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Boston Marathon athlete performance outcomes and intra-event medical encounter risk associated with low energy availability indicators

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ABSTRACT

Objective To determine the association between survey-based self-reported problematic low energy availability indicators (LEA-I) and race performance and intra-event medical encounters during the Boston Marathon.

Methods 1030 runners who were registered for the 2022 Boston Marathon completed an electronic survey (1–4 weeks pre-race) assessing LEA-I, training and medical history. De-identified survey data were linked to event wearable timing chips and medical encounter records. LEA-I was defined as: an elevated Eating Disorder Examination Questionnaire score, elevated Low Energy Availability (LEA) in Females Questionnaire score, LEA in Males Questionnaire with a focus on gonadal dysfunction score and/or self-report of diagnosed eating disorder/disordered eating.

Results The prevalence of LEA-I was 232/546 (42.5%) in females and 85/484 (17.6%) in males. Athletes without LEA-I (non-LEA-I) achieved significantly better race times versus those with LEA-I (accounting for demographic and anthropomorphic data, training history and marathon experience), along with better division finishing place (DFP) mean outcomes (women's DFP: 948.9±57.6 versus 1377.4±82.9, p<0.001; men's DFP: 794.6±41.0 versus 1262.4±103.3, p<0.001). Compared with non-LEA-I athletes, LEA-I athletes had 1.99-fold (95% CI: 1.15 to 3.43) increased relative risk (RR) of an intra-event medical encounter of any severity level, and a 2.86-fold increased RR (95% CI:1.31 to 6.24) of a major medical encounter.

Conclusion This is the largest study to link LEA-I to intra-event athletic performance and medical encounters. LEA-I were associated with worse race performance and increased risk of intra-event medical encounters, supporting the negative performance and medical risks associated with problematic LEA-I in marathon athletes.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Previous cross-sectional studies in small cohorts have demonstrated associations between problematic low energy availability indicators and negative health and performance outcomes.

WHAT THIS STUDY ADDS

⇒ To our knowledge, this is the largest study based on a major mass participation endurance event to demonstrate an association between self-reported low energy availability indicators and worse athletic performance and increased risk of intra-event medical encounters.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE, OR POLICY

⇒ Our findings may raise awareness among athletes and their health and performance entourage about the associations between low energy availability indicators and unfavourable sports performance outcomes and exercise-associated medical risks. Screening interventions for low energy availability indicators in mass endurance event participants should be tested.

INTRODUCTION

Relative Energy Deficiency in Sport (REDs) is a syndrome associated with problematic low energy availability (LEA), which is a prolonged and/or severe mismatch between energy intake and exercise energy expenditure.[1] The causes of LEA are multifaceted and can sometimes result from eating disorders (ED) and disordered eating (DE) behaviours, and/or an unintentional energy mismatch.[2–4] The presentation of LEA exists on a spectrum, ranging from adaptable LEA, characterised by short-term LEA with mild and reversible effects, to problematic LEA, which may eventually be associated with various REDs features including negative health (eg, impaired bone health, reproductive dysfunction, gastrointestinal problems) and performance (eg, decreased training response, decreased endurance performance, decreased muscle strength) effects.[1] Reported prevalence estimates of REDs, LEA and associated indicators in the literature range widely due to variations in athlete population, methodological inconsistencies and study volunteer biases, but have been reported as approximately 23–80% in female and 15–70% in male athletes.[1] Endurance athletes are at an elevated risk of LEA and REDs due to extreme exercise energy expenditure, often

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across multiple seasons,[5] in addition to the influence of endurance sport culture's long-standing drive for leanness.[6]

REDs and LEA-related research suggest that, when applied in the appropriate sport population context, validated surveys can serve as an accurate evaluation of indicators of overall health and long-term energy status.[7] Well-designed and tested surveys allow for broader dissemination to improve screening, prevention and early treatment of REDs.[8 9] Such initiatives can also expand the scope of research endeavours, including broadening and diversifying subject recruitment in the field.

As running event participation grows in popularity,[10] efforts to study the epidemiology of medical encounters at mass-endurance events have increased.[11 12] Although some studies have identified certain intrinsic and extrinsic risk factors for medical compromise during marathon events,[12–15] evidence surrounding athlete-specific modifiable risk factors has been limited, leaving a lag in the development of athlete-centred prevention recommendations.

