



Review

An evaluation of the training determinants of marathon performance: A meta-analysis with meta-regression

Cailbhe Doherty^{a,b,*}, Alison Keogh^{a,b}, James Davenport^{a,b}, Aonghus Lawlor^a, Barry Smyth^a, Brian Caulfield^{a,b}

^a Insight Centre for Data Analytics, University College Dublin, Ireland

^b School of Public Health, Physiotherapy and Population Science, University College Dublin, Dublin, Ireland

ARTICLE INFO

Article history:

Received 27 December 2018
Received in revised form 29 March 2019
Accepted 17 September 2019
Available online 18 October 2019

Keywords:

Running [MeSH]
Exercise [MeSH]
Physical fitness [MeSH]
Physical endurance [MeSH]
Endurance training [MeSH]
Marathon

ABSTRACT

Objectives: Marathoners rely on expert-opinion and the anecdotal advice of their peers when devising their training plans for an upcoming race. The accumulation of results from multiple scientific studies has the potential to clarify the precise training requirements for the marathon. The purpose of the present study was to perform a systematic review, meta-analysis and meta-regression of available literature to determine if a dose-response relationship exists between a series of training behaviours and marathon performance.

Design: Systematic review, meta-analysis and meta-regression.

Methods: A systematic search of multiple literature sources was undertaken to identify observational and interventional studies of elite and recreational marathon (42.2 km) runners.

Results: Eighty-five studies which included 137 cohorts of runners (25% female) were included in the meta-regression, with average weekly running distance, number of weekly runs, maximum running distance completed in a single week, number of runs ≥ 32 km completed in the pre-marathon training block, average running pace during training, distance of the longest run and hours of running per week used as covariates. Separately conducted univariate random effects meta-regression models identified a negative statistical association between each of the above listed training behaviours and marathon performance (R^2 0.38–0.81, $p < 0.001$), whereby increases in a given training parameter coincided with faster marathon finish times. Meta-analysis revealed the rate of non-finishers in the marathon was 7.27% (95% CI 6.09%–8.65%).

Conclusions: These data can be used by athletes and coaches to inform the development of marathon training regimes that are specific to a given target finish time.

© 2019 Sports Medicine Australia. Published by Elsevier Ltd. All rights reserved.

Practical implications

The results of this analysis can inform program development for individuals seeking to achieve a specific time in the marathon footrace. For instance, based on the results of each univariate meta-regression analysis, an individual seeking to achieve a time of 4:00:00 would need to complete, on average, 44 km or 4.5 h of running per week to achieve this time. The average training pace associated with this finish time is 97% of their eventual marathon pace (or 5:31/km), and their weekly training distance over the entire training block should peak at 63 km. The longest training run associated with a finish time of 4:00:00 is 23 km. The results of our

analysis would suggest that individuals who achieve 4:00:00 in the marathon do not need to complete a run ≥ 32 km in length during their training. These parameters can be used as a guide for prospective marathoners for the requirements of completing a marathon in a given target time. To assist the practical implementation of these results, a reference table of the training requirements for a given marathon finish time are presented in Supplemental Table 4.

1. Introduction

The number of recreational runners enrolling in mass-participation running events such as the marathon has been steadily growing. Frank Shorter's victory in the Olympic men's marathon in 1972 often credited with inspiring this 'running boom'. In the decade after Shorter's victory, worldwide marathon participation increased by 221%, and it continues to rise¹ today. In

* Corresponding author.

E-mail address: Cailbhe.doherty@insight-centre.org (C. Doherty).

2016, >5000 marathons were held worldwide attracting >1.8 million participants.¹ The largest of these events are the marathon 'majors' -- Berlin, Boston, Chicago, London, New York and Tokyo -- which collectively attracted 229,795 runners in 2016.¹

Performance during the marathon is determined by a variety of factors, including the physiological characteristics,² anthropometry,³ nutrition,⁴ age,⁵ sex³ and training behaviours^{5–7} of the runner. Runners manipulate the frequency, intensity, and volume of their training in a variety of ways to optimize their marathon performance.^{6,8} For instance, runners' average weekly training distance,⁵ the number of 32 km (20-mile) runs they complete⁷ and their average training pace⁹ during the pre-marathon training block have a demonstrable statistical association with eventual marathon race time.

However, the precise training requirements for a runner who is trying to achieve a pre-specified target finish time remain unclear. Typically, prospective marathoners rely on their own experience, expert-opinion and anecdotal guidance when devising their training plans for an upcoming race.¹⁰ While numerous laboratory-based studies have investigated the physiological determinants of running performance, in both elite and recreational runners,^{2,11} a pragmatic analysis of real-world training behaviors, and their association with competitive marathon performance in these groups, remains elusive.

One of earliest investigations into the training determinants of marathon performance was published in a 1973 issue of *Runner's World Magazine* and written by Paul Slovic.¹² Since then, a body of research has developed, documenting the training behaviors of heterogeneous groups of runners -- elite and recreational,⁵ young and old,¹³ male and female¹¹ -- and their final finish times in the marathon. To date, these data remain siloed, and are therefore largely redundant for a large proportion of runners who do not match the profile of the studied sample. As a result, the dose-response relationship between marathon performance, and different training parameters, remains unclear, highlighting a critical gap in our understanding of the training requirements of completing a marathon in a pre-specified time.

