2021; Nicol et al., 1991b), it seems unlikely that the more durable runners, who slowed the least, were less able to produce force. Instead, the greater reduction in vertical oscillation observed in this group may reflect a biomechanical adjustment that supports economical movement under fatigue. Lower vertical oscillation is associated with improved running economy (Folland et al., 2017; Van Hooren et al., 2024), and may help offset some of the energetic cost of prolonged running. Additionally, increased step frequency has been shown to reduce vertical oscillation (Schubert et al., 2014), and may partly explain the pattern observed in the low decoupling group. However, the precise mechanism underlying this adjustment to vertical oscillation cannot be definitively determined from the current data. Indeed, underlying factors such as running experience, fitness, or pacing strategy may also contribute to these changes.

Limitations

To assess durability, the ratio of HR and grade adjusted speed was used. Importantly, HR kinetics differ from those exhibited by $\dot{V}O_2$ during exercise (Zuccarelli et al., 2018), and during marathon running HR and $\dot{V}O_2$ become dissociated when speed is reduced (Billat et al., 2022). Given the different environmental constraints between participants, heat, humidity, and fluid intake may have affected cardiac strain through changes to blood volume (Coyle, 1998). Therefore, HR may not provide a true representation of metabolic cost during marathon running, although it may still represent an increase in cardiac work. However, Smyth et al. (2022) demonstrated runners exhibiting lower levels of HR-to-speed decoupling were able to maintain a higher fraction of critical speed (i.e., better durability) throughout the marathon. Further, HR for some participants was measured using wrist-worn photoplethysmography (Supplemental File 1), the validity of which has been questioned (Fuller et al., 2020; Zhang et al., 2020). However, these devices have been shown to demonstrate acceptable validity against criterion measures of HR (Zhang et al., 2020). Finally, while HR and speed exhibit different ranges of variability during a marathon, potentially weighting the decoupling ratio more heavily toward changes in speed, previous research has shown that both the magnitude and onset of decoupling are independently associated with endurance performance (Smyth et al., 2022; De Pauw et al., 2024) and changes to physiological thresholds (Rothschild et al., 2025). Although similar decoupling values may arise from different physiological or behavioural mechanisms, the metric remains a valid and interpretable proxy for durability when contextualised appropriately

Although the energetic consequence of different gradient changes was quantified by grade adjustment (Minetti et al., 2002), this approach does not fully account for the distinct mechanical demands of uphill and downhill running. Indeed, changes to running biomechanics have been shown with different gradients (Vernillo et al., 2017). Further to this, downhill running in particular results in greater muscle damage (Giandolini et al., 2016), leading to altered muscle structure and function (Bontemps et al., 2020). Therefore, variations in course profile may have influenced biomechanical parameters due to differences in muscle damage. Due to the nature of data collection, no pacing instructions were given, and so apparent poor durability may be the result of poor pacing strategies. The shared sensor origin through which biomechanical parameters are derived may result in correlation between metrics, particularly speed, and any error of the original signal may be compounded. However, the reliability of the footpod used (Cartón-Llorente et al., 2021; Cerezuela-Espejo et al., 2021; García-Pinillos et al., 2021; Imbach et al., 2020), coupled with runner-specific speed-adjustments support the robustness of these findings. Further to this, there is potential for poor fixation of the Stryd footpod or user-entered information (e.g., mass) which may have affected the accuracy of some results (e.g., stiffness). However, due to substantial logistical and financial barriers, conducting a study that controls for all these factors presents significant challenges. Some of these factors could be addressed through laboratory studies which could incorporate measurement of factors associated with durability (e.g., pulmonary gas exchange). Finally, only four (out of 69) runners recruited were female, despite concerted efforts of the research team to recruit more. This limits the generalisability of the findings to a female population, which exhibits differences in running biomechanics (Besson et al., 2022), pacing (Cuk et al., 2020), durability (Smyth et al., 2022), and fatigability (Hunter, 2016). Due to this limitation, further research with greater numbers of female participants should be carried out to examine the relationship between physiological durability and running biomechanics.