The purpose of this study was to assess indicators of LEA (LEA-I) based on self-reported physical symptoms as well as eating, training and injury history in a large, diverse cohort of athletes registered to run the 2022 Boston Marathon. We additionally aimed to evaluate the relationship between LEA-I and (1) marathon race performance and (2) intra-event medical encounters.

METHODS

Athlete recruitment

This was an observational cohort study with cross-sectional data collection. Institutional Review Board approval was obtained. Eligibility criteria included age ≥18 years and registration for the 2022 Boston Marathon. 10 volunteers with marathon experience tested the survey and provided pre-implementation feedback. An invitation for study participation was highlighted in a weekly email-newsletter sent by the race host organisation (Boston Athletic Association) for 4 weeks pre-race and via posters at the pre-race expo. Participants provided informed consent and completed a pre-race survey (~10 min duration) using a secure web-based software platform (REDCap (Research Electronic Data Capture) 2022,[16] Host: Harvard University) with de-identified survey data linked to electronic timing data and intra-event medical encounter data.

Demographics and training data

Participants self-reported demographic and anthropomorphic information (table 1) along with marathon experience and training history, which were used to determine athlete training and performance tiering.[17] Athletes reported self-identified female or male sex, and their 2022 Boston Marathon official registered gender division (ie, women's or men's: open, masters, para or wheelchair divisions). The survey also included questions on medical history, injury/illness history and training patterns.

Low energy availability indicators definition

LEA-I in female participants was defined as meeting one or more of three criteria:

a. Self-report of diagnosed current or prior ED/DE.
b. Eating Disorder Examination Questionnaire (EDE-Q) global score >2.30 (sensitivity=90%, specificity=100%).[18 19]
c. LEA in Females Questionnaire (LEAF-Q) score ≥8 (sensitivity=78%, specificity=90%).[20] We used additional questions to assess for potential medical causes of menstrual irregularity other than LEA including: (1) hormonal medication/contraception use (within past 90 days); (2) polycystic ovary syndrome (PCOS) diagnosis; (3) pregnancy within past 12 months; and (4) age-appropriate (>45 years) menopause,[21] in which case these participants were not included in scoring for the LEAF-Q general menstrual function section, but did receive scores for menarche history and all other survey components.

LEA-I in males was defined as meeting one or more of three criteria:

a. Self-report of diagnosed current or prior ED/DE.
b. EDE-Q global score >1.68 (sensitivity=77%, specificity=77%).[22]
c. Gonadal dysfunction assessed using five questions from the LEA in Males Questionnaire (LEAM-Q) for athletes ages 18–50 years, with reduced libido compared with baseline found to have associations with biomarkers of LEA (eg, low total testosterone (sensitivity=87%, specificity=26%), low triiodothyronine (sensitivity=64%, specificity=86%), decreased insulin (sensitivity=96%, specificity=28%) and low-free testosterone:cortisol ratio (sensitivity=63%, specificity=57%)).[23]

Competition performance data

Standard event wearable time chip data were recorded at the course start, 5 km increments and finish (Dilltree Inc 2022, Real-Time Race Tracking). Official race timing and division finishing place (age and gender stratified divisions) results were obtained.

Intra-event medical encounter data

Intra-event medical encounter data were collected via a secure electronic tracking platform at 30 medical stations along the course and finish area (Sportzpeak Inc 2022, RaceSafe). Data collected included medical encounter location, triage status and disposition. For study participants admitted to medical stations, medical records were reviewed for extraction of presenting symptoms/medical problems. Medical encounters were classified as (1) minor (did not result in medical station admission, race withdrawal or hospital transport); (2) moderate (non-life-threatening condition requiring medical station admission, race withdrawal and/or hospital transport); or (3) serious (life-threatening condition requiring immediate treatment, admission to medical station intensive care unit and/or hospital transport).[24] Medical encounters within the (2) moderate and (3) serious classifications were aggregated as 'major medical encounters'. Illnesses were categorised by body system, and injuries categorised as sudden onset traumatic injury or gradual onset overload injury.[25]

Statistical analyses

Respondent descriptive statistics were used for categorical variables (frequency, percentages), along with continuous variables reported as mean and SD.

For our primary study aim, between-group comparisons were performed between athletes with LEA-I and those without LEA-I (non-LEA-I), separately for females and males on demographic/anthropomorphic data, training and performance variables using analyses of variance, and χ^2 tests for categorical variables. Binomial logistic regression models were used to evaluate associations between LEA-I and prevalence of bone stress injury (BSI) within the past 12 months, and illness or injuries (ie, sudden onset traumatic, gradual onset overload (bone or soft tissue)) impacting training within the past 6 months, with calculated ORs.