While individual studies have failed to characterize the training parameters required to achieve a given marathon finish time, the accumulation of results from individual studies, through meta-analysis and meta-regression, has the potential to clarify this relationship. Such an approach would allow for both an examination of the magnitude of training-induced improvements in marathon performance, for a variety of parameters, and the larger sample size may strengthen the validity of results obtained from numerous smaller training studies. Therefore, the aim of this study is to conduct a systematic review and meta-regression of available research studies to investigate the effect of different training behaviors in determining marathon performance.

2. Methods

2.1. Protocol

The protocol for this review was not deemed eligible for registration in PROSPERO as it related primarily to athletes and athletic performance (14/09/2018).

2.2. Search strategy, study selection and qualitative analyses

Search of the PubMed, Scopus, SportDISCUS, Google Scholar and the TRIP electronic databases was implemented in August 2018. The database search was further supplemented with a manual search of the reference lists in each review. These processes retrieved a set of articles closely related to marathon training and performance.

The search strategy was constructed for Medline and completed in a stepwise manner using Boolean operators (Supplemental Table 1).

The search strategy was adapted for each database. No restrictions were applied in any of the databases when the search was completed. Two authors (CD and JD) evaluated study quality using an adapted version of the STROBE guidelines for rating observational studies.¹⁴ The adapted version of the STROBE assessment criteria was devised by author consensus to suit the expected kind of studies and study designs identified via the search strategy. Any discrepancies were resolved through discussion and a group consensus meeting, where required. All studies deemed eligible for inclusion were rated on 11 criteria which were derived from items 1, 3, 6, 7, 12 and 14 of the original checklist (Table 1).

2.3. Inclusion and exclusion criteria

Studies of elite and recreational marathon runners were considered for the systematic review provided they met the following inclusion criteria:

- They included endurance athletes who participated in a marathon footrace (42.2 km)
- If athletes were aged >18 years old.
- If athletes were either amateur or professional
- If the study measured training load, volume or intensity in association with marathon finish time.

Studies were excluded in the following cases:

- If they were not reported in English
- If the studies focused on injured participants or participants who did not start the marathon.

2.4. Data extraction and synthesis

Qualitative and quantitative data were extracted from study reports by two authors (CD and AK) using a piloted extraction form and the corresponding authors were contacted by email in cases where additional information was required.

Subject characteristics (age, sex and ability [elite or recreational]), sample size, intervention length, training frequency, training intensity and all other quantitative descriptors of training protocol were extracted.

In instances where the ability of the sampled subjects (elite or recreational marathoners) was not explicitly defined by the authors of the study, it was inferred by the average finish time of the sample (2 h 12 min for men and 2 h 31 min for women).¹¹ Furthermore, all athletes at national or international competitive level were defined as 'elite'.

For studies where periodization was incorporated into the training intervention, the mean value was calculated over the entire training block where appropriate. The marathon finish time associated with these training parameters was extracted in the form of means \pm SD; when SEM was reported SD was calculated using the reported SEM and sample size.

If marathon finish times were reported for separate subgroups (e.g. males and females), then the training programs for these subgroups were also extracted. In instances where these data were not presented, authors were contacted. If data could not be acquired following author contact, the mean values for the entire sample of participants was used.

Event rates for completion and non-completion and their associated training behaviours were also extracted, where reported. In cases where all participants were reported to have completed the

Table 1
Modified version of the STROBE criteria that was used to evaluate study quality.

#	Strobe reference	Criterion
1	1(a)	Indicate the study's design with a commonly used term in the title or the abstract (y/n)
2	3	State specific aims/objectives, including any prespecified hypotheses (y/n)
3	14(a)	Give characteristics of marathon event (location, environment, date etc) (y/n)
4	14(a)	Outline the numbers of males and females included in the study (y/n)
5	14(a)	Outline anthropometric feature of participants (height, age, weight) (y/n)
6	6	If certain participants were excluded either a priori or post hoc (e.g. females, non-elite athletes), give a reason for this. (y/n)
7	7	Describe the length of the follow-up. To what period of time did the training behaviours relate? (y/n)
8	12(a)	Describe all statistical methods, including those used to control for confounding (y/n)
9	7	Provide finish time with a measure of variance, or the means to calculate this from the available data (y/n)
10	7	Sufficiently describe training behaviours (with means and a measure of variance) (y/n)
11	12(c)	Explain how missing data were addressed (y/n/NA)

marathon (i.e. there were zero 'non-finishers' events), a correction of 0.5 was added to each count.¹⁵

2.5. Meta-regression and meta-analysis

In order to determine whether the training parameters described in the studies could explain the variance in marathon performance, a meta-regression using the available training parameters as covariates was conducted.¹⁶ Due to the heterogeneity in the types of training parameters being reported, separate regression models were prepared for each training parameter, provided 10 studies reported on that parameter. Heterogeneity across studies was estimated using the I^2 statistic.¹⁷ A random-effects model was adopted based on the data type (continuous).¹⁸ Where possible, subgroup analyses were performed to explore the sources of heterogeneity according to the following study characteristics: marathon experience (#marathons completed), sex (male vs. female) and age. Funnel plots and Begg's test were used to assess for potential bias in the included sample of studies.