Conclusion

This study provides insight into the relationship between physiological durability and biomechanical changes during marathon running. The findings suggest that most commonly observed biomechanical changes following prolonged running are largely mediated by changes in speed. Notably, more durable runners were the only group to exhibit changes in speed-adjusted biomechanics. These patterns may reflect correlates of greater fatigue resistance or neuromuscular control, though the underlying mechanisms cannot be definitively determined. Future research should investigate specific interventions that could enhance durability, potentially reducing fatigue-related biomechanical shifts and exploring the self-optimisation of gait characteristics over longer durations

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Tables and Figures

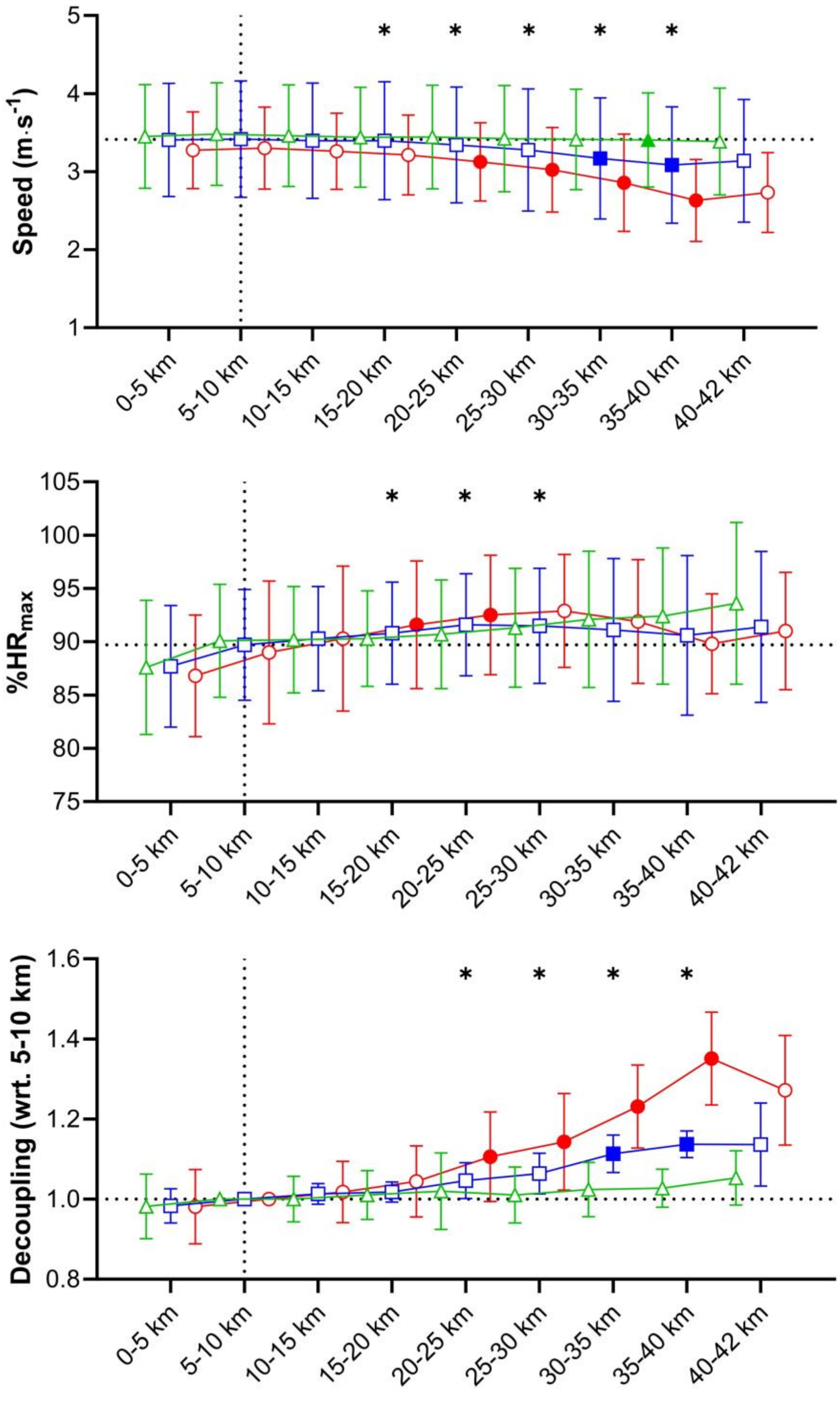

Figure 1. Time-course of HR, grade adjusted speed, and decoupling magnitude throughout the marathon. Green triangles, blue squares, and red circles denotes low, moderate, and high decoupling groups, respectively. Error bars denote SDs. Asterisks denote significant differences between segments ($P < 0.05$). Filled markers indicate a significant difference from the 5–10 km segment within the respective group ($P < 0.05$). The horizontal dotted line represents the mean of the 5–10 km segment.