To address the secondary study aims, homogeneity assumptions were checked and thus separate multivariate analyses of

Table 1 2022 Boston Marathon study participants—starter descriptive characteristics

	Characteristics	Overall* (N=1030)	Female* (N=546)	Male* (N=484)
Demographics/ anthropometrics	**Age, years**	46.8 (13.7)	42.9 (12.9)	51.2 (13.1)
	BMI, kg/m2	21.9 (2.7)	21.1 (2.6)	22.7 (2.5)
	Race			
	White	893 (86.7)	475 (86.9)	418 (86.3)
	Asian American or Pacific Islander	51 (5)	27 (4.9)	24 (5.0)
	Black or African American	7 (0.7)	5 (0.9)	2 (0.4)
	American Indian or Alaskan Native	4 (0.4)	2 (0.4)	2 (0.4)
	Other race (write in)	6 (0.6)	1 (0.2)	5 (1.0)
	More than one race	4 (0.4)	3 (0.6)	1 (0.2)
	Ethnicity			
	Hispanic/Latino	65 (6.3)	33 (6.0)	32 (6.6)
	Non-Hispanic/Latino	965 (93.7)	513 (94.0)	452 (93.4)
	Country of residence			
	North American: USA (83.4%); Canada (6.4%); <1% each: Costa Rica, Dominican Republic, Mexico	934 (90.6)	510 (93.4)	424 (87.6)
	European: UK (2.5%); <1% each: Albania, Croatia, Finland, France, Germany, Greece, Ireland, Italy, Netherlands, Norway, Spain, Sweden, Switzerland	66 (6.4)	25 (4.4)	41 (8.3)
	South American: <1% each: Argentina, Brazil, Colombia, Ecuador, Uruguay	19 (1.8)	5 (0.9)	14 (2.8)
	Asian: <1% each: Hong Kong, India, South Korea, Philippines	7 (0.7)	3 (0.5)	4 (0.8)
	African: <1% each: Kenya, South Africa	2 (0.2)	1 (0.2)	1 (0.2)
	Australian/Oceanian: <1% each: Australia, New Zealand	2 (0.2)	2 (0.4)	0 (0.0)
Registration type and running experience	**Boston Marathon division†**			
	Running (open/majors) division	1027 (99.7)	543 (99.5)	484 (100)
	Subgroup: para-athletics	3 (0.3)	3 (0.5)	0
	Registration method			
	Time qualifier	755 (75.4)	411 (75.2)	344 (71.1)
	Other (ie, charity team)	275 (24.6)	135 (24.8)	140 (28.9)
	Training and performance classification‡			
	Tier 5—world class	1 (0.1)	0 (0)	1 (0.2)
	Tier 4—elite/international	6 (0.6)	5 (0.9)	1 (0.2)
	Tier 3—highly trained/national	347 (33.7)	217 (39.5)	130 (26.9)
	Tier 2—trained/developmental	671 (65.1)	321 (58.8)	350 (72.3)
	Tier 1—recreational	5 (0.5)	3 (0.5)	2 (0.4)
	Prior marathons finished	16 (26)	14 (26)	20 (26)
	Running training experience, years	9 (8)	8 (7)	10 (9)
2022 Boston Marathon race performance	**Net finish time, hours:minutes:seconds**	3:39:00 (0:23:06)	3:45:14 (0:21:30)	3:28:20 (0:24:54)
	Division finishing place	1107.2 (32.3)	1129.3 (49.1)	872.2 (39.1)
	Division finishing place percentile (%ile)	50.2%ile (1.5)	50.8%ile (2.1)	58.6%ile (1.8)
	Half marathon split ratio, second half: first half elapsed time	1.07 (0.45)	1.06 (0.45)	1.07 (0.46)
Intra-event medical encounters	**Medical encounter incidence (%)**	49 (4.8)	29 (5.3 F)	20 (4.1 M)
	Medical encounter incidence per 1000 starters	47.6 per 1000		
Energy availability	**Presence of low energy availability indicators**	317 (30.8)	232 (42.5)	85 (17.6)
	Absence of low energy availability indicators	698 (69.2)	314 (56.5)	399 (82.4)