The rate of non-finishers in the marathon were examined using meta-analysis on the basis of the availability of these data. Heterogeneity across studies was estimated using the I^2 statistic.¹⁷ I^2 values greater than 50% were considered to represent substantial heterogeneity, and in such cases, a random effects model was used. 95% CIs were subsequently generated.

Meta-regression and meta-analysis procedures were conducted using the Comprehensive Meta-Analysis software program (CMA, Biostat Inc., Englewood, New Jersey, USA). Statistical significance for all analyses was accepted at $p < 0.01$.

3. Results

3.1. Study selection (results)

The initial search strategy produced 8850 articles. A PRISMA diagram of the search strategy is available in Fig. 1. A total of 91 studies for which finish times and training parameters included. However, it was apparent that duplicate data were reported in separately published studies of the same cohorts of runners^{3,6,19–24}. In such instances, duplicate data were removed after the review of full-texts. 85 studies of 137 cohorts of runners met the inclusion criteria (Fig. 1).

3.2. Characteristics of the included studies

The pooled sample size from the 137 separate samples included in the 85 articles comprised 8945 runners (25% female)^{2,5–8,11,20,21,25–32} and supplemental references 1–58. Based on the authors' definition, the grouped sample comprised of 86% recreational marathoners, 4% elite marathoners and 10% mixed cohorts of recreational and elite marathoners. The geographical

location of the studied samples was predominantly from the US (60.51%) and Europe (29.82%). A wide variety of training descriptors were used in the included studies. These are presented in Supplemental Table 2.

3.3. Quality assessment

All studies were measured using the adapted version of the STROBE guidelines for rating observational studies¹⁴; the scores ranged from 1 to 11, with a mean of 8.08 ± 1.8 (Supplemental Table 3).

3.4. Data analysis

Visual inspection of the funnel plot (Supplemental Fig. S1) suggests the potential for bias, because slower finish times are associated with higher standard errors of estimate. Begg and Mazumdar's rank correlation test was significant (Kendall's $\tau = 0.19$, $p < 0.01$), indicating a relationship between finish time and precision. The results of the analysis should be considered with this in mind, however, this is likely a consequence of the larger heterogeneity in performance capability associated with recreational athletes.

3.5. Meta regression

Meta-regression was used to examine the association between training characteristics and marathon performance (finish time). Study covariates subjected to meta-regression included average weekly running distance ($n = 110$), number of weekly runs ($n = 46$), maximum running distance completed in a single week ($n = 28$), number of runs ≥ 32 km completed in the pre-marathon training block ($n = 27$), average running pace (expressed as a percentage of eventual marathon pace; $n = 26$), distance of the longest run ($n = 25$) and hours of running per week ($n = 22$), as these outcomes contained the most trials (Supplemental Table 2). While a large number of trials presented certain training characteristics like average running weekly distance, it was rare for the same study to report multiple training characteristics. As a consequence of this, meta-regression was limited to univariate analysis. Logarithmic transformation of data related to average weekly training distance eliminated skewness, enabling appropriate meta-regression.

3.5.1. Average weekly running distance

A marathoners average weekly running distance was significantly associated with marathon finish time in the pooled sample of runners (coefficient $\ln^* = -67.8907$ km/min in marathon time, 95% CI -79.3726 to -56.4088 $Q = 134.30$, $p < 0.001$ $\text{Tau}^2 = 984.2212$, $\text{Tau} = 31.3723$, $I^2 = 99.93\%$, $Q = 134.30$, $df = 1$, $p < 0.001$ $\text{Tau}^2 = 984.2212$, $\text{Tau} = 31.3723$, $I^2 = 99.93\%$, $Q = 176,460.48$, $df = 126$, $p < 0.001$ R^2 analog = 0.70)