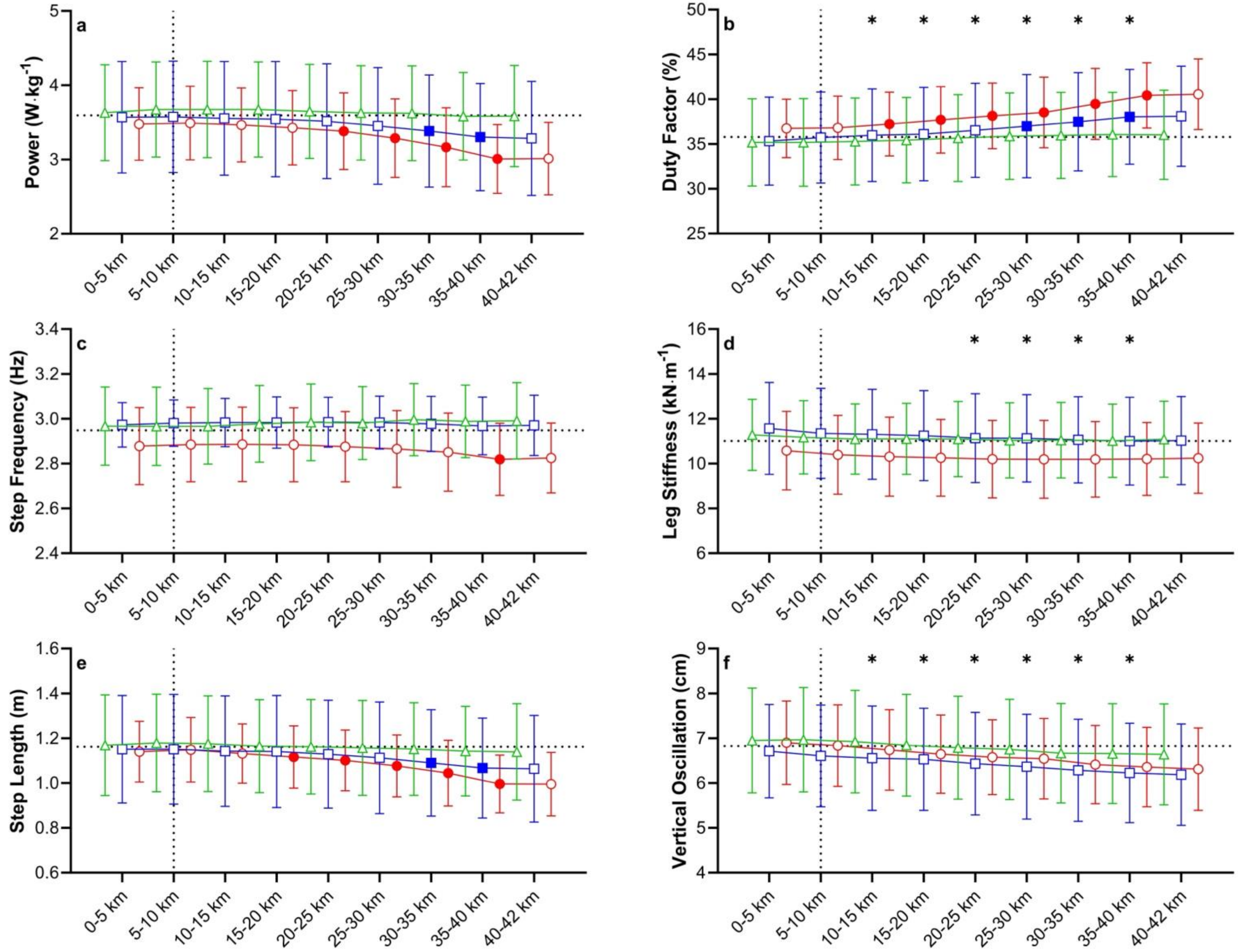

Figure 2. Mean baseline (5-10 km) measures of, and time-course changes to, a) power, b) duty factor, c) step frequency, d) leg stiffness, e) step length, and f) vertical oscillation during the marathon. Green triangles, blue squares, and red circles denotes low, moderate, and high decoupling groups, respectively. Error

bars denote SDs. Asterisks denote significant differences between segments ($P < 0.05$). Filled markers indicate a significant difference from the 5–10 km segment within the respective group ($P < 0.05$). The horizontal dotted line represents the mean of the 5–10 km segment.