*Categorical variables are reported as number of study participants count (%); continuous variables are reported as mean (SD). Medical incidence data are presented as a count per 1000 starters.
†Self-identified gender and age-grouped competitive division were provided by the participant at the time of event registration.
‡Training and performance classification tier.[17]

covariance (MANCOVAs) for females and males were used to evaluate the relationships between finish times with LEA-I status, covarying for demographic/anthropomorphic data, training and performance tier,[17] marathon experience, weekly training distance, BSI within the past 12 months and illness or injuries (bone or soft tissue) impacting training within the past

6 months. Levene's test was used to assess the assumption of equal variances. Mean differences with 95% CIs and Cohen's d effect sizes were used to determine the magnitude of LEA-I group effects (interpreted as <0.1 trivial, 0.1–0.3 small, 0.3–0.5 moderate and >0.5 large).[26] Logistic regression was performed to assess the impact of several factors (ie, age, sex, body mass index (BMI), LEA-I group, training and performance tier, training days in the last 6 months impacted by injury or illness) on the likelihood that respondents would experience an intra-event medical encounter. Predictor variables were first checked for multicollinearity, and the model was tested for overall statistical significance using the Omnibus Test of Model Coefficients. Alpha was set to 0.05 for all statistical analyses. Data preparation and analyses were conducted in Excel (V.16.65) and Jamovi software (V.2.3.18.0).

Equity, diversity and inclusion statement

Our research team is 63% women, including investigators from five countries. The study population includes representation from 32 countries and six continents, is balanced between women (53%) and men (47%) and includes a spectrum of ages. We acknowledge the majority of our study population was from North American countries and identified their race as white, thus findings may be skewed to this population.

RESULTS

Event Data & Study Participant Demographics

The 2022 Boston Marathon was held on 18 April, along the traditional point-to-point course (26.2 mi/42.2 km) with 815 ft/248 m elevation gain and 1275 ft/388 m elevation loss. Weather conditions were temperate with low environmental stress; WetBulb Globe Temperatures (WBGT) continuously measured at three locations ranged from 2.8°C to 14.1°C, mean±SD: 10.2°C±2.7°C, (unpublished data), which closely approximated WBGT trends in recent Boston Marathon years with a 09:00 start.[27] Of 28 586 registrants, 25 304 (88.5%) started (women's division: 10 819, men's division: 14 485), with 98.4% of starters finishing the race.

A total of 1063 athletes enrolled in the study (female: 563, male: 500), completing informed consent and the pre-race questionnaire, reflecting a 3.7% overall response rate from among the 28 586 registered athletes who received the study recruitment information via email. Of those respondents, 1030/1063 (96.9%) started the race (female: 546/563 (97.0%), male: 484/500 (96.8%)) and were included in full outcomes analyses (table 1).

LEA-I status

A total of 232/546 (42.5%) female and 85/484 (17.6%) male participants were classified as having at least one criterion of LEA-I (table 1). For both female and male participants, the mean age of the LEA-I groups was slightly lower than the non-LEA-I groups and there was no significant difference in BMI between LEA-I versus non-LEA-I groups (table 2). The proportion of time-qualified registrants (versus charity team registrants) did not differ between LEA-I versus non-LEA-I groups (table 2).

Female LEA-I

Of the 42.5% of female participants defined as having LEA-I, most met the criteria via LEAF-Q scores: 188/232 (81%), with 64/232 (27.6%) by EDE-Q, and 97/232 (41.8%) by ED/DE self-report (figure 1a). 355/546 (65.0%) female participants reported 'other' potential causes of menstrual irregularity: 185 with hormonal medication/contraception use; 17 reported PCOS diagnosis, 9 were pregnant ≤12 months prior and 144 indicated

Table 2 Analysis of variance comparison of demographics/anthropomorphics, training volume, marathon race performance and binomial logistic regression comparison of pre-race injury/illness prevalence and marathon race performance between athletes with and without low energy availability indicators