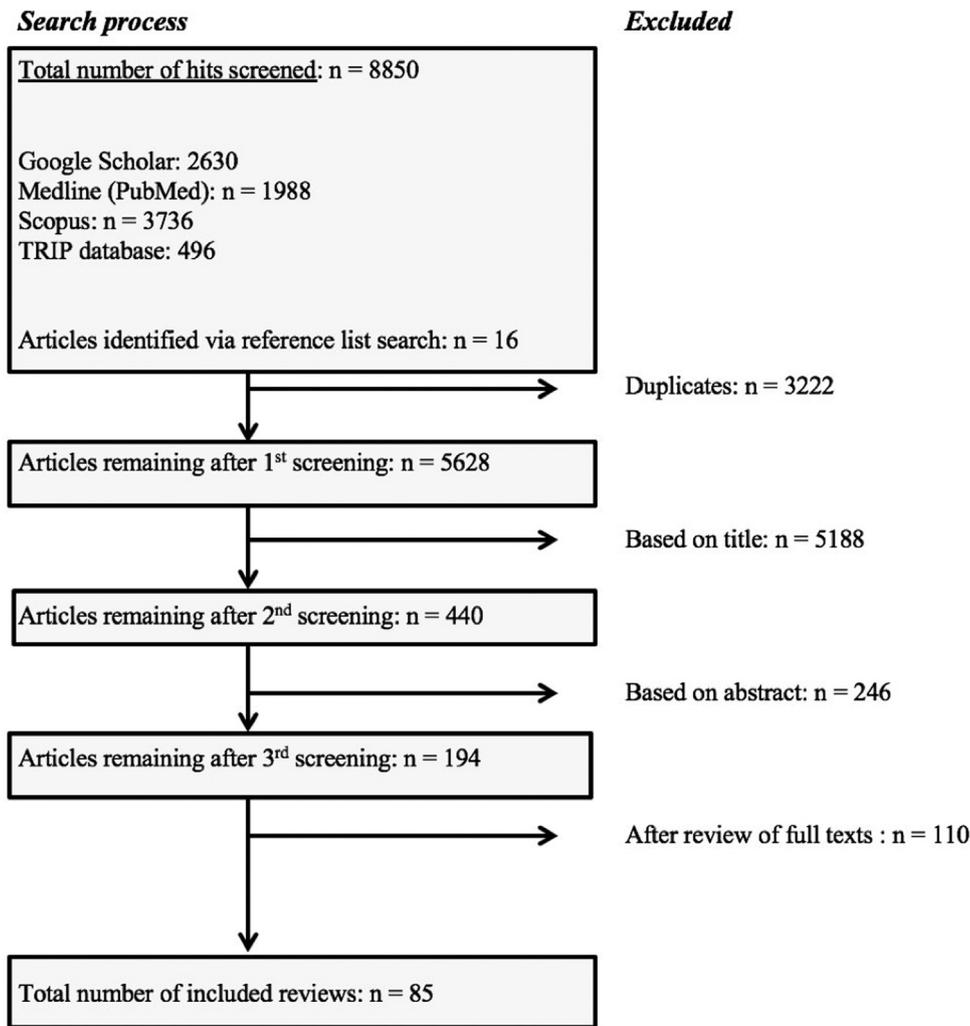


Fig. 1. PRISMA diagram outlining the results of the screening and selection processes.

3.5.2. Number of weekly runs

No. of weekly runs was significantly associated with marathon finish time in the pooled sample of runners (coefficient -12.585 runs/min in marathon time, 95% CI -14.5401 to -10.6299 $Q = 159.17$, $p < 0.001$ $Tau^2 = 443.1359$, $Tau = 21.0508$, $I^2 = 99.74\%$, $Q = 19,887.11$, $p < 0.001$ R^2 analog = 0.45; Supplemental Fig. S3).

3.5.3. Number of runs ≥ 32 km

#runs > 32 km was significantly associated with marathon finish time in the pooled sample of runners (coefficient -6.2325 runs/min in marathon time, 95% CI -7.9438 to -4.5211 $Q = 50.95$, $df = 1$, $p < 0.001$ $Tau^2 = 418.9286$, $Tau = 20.4677$, $I^2 = 99.87\%$, $Q = 23,131.70$, $df = 29$, $p < 0.001$ R^2 analog = 0.81; Supplemental Fig. S4).

3.5.4. Maximum running distance completed in a single week

Maximum running distance in 1-week was significantly associated with marathon finish time in the pooled sample of runners (coefficient -0.7687 km/min in marathon time, 95% CI -0.8562 to -0.6812 $Q = 296.38$, $p < 0.001$ $Tau^2 = 120.7881$, $Tau = 10.9904$, $I^2 = 98.86\%$, $Q = 2373.14$, $p < 0.001$ R^2 analog = 0.80; Supplemental Fig. S5).

3.5.5. Distance of the longest run

Longest training run was significantly associated with marathon finish time in the pooled sample of runners (coefficient -5.6414 km/min in marathon time, 95% CI -7.541 to -3.7417

$Q = 33.88$, $p < 0.001$ $Tau^2 = 558.1360$, $Tau = 23.6249$, $I^2 = 99.77\%$, $Q = 11,068.30$, $p < 0.001$ R^2 analog = 0.38; Supplemental Fig. S6).

3.5.6. Average running pace

Average training pace as a % of eventual race pace was significantly associated with marathon finish time in the pooled sample of runners (coefficient -1.6353% marathon pace/min in marathon time, 95% CI -1.9859 to -1.2848 $Q = 83.58$, $p < 0.001$ $Tau^2 = 187.6315$, $Tau = 13.6979$, $I^2 = 94.08\%$, $Q = 439.32$, $p < 0.001$ R^2 analog = 0.67; Supplemental Fig. S7).

3.5.7. Hours of running per week

Weekly training hours was significantly associated with marathon finish time in the pooled sample of runners (coefficient -16.0132 h/min in marathon time, 95% CI -19.6508 to -12.3757 $Q = 74.45$, $p < 0.001$ $Tau^2 = 214.9318$, $Tau = 14.6606$, $I^2 = 99.22\%$, $Q = 2962.89$, $p < 0.001$ R^2 analog = 0.78; Supplemental Fig. S8).

The results of the univariate random effects meta-regression analysis for each training characteristic are presented in Table 2.

3.6. Meta-analysis

56 studies (samples) reported non-finish event rates (range 0–27%). The I^2 statistic indicated low heterogeneity between studies, so a fixed-effects model was used in meta-analysis.

Table 2
Results of the univariate random effects meta-regression analysis for each training characteristic.