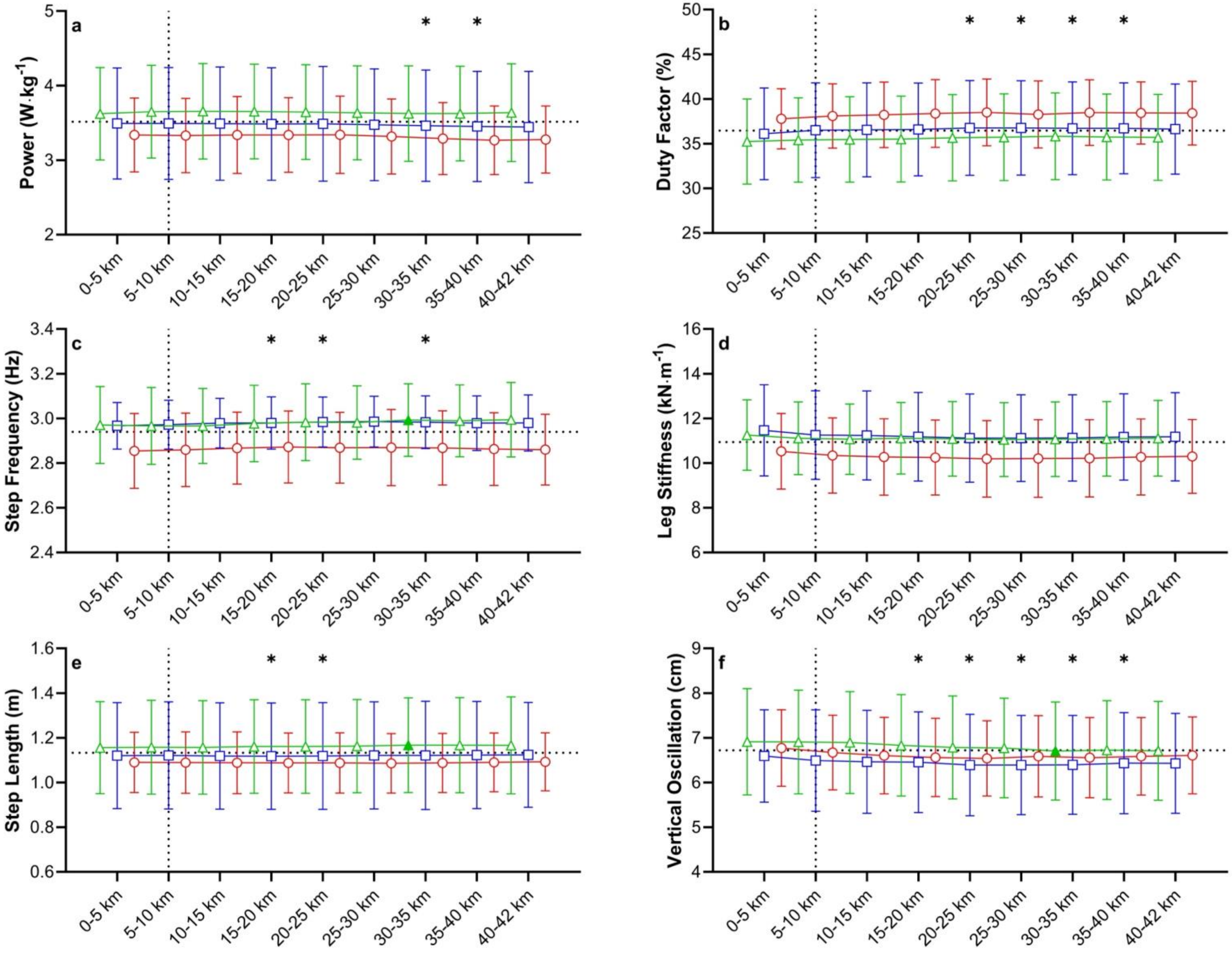

Figure 3. Mean baseline (5-10 km) measures of, and time-course changes to, a) speed-adjusted power, b) speed-adjusted duty factor, c) speed-adjusted step frequency, d) speed-adjusted leg stiffness, e) speed-adjusted step length, and f) speed-adjusted vertical oscillation during the marathon. Green triangles, blue squares, and red circles denotes low, moderate, and high decoupling groups, respectively. Error bars denote SDs. Asterisks denote significant differences