		Female N=546*			Male N=484*		
Category	Outcome	LEA-I starters n=232 (42.5%)	Non-LEA-I starters n=314 (57.5%)	*F*-statistic or χ^2 statistic; p value	LEA-I starters n=85 (17.6%)	Non-LEA-I starters n=399 (82.4%)	*F*-statistic or χ^2 statistic; p value
Demographics/ anthropometrics	Age, years	38.8 (12.2)	46.1 (12.6)	81.41; p<0.001***	41.8 (12.6)	53.2 (12.6)	42.14; p<0.001***
	BMI, kg/m^2	21.0 (2.6)	21.2 (2.6)	0.44; p=0.513	22.8 (2.6)	22.7 (2.4)	0.11; p=0.745
2022 registration method	Time qualifier	183 (78.9)	228 (72.6)	2.81; p=0.094	56 (65.9)	288 (72.1)	1.35; p=0.245
	Other (ie, charity team)	49 (21.1)	86 (27.3)		29 (34.2)	111 (27.8)	
Training volume	Typical running training distance per week in last 4 months (km)	67.0 (39.7)	64.8 (27.0)	0.58; p=0.452	73.4 (38.3)	75.4 (26.2)	0.06; p=0.811
2022 performance outcome	Division finishing place Division finishing place percentile (%ile)	1377.4 (82.9) 40.0%ile (3.6%)	948.9 (57.6) 58.7%ile (2.5%)	14.18; p<0.001***	1262.4 (103.3) 40.1%ile (4.9%)	794.6 (41.0) 62.3%ile (2.0%)	30.44; p<0.001***
Category	**Outcome**	**LEA-I starters n=232 (42.5%)**	**Non-LEA-I starters n=314 (57.5%)**	**OR (95% CI) p value**	**LEA-I starters n=85 (17.6%)**	**Non-LEA-I starters n=399 (82.4%)**	**OR (95% CI) p value**
Prevalence of injury/illness prior to race	Gradual onset overload injury (bone or soft tissue)+time loss in last 6 months†	120 (51.7)	22 (7.0)	14.22 (8.59 to 23.54) p<0.001***	44 (51.7)	140 (35.1)	1.99 (1.24 to 3.19) p=0.004**
	Sudden onset traumatic injury+time loss in last 6 months†	14 (6.0)	30 (9.6)	0.61 (0.32 to 1.18) p=0.139	10 (11.8)	36 (9.0)	1.34 (0.64 to 2.83) p=0.435
	Illness+time loss in last 6 months†	77 (33.2)	51 (16.2)	2.56 (1.71 to 3.85) p<0.001***	50 (58.8)	57 (14.3)	8.57 (5.12 to 14.3) p<0.001***
	Bone stress injury in last 12 months	24 (10.3)	13 (4.1)	2.67 (1.33 to 5.37) p=0.006**	16 (18.8)	25 (6.3)	3.47 (1.76 to 6.83) p<0.001***

*p<0.05, **p<0.01, ***p<0.001.
*Categorical variables are reported as number of study participants count (%); continuous variables are reported as mean (SD).
†Injury or illness resulting in missed/modified training days.
BMI, body mass index; LEA-I, low energy availability indicators.

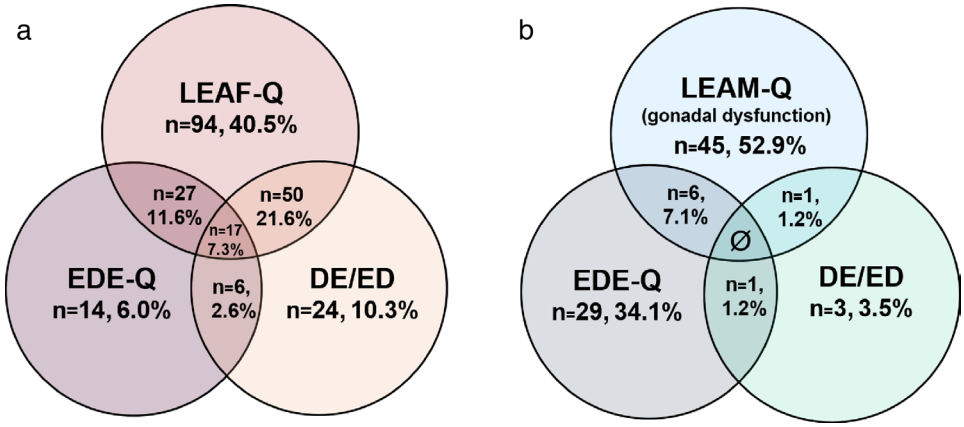

Figure 1 Venn diagrams of self-reported low energy availability indicators (LEA-I) among (a) female and (b) male study participants. (a) Female participants with LEA-I (n=232). (b) Male participants with LEA-I (n=85). DE/ED, self-reported diagnosed/disordered eating/eating disorders; EDE-Q, Eating Disorder Examination-Questionnaire; LEAF-Q, Low Energy Availability in Females Questionnaire; LEAM-Q, Low Energy Availability in Males Questionnaire (focus on gonadal dysfunction questions).

age-appropriate menopause, and thus were not scored for the LEAF-Q questions on current menstrual function.