	Average weekly distance	No. of weekly runs	#runs >32 km	Maximum running distance in 1-week	Longest training run	Average training pace as a % of eventual race pace	Weekly training hours
Coefficient	-67.8907	-12.585	-6.2325	-0.7687	-5.6414	-1.6353	-16.0132
Y	497.2745	279.6624	229.1022	288.4311	382.4451	398.7133	312.0045
N studies	128	54	31	29	28	28	25
Standard error	5.8582	0.9975	0.8731	0.0446	0.9692	0.1789	1.8559
95% Upper	-56.4088	-10.6299	-4.5211	-0.6812	-3.7417	-1.2848	-12.3757
95% Lower	-79.3726	-14.5401	-7.9438	-0.8562	-7.541	-1.9859	-19.6508
Z-value	-11.59	-12.62	-7.14	-17.22	-5.82	-9.14	-8.63
P-Value	p < 0.001	p < 0.001	p < 0.001	p < 0.001	p < 0.001	p < 0.001	p < 0.001
Q	134.3	159.17	50.95	296.38	33.88	83.58	74.45
R2	0.7	0.45	0.81	0.8	0.38	0.67	0.78

When results of the 56 studies trials were combined the event rate for non-completion was 7.27% (95% CI 6.09%–8.65%; Supplemental Fig. S9).

4. Discussion

Our search identified 85 studies, which themselves reported finish time data and associated training behaviors for 137 cohorts of marathon runners (25% female). Considering the heterogeneity in the performance capabilities of the included samples (the slowest group included in our analysis had a finish time of 05:07:36, while the fastest group had a finish time of 02:07:00), there was also substantial variation in the training behaviors in these groups. This heterogeneity was evident in the funnel plot, whereby slower finish times were associated with lower estimates of precision, which is likely a consequence of the larger heterogeneity in performance capability associated with recreational athletes.

The research spanned five decades; the earliest published study included in our analysis was from 1971, with 7 studies published between 1970–79, 21 between 1980–1989, 10 between 1990–99, 11 between 2000–09 and 36 from 2010 to date. The recent increase in the quantity of studies investigating the training behaviours of marathoners coincides with the recent increase in research being produced in the field of sport and exercise science,³³ and may have been facilitated by the growing number of people who partake in a marathon each year,³⁴ the recent increase in the number of runners who use GPS tracking devices³⁵ and finally, the growing practice of self-monitoring with mobile fitness tracking platforms such as Runkeeper, Strava and MapMyRun.

However, only five of the studies included in this review (8 samples of athletes) used GPS devices to quantify training volumes.^{20,21,36–38} So, despite the increased prevalence of direct self-monitoring and tracking, this was not represented in the research included in this review. Six studies relied on athletes' training diaries completed throughout the pre-marathon training block,^{8,25,27,28,31,32} with the remaining 79 garnering this information via a self-report questionnaire completed at a discrete timepoint, typically close to race-day. The accuracy of estimates of training behaviors determined via self-report sampling is potentially associated with a higher level of measurement error.³⁹ However, questionnaires, logs, and diaries have been used for close to five decades to determine the frequency, duration, intensity, and type of exercise exposures for a variety of outcomes,⁴⁰ and have been shown to be accurate when describing high intensity exercise.⁴¹ Attempts to reconcile data garnered via self-reporting compared with direct measures such as GPS tracking devices have shown that the error associated with subjective determination is not systematic but random.⁴² In consideration of this, and as a majority of studies included in this review used self-report as the primary mechanism for determining training behaviours, the

pooling of these data sources through meta-regression is deemed appropriate.

In the included studies, the most frequently reported training behavior was average weekly running distance (110 studies; range = 29–213 km/week), followed by number of weekly runs (46 studies; range = 4–13/week), maximum running distance completed in a single week (28 studies; range = 57–266 km/week), number of runs \geq 32 km in the pre-marathon training block (27 studies; range = 0–19), average running pace in training (26 studies; range = 0.89–1.64 times eventual average marathon pace), longest run completed (25 studies; range = 23–41 km) and hours of running per week (22 studies; range = 3–10 h/week). We conducted eight separate univariate meta-regression analyses for these parameters, as an insufficient number of studies reported enough variables in combination to build a multivariate model. In each case, the analyses revealed a statistically significant negative association between marathon finish time and each training parameter at the level of our a-priori alpha. That is, increases in any one of the training parameters listed above was associated with decreases in marathon finish time.

To the best of our knowledge, the current paper is the first systematic review of the available research into the training behaviours of marathon runners with statistical pooling through meta-regression to identify their relationship with eventual marathon finish time. The results of this review can be used to assist coaches and athletes in marathon training program development, although their practical utility is somewhat limited by simplifications made by the authors conducting the research to facilitate analysis and statistical pooling. As such, the results of this analysis cannot provide a comprehensive overview of the training behaviours required to achieve a specific time in the marathon. For instance, while the number of runs \geq 32 km is a frequently reported characteristic in the available research, this kind of dichotomous classification limits the external validity of the analysis.