between segments ($P < 0.05$). Filled markers indicate a significant difference from the 5–10 km segment within the respective group ($P < 0.05$). The horizontal dotted line represents the mean of the 5–10 km segment.

Table 1. Marathon performance and decoupling characteristics of the participants			
		Sig.	Hedge's g
Marathon Finish Time (mins)			
Low Decoupling	202.5 (57.1)		0.272
Moderate Decoupling	230.0 (60.2)		0.256
High Decoupling	241.9 (62.9)		0.613
All	222.5 (60.4)		
Marathon Speed ($m \cdot s^{-1}$)			
Low Decoupling	3.40 ± 0.63		0.201
Moderate Decoupling	3.26 ± 0.72		0.362
High Decoupling	3.02 ± 0.54		0.618
All	3.23 ± 0.67		
Decoupling Magnitude (au)			
Low Decoupling	1.03 (0.07)	a	2.536
Moderate Decoupling	1.12 (0.06)	b	2.487
High Decoupling	1.32 (0.19)	c	4.390
All	1.11 (0.18)		
Decoupling onset (km)			
Low Decoupling	30.5 (24.6)		0.775
Moderate Decoupling	19.5 (7.5)		0.012
High Decoupling	20.0 (5.5)		0.742
All	20.0 (17.0)		

The subscripts a, b and c indicate whether a significant difference ($P < 0.05$) was observed between low vs. moderate decoupling, moderate vs. high decoupling, and low vs. high decoupling, respectively. Decoupling magnitude represents the internal-to-external work rate ratio in the 35–40 km segment and is given as a fraction of the 5-10 km baseline segment. Normally distributed data are presented as mean ± SD, whereas non normally distributed data are presented as median (IQR).

Table 2. Proportion of variance (R^2) of biomechanical parameters explained by speed across 6-40 km.

Biomechanical parameters	R^2
Step Length	0.921 ± 0.108
Duty Factor	0.684 ± 0.278
Vertical Oscillation	0.379 ± 0.303
Step Frequency	0.340 ± 0.300
Leg Stiffness	0.299 ± 0.285
Power	0.588 ± 0.342

Table 3. Onset of breakpoints for biomechanical parameters.

	Absolute					Speed-Adjusted				
Biomechanical Parameter	Breakpoint onset (km)	Sig.	Mean Bias (km)	95% CI (km)		Breakpoint onset (km)	Sig.	Mean Bias (km)	95% CI (km)	
				Lower	Upper				Lower	Upper
Power										
Low Decoupling	39.25 ± 5.61	a	10.70	6.17	15.23	41.30 ± 2.77		12.75	8.27	17.23
Moderate Decoupling	32.79 ± 7.92		12.24	6.56	17.92	41.01 ± 2.86		20.46	16.58	24.33
High Decoupling	26.91 ± 6.99	c	6.25	1.14	11.37	40.90 ± 1.61		20.25	16.37	24.13
All	33.98 ± 8.40		9.92	7.08	12.76	41.11 ± 2.51		17.05	14.50	19.59
Speed										
Low Decoupling	38.65 ± 6.94	a	10.10	5.40	14.79					
Moderate Decoupling	33.84 ± 7.77	b	13.29	8.06	18.52					
High Decoupling	26.69 ± 7.09	c	6.04	0.99	11.09					
All	33.96 ± 8.67		9.91	7.07	12.74					
Stiffness										
Low Decoupling	38.53 ± 7.44		9.98	6.17	15.23	40.66 ± 3.61		12.10	7.80	16.40
Moderate Decoupling	33.23 ± 10.57		12.68	7.09	18.27	38.95 ± 7.70		18.40	14.04	22.75
High Decoupling	35.89 ± 10.06		15.24	9.41	21.07	41.52 ± 1.38		20.87	16.80	24.94
All	36.27 ± 9.31		12.21	9.29	15.13	40.40 ± 4.86		16.34	13.77	18.91
Step frequency										
Low Decoupling	42.20 ± 0.00		13.64	9.34	17.95	42.20 ± 0.00		13.64	9.34	17.95

Moderate Decoupling	41.02 ± 3.06		20.47	16.45	24.48	41.58 ± 2.31		21.03	17.15	24.90
High Decoupling	39.27 ± 4.55	c	18.62	14.64	22.60	42.20 ± 0.00		21.54	17.42	25.67
All	41.05 ± 3.09		16.99	14.54	19.45	42.02 ± 1.25		17.96	15.44	20.47
Vertical Oscillation										
Low Decoupling	33.67 ± 9.60		5.12	0.40	10.64	36.67 ± 7.89		8.12	2.92	13.32
Moderate Decoupling	30.46 ± 10.70		9.91	4.52	15.29	38.37 ± 7.00		17.82	13.16	22.48
High Decoupling	28.16 ± 11.65		7.50	-0.26	15.27	40.38 ± 3.52		19.72	15.08	24.37
All	31.22 ± 10.62		7.16	3.74	10.59	38.18 ± 6.78		14.13	11.05	17.20
Duty Factor										
Low Decoupling	38.05 ± 5.79		9.50	4.87	14.13	40.82 ± 3.18		12.26	7.67	16.86
Moderate Decoupling	32.60 ± 8.91		12.05	6.83	17.27	41.31 ± 2.15		20.76	18.06	25.23
High Decoupling	28.33 ± 7.12	c	7.67	2.39	12.96	41.75 ± 1.32		21.10	16.99	25.22
All	33.79 ± 8.16		9.74	6.95	12.53	41.22 ± 2.49		17.16	14.55	19.77
Step length										
Low Decoupling	37.44 ± 6.67		8.89	4.15	13.63	42.20 ± 0.00		12.63	8.12	17.14
Moderate Decoupling	33.70 ± 7.76	b	13.15	7.91	18.39	42.20 ± 0.00		21.64	18.06	25.23
High Decoupling	25.91 ± 8.23	c	5.25	-0.50	11.01	42.08 ± 0.50		21.43	17.27	25.59

All	33.18 ± 8.75		9.12	6.18	12.07	41.72 ± 1.62		17.67	15.06	20.28

The subscripts a, b and c indicate whether a significant difference ($P < 0.05$) was observed between low vs. moderate decoupling, moderate vs. high decoupling, and low vs. high decoupling, respectively. Positive values in mean bias and 95% confidence intervals (CI) indicate the onset of change in biomechanical parameters occurs later relative to the onset of physiological decoupling.

Table 4. Matrix of correlations coefficient between magnitude of decoupling and biomechanical variables, assessed during a marathon.

	Decoupling Magnitude
∆ Power	**r = -0.624 (-0.750, -0.455) P < 0.001**
∆ Speed	**r = -0.752 (-0.840, -0.627) P < 0.001**
∆ Stiffness	r = -0.077 (-0.308, 0.163) P = 0.529
∆ Step frequency	**r = -0.460 (-0.628, -0.251) P < 0.001**
∆ Vertical Oscillation	r = -0.222 (-0.436, 0.016) P = 0.067
∆ Duty Factor	**r = 0.516 (0.319, 0.671) P < 0.001**
∆ Step Length	**r = -0.581 (-0.719, -0.399) P < 0.001**
∆ Speed-adjusted Power	**r = -0.255 (-0.464, -0.020) P < 0.001**
∆ Speed-adjusted Stiffness	r = -0.024 (-0.259, 0.214) P = 0.846
∆ Speed-adjusted Step frequency	r = -0.182 (-0.401, 0.057) P = 0.135
∆ Speed-adjusted Vertical Oscillation	**r = 0.269 (0.034, 0.475) P = 0.026**
∆ Speed-adjusted Duty Factor	r = -0.013 (-0.249, 0.225) P = 0.917
∆ Speed-adjusted Step Length	r = 0.169 (-0.070, 0.390) P = 0.164

Data are reported as Pearson's product-moment (r) correlation coefficients (95% confidence intervals). ∆ of biomechanical variables represents the fractional difference between 5-10km and 35-40 km segments. Values in bold denote significant associations.