There were also several important training behaviours for which statistical pooling was not possible due to a dearth of studies. Specifically, any potential statistical association between variables such as the average duration of a training session (nine studies^{3,6,21,22,43–47}), whether interval sessions were completed (binary classification; two studies^{38,48}), whether 'Fartlek' training was completed (binary classification; one study⁴⁹) and the number of hours of resistance training completed per week (one study³⁸) could not be explored.

Similarly, with regards to the different paces at which training sessions should be conducted, we were unable to explore the relationship between marathon finish time and the ratio of running distance at marathon pace (five studies^{11,26,27,29,50}), weekly distance at tempo pace (defined as being between 10-mile and half-marathon pace; five studies^{11,26,27,29,50}), weekly distance at 10 km pace (four studies^{11,26,29,50}), weekly distance at 'interval' pace (two studies^{27,50}), weekly distance at 5 km pace (one study²⁹)

weekly distance at 3 km pace (two studies^{11,26}). Furthermore, only one study⁵¹ reported the training programs of marathon finishers and non-finishers, so the existence of a minimum threshold for a given training stimulus necessary to complete a marathon (previously termed the ‘collapse point’ in popular running fora⁵²), remains unclear.

Finally, only five studies^{30,38,53–55} provided any information on training intensity and its periodisation over the entirety of the marathon training period. In summary, due to a dearth of research, quantitative synthesis through meta-regression could not be undertaken to elucidate any statistical association between these training behaviours and marathon finish time, nor was it possible to identify the training characteristics of marathon ‘non-finishers’.

The greatest predictive capacity based on the r-squared value of the variables included in the univariate meta-regression analysis was for the number of runs completed that were ≥ 32 km in length (r-squared = 0.81). While not elucidated through the current analysis, there are likely a collection of variables not directly related to training that play an important role in the determination of marathon performance. For instance, it is probable that a marathoner’s pre-race⁵⁶ and in-race nutrition strategies,⁴ their pacing during the race⁵⁷ and their racing experience²⁵ are all important contributors to overall performance on race-day. Furthermore, the boundaries of the linear relationships identified through our analysis are not clear. For instance, while a significant relationship between training distance and marathon performance was identified, the thresholds at which these associations begin, and beyond which they begin to weaken, remains unclear. For example, the current data could be used to infer that to achieve a sub 2-h marathon that one need to complete 260 km per week, on average, during their training. It is the authors contention that there likely exists a threshold beyond which an increase in average weekly distance does not associate with a faster finish time, and, based on this example, that breaking the 2-h barrier necessitates more than simply increasing one’s average weekly training distance. Specifically, any inferences about the training behaviours associated with a given marathon finish time should be limited to the data points represented in the current analysis (i.e. for finish times between 02:07:00 and 05:07:36). Importantly, the statistical association of these data points to eventual marathon performance was determined by univariate analysis. As it was rare for individual studies included in this investigation to report multiple training characteristics, meta-regression was limited to univariate analysis. As such, it was not possible to elucidate the potential interactions between the variables included in this report; such potentialities should not be overlooked, and should be considered when interpreting our results.

Results of the meta-analysis of 56 trials revealed the rate of non-completion in the marathon to be 7.27% (95% CI 6.09%–8.65%). To the authors’ knowledge, this analysis provides the first indication of the rate of non-completion in a heterogenous group of marathons from around the world, a statistic which has remained elusive to date. In 2015, based on an analysis of race results published on the organisers’ websites, the rate of non-completion in the ‘marathon majors’ was 22.6% in the Berlin Marathon, 2.1% in the Boston marathon, 18.7% in the Chicago marathon, 14.1% in the London marathon and 3.6% in the Tokyo marathon.

Based on the locations of the marathons listed in the included studies or, if this was not available, the location of the research institution where the study was conducted, 61% of the marathoners included in our analysis were from the United States of America, 30% were from Europe, 4% from Australia, 2% from South Africa, 1% from China, 1% from Japan with the remaining from Israel. Considering that, as of 2016, Japan has the most marathon participants of

any country at 33% of the annual marathon participation rate,¹ our dataset may not be reflective of the global population of marathoners.

4.1. Limitations

Despite the novelty of our findings and the potential practical value they may have to coaches and athletes in assisting them with the development of their training regimes, this research has a number of important limitations. Firstly, and as is evident from the passage above, because we were limited by the number of papers reporting several training variables in conjunction, we were only able to formulate univariate regression models, and as such, the interplay between the different parameters of training remain unclear. Next, of the 80% of studies that reported the sex-distribution of the studied sample, 75% of research participants were male and 25% were female. While available participation statistics^{1,57} would suggest that more males than females complete marathons worldwide, the current dataset still represents an over-bias towards male marathoners. Only four studies^{11,26,29,58} reported the training behaviours of males and females separately and as such, we were unable to devise separate, sex-specific univariate meta-regression models. Future research should seek to identify the sex-specific training demands of marathon participation. This is of particular considering the increasing levels of female participation in the marathon.⁵⁹ Furthermore, the data pooled in this analysis was predominantly from studies conducted in the United States and Europe, despite the fact that the more people in Japan do a marathon per year than any other country. It is unclear whether this geographical bias has had any impact on our results, however.

Acknowledgements

This research is co-funded by the European Regional Development Fund (ERDF) under Ireland’s European Structural and Investment Funds Programmes 2014–2020, under the ‘runAid’ project title.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.jsams.2019.09.013>.

References

- (ARRS) TAOARRS. Marathon lists. <https://arrs.run/MaraList.htm>.
- di Prampero PE, Atchou G, Bruckner JC et al. The energetics of endurance running. *Eur J Appl Physiol Occup Physiol* 1986; 55(3):259–266.
- Schmid W, Knechtle B, Knechtle P et al. Predictor variables for marathon race time in recreational female runners. *Asian J Sports Med* 2012; 3(2):90–98.
- Hansen EA, Emanuelsen A, Gertsen RM et al. Improved marathon performance by in-race nutritional strategy intervention. *Int J Sport Nutr Exerc Metab* 2014; 24(6):645–655.
- Dotan R, Rotstein A, Dlin R et al. Relationships of marathon running to physiological, anthropometric and training indices. *Eur J Appl Physiol Occup Physiol* 1983; 51(2):281–293.
- Barandun U, Knechtle B, Knechtle P et al. Running speed during training and percent body fat predict race time in recreational male marathoners. *Open Access J Sports Med* 2012; 3:51–58.
- Slovic P. Empirical study of training and performance in the marathon. *Res Q* 1977; 48(4):769–777.
- Hagan RD, Upton SJ, Duncan JJ et al. Marathon performance in relation to maximal aerobic power and training indices in female distance runners. *Br J Sports Med* 1987; 21(1):3–7.
- Foster C, Daniels J. Running by the numbers. *Runners World* 1975; 10:14–17.
- Midgley AW, McNaughton LR, Jones AM. Training to enhance the physiological determinants of long-distance running performance: can valid recommendations be given to runners and coaches based on current scientific knowledge? *Sports Med* 2007; 37(10):857–880.

11. Billat VL, Demarle A, Slawinski J et al. Physical and training characteristics of top-class marathon runners. *Med Sci Sports Exerc* 2001; 33(12):2089–2097.
12. Slovic P. Distance training, Chapter 11, in *The Complete Runner*, World TEOs, editor, Mountain View, Calif, World Publications, 1973, 94040.
13. Nikolaidis PT, Knechtle B. Pacing in age group marathoners in the “New York City Marathon”. *Res Sports Med* 2018; 26(1):86–99.
14. Heat stroke and related heat stress disorders. *Dis Mon* 1989; 35(5):306–377.
15. Higgins J, Green S. *Cochrane Handbook for Systematic Reviews of Interventions 5.1.0* [Updated March 2011]. Available from <https://training.cochrane.org/handbook>.
16. Pigott T. *Advances in meta-analysis*, Springer, 2012.
17. Higgins J, Thompson S, Deeks J et al. Measuring inconsistency in meta-analyses. *Br Med J* 2003; 327:557.
18. Lipsey M, Wilson D. *Practical meta-analysis*, SAGE Publications, 2001.
19. Tanda G. Prediction of marathon performance time on the basis of training indices. *J Hum Sport Exerc* 2011; 6(3):511–520.
20. Tanda G, Knechtle B. Effects of training and anthropometric factors on marathon and 100 km ultramarathon race performance. *Open Access J Sports Med* 2015; 6:129–136.
21. Tanda G, Knechtle B. Marathon performance in relation to body fat percentage and training indices in recreational male runners. *Open Access J Sports Med* 2013; 4:141–149.
22. Zillmann T, Knechtle B, Rust CA et al. Comparison of training and anthropometric characteristics between recreational male half-marathoners and marathoners. *Chin J Physiol* 2013; 56(3):138–146.
23. Rust CA, Knechtle B, Knechtle P et al. Similarities and differences in anthropometry and training between recreational male 100-km ultra-marathoners and marathoners. *J Sports Sci* 2012; 30(12):1249–1257.
24. Rust CA, Knechtle B, Knechtle P et al. A comparison of anthropometric and training characteristics between recreational female marathoners and recreational female Ironman triathletes. *Chin J Physiol* 2013; 56(1):1–10.
25. Atkinson G, Taylor CE, Morgan N et al. Pre-race dietary carbohydrate intake can independently influence sub-elite marathon running performance. *Int J Sports Med* 2011; 32(8):611–617.
26. Billat V, Demarle A, Paiva M et al. Effect of training on the physiological factors of performance in elite marathon runners (males and females). *Int J Sports Med* 2002; 23(5):336–341.
27. Bovens AMP, Janssen GME, Vermeer HGW et al. Occurrence of running injuries in adults following a supervised training program. *Int J Sports Med* 1989; 10(SUPPL. 3):S186–S190.
28. Janssen M, Scheerder J, Thibaut E et al. Who uses running apps and sports watches? Determinants and consumer profiles of event runners’ usage of running-related smartphone applications and sports watches. *PLoS One* 2017; 12(7):e0181167.
29. Karp JR. Training characteristics of qualifiers for the U.S. Olympic Marathon Trials. *Int J Sports Physiol Perform* 2007; 2(1):72–92.
30. Lucia A, Chicharro JL, Perez M et al. Reproductive function in male endurance athletes: sperm analysis and hormonal profile. *J Appl Physiol* (1985) 1996; 81(6):2627–2636.
31. Luden N, Hayes E, Minchev K et al. Skeletal muscle plasticity with marathon training in novice runners. *Scand J Med Sci Sports* 2012; 22(5):662–670.
32. Nieman DC, Buckley KS, Henson DA et al. Immune function in marathon runners versus sedentary controls. *Med Sci Sports Exerc* 1995; 27(7):986–992.
33. Bastian H, Glasziou P, Chalmers I. Seventy-five trials and eleven systematic reviews a day: how will we ever keep up? *PLoS Med* 2010; 7(9):e1000326.
34. Milroy A, Gasparovic J. Association of Road Running Statistics. <https://arrs.run>. [Accessed 1 October 2018].
35. Pobiruchin M, Suleder J, Zowalla R et al. Accuracy and adoption of wearable technology used by active citizens: a marathon event field study. *JMIR mHealth uHealth* 2017; 5(2):e24.
36. Galbraith A, Hopker J, Cardinale M. Accuracy and adoption of wearable technology used by active citizens: a marathon event field study A 1-year study of endurance runners: training, laboratory tests, and field tests. *Int J Sports Physiol Perform* 2014; 9(6):1019–1025.
37. Haney Jr TA, Mercer JA. A description of variability of pacing in marathon distance running. *Int J Exerc Sci* 2011; 4(2):133–140.
38. Spilsbury KL, Fudge BW, Ingham SA et al. Tapering strategies in elite British endurance runners. *Eur J Sport Sci* 2015; 15(5):367–373.
39. Ainsworth BE, Caspersen CJ, Matthews CE et al. Recommendations to improve the accuracy of estimates of physical activity derived from self report. *J Phys Act Health* 2012; 9(Suppl 1):S76–84.
40. Epstein L, Miller GJ, Stitt FW et al. Vigorous exercise in leisure time, coronary risk-factors, and resting electrocardiogram in middle-aged male civil servants. *Br Heart J* 1976; 38(4):403–409.
41. Ainsworth BE, Richardson MT, Jacobs Jr DR et al. Accuracy of recall of occupational physical activity by questionnaire. *J Clin Epidemiol* 1999; 52(3):219–227.
42. Prince SA, Adamo KB, Hamel ME et al. Comparison of direct versus self-report measures for assessing physical activity in adults: a systematic review. *Int J Behav Nutr Phys Act* 2008; 5:56.
43. Hug B, Heyer L, Naef N et al. Tapering for marathon and cardiac autonomic function. *Int J Sports Med* 2014; 35(8):676–683.
44. Kim YJ, Kim CH, Park KM. Excessive exercise habits of runners as new signs of hypertension and arrhythmia. *Int J Cardiol* 2016; 217:80–84.
45. Kim YJ, Park Y, Kang DH et al. Excessive exercise habits in marathoners as novel indicators of masked hypertension. *BioMed Res Int* 2017; 2017:1342842.
46. Takeshima N, Tanaka K. Prediction of endurance running performance for middle-aged and older runners. *Br J Sports Med* 1995; 29(1):20–23.
47. Tanaka K, Takeshima N, Kato T et al. Critical determinants of endurance performance in middle-aged and elderly endurance runners with heterogeneous training habits. *Eur J Appl Physiol Occup Physiol* 1990; 59(6):443–449.
48. Vickers AJ, Vertosick EA. An empirical study of race times in recreational endurance runners. *BMC Sports Sci Med Rehabil* 2016; 8(1):26.
49. McKelvie SJ, Valliant PM, Asu ME. Physical training and personality factors as predictors of marathon time and training injury. *Percept Mot Skills* 1985; 60(2):551–566.
50. Janssen GM, Graef CJ, Saris WH. Food intake and body composition in novice athletes during a training period to run a marathon. *Int J Sports Med* 1989; 10(Suppl. 1):S17–S21.
51. Yeung SS, Yeung EW, Wong TW. Marathon finishers and non-finishers characteristics. A preamble to success. *J Sports Med Phys Fitness* 2001; 41(2):170–176.
52. Young K. The theory of collapse. *Runners World* 1973:9–10.
53. Esteve-Lanao J, Moreno-Perez D, Cardona CA et al. Is marathon training harder than the ironman training? An ECO-method comparison. *Front Physiol* 2017; 8:298.
54. Stellingwerf T. Case study: nutrition and training periodization in three elite marathon runners. *Int J Sport Nutr Exerc Metab* 2012; 22(5):392–400.
55. Helgerud J. Maximal oxygen uptake, anaerobic threshold and running economy in women and men with similar performances level in marathons. *Eur J Appl Physiol Occup Physiol* 1994; 68(2):155–161.
56. Burke LM, Read RS. A study of carbohydrate loading techniques used by marathon runners. *Can J Sport Sci* 1987; 12(1):6–10.
57. Nikolaidis PT, Knechtle B. Effect of age and performance on pacing of marathon runners. *Open Access J Sports Med* 2017; 8:171–180.
58. Legaz Arrese A, Gonzalez Badillo JJ, Serrano Ostariz E. Differences in skinfold thicknesses and fat distribution among top-class runners. *J Sports Med Phys Fitness* 2005; 45(4):512–517.
59. Reese R. Women in Marathons. <https://www.runnersworld.com/runners-stories/a20794033/women-in-marathons/1/10/2018>.