Male LEA-I

Of the 17.6% of male participants defined as having LEA-I, 36/85 (42.4%) met the criteria via the EDE-Q and 5/85 (5.9%) by ED/DE self-report, while 52/85 (61.2%) met the criteria via the LEAM-Q gonadal dysfunction questions (figure 1b). For the LEAM-Q gonadal dysfunction questions, 251/484 (51.9%) of male participants were ages 18–50 years and therefore were scored on this instrument, while those over age 50 did not receive scores on this section.

Pre-race injury and illness prevalence

For both female and male participants, LEA-I athletes had higher odds of pre-race overload injury involving bone or soft tissue (female: OR: 14.22, 95% CI: 8.59 to 23.54, p<0.001; male: OR: 1.99, 95% CI: 1.24 to 3.19, p=0.004) and illness (female: OR: 2.56, 95% CI: 1.71 to 3.85, p<0.001; male: OR: 8.57, 95% CI: 5.12 to 14.30, p<0.001) causing lost/modified training days within the past 6 months, and specifically BSI within the past 12 months (female: OR: 2.67, 95% CI: 1.33 to 5.37, p=0.006; male: OR: 3.47, 95% CI: 1.76 to 6.83, p<0.001) compared with non-LEA-I athletes (table 2).

Marathon performance

Overall MANCOVA models were significant for both females and males (p<0.001); LEA-I was a significant predictor for race performance such that study participants with LEA-I demonstrated worse finish times compared with their non-LEA-I counterparts with moderate-to-large effect (females: d=0.33, males: d=0.53) when covarying for demographic/anthropomorphic data, training history and marathon experience (table 3). For both females and males, age, number of previous marathons,

Table 3 Relationship between marathon race performance and low energy availability indicators status, covarying for key factors

	Females Overall MANCOVA: *F*=55.22, p<0.001*** Levene's test: *F*=1.37, p=0.24			Males Overall MANCOVA: *F*=54.42, p<0.001*** Levene's test: *F*=0.01, p=0.92		
	Official race time			Official race time		
Predictor for marathon performance	*F*-statistic	P value	Mean difference (95% CI); Cohen's d	*F*-statistic	P value	Mean difference (95% CI); Cohen's d
Low energy availability indicators status	14.68	<0.001***	0.20 (0.09, 0.31); d=0.33	29.50	<0.001***	0.34 (0.18, 0.49); d=0.53
Model covariates	*F*-statistic	P value		*F*-statistic	P value	
Age (years)	114.88	<0.001***		215.59	<0.001***	
BMI (kg/m^2)	1.35	0.251		0.29	0.101	
Training and performance classification tier*	0.50	0.478		6.34	0.012*	
Number of previous marathons	26.61	<0.001***		27.39	<0.001***	
Typical running training distance per week in last 4 months (km)	4.38	0.004**		5.47	0.020*	
Gradual onset overload injury (bone or soft tissue)+time loss in last 6 months	0.01	0.990		0.25	0.618	
Sudden onset traumatic injury+time loss in last 6 months	5.45	0.020*		0.02	0.899	
Illness+time loss in last 6 months	4.78	0.029*		5.82	0.016*	
Bone stress injury in last 12 months	1.28	0.259		0.97	0.326	

*p<0.05, **p<0.01, ***p<0.001.
*Training and performance classification tier.[17]
BMI, body mass index; MANCOVA, multivariate analyses of covariance.

Table 4 Comparison of intra-event medical encounter incidence between starters with and without low energy availability indicators

		Overall medical encounter incidence (n=1030)	LEA-I starters (n=317)	Non-LEA-I starters (n=713)	Relative risk (95% CI)	P value
Medical encounter characteristics	**Total medical encounters**	49 (4.8%)	23 (7.3%)	26 (3.7%)	1.99 (1.15 to 3.43)	p=0.013*
	Major medical encounters Serious Moderate	25 (2.4%) 6 (0.6%) 19 (1.9%)	14 (4.4%) 4 (1.3%) 10 (3.2%)	11 (1.5%) 2 (0.3%) 9 (1.3%)	2.86 (1.31 to 6.24)	p=0.008**
	Minor medical encounters	24 (2.3%)	9 (2.8%)	15 (2.1%)	1.35 (0.59 to 3.05)	p=0.471
	Disposition					
	Did not finish—total Did not finish (intra-event transport) Did not finish (hospital transport) Returned to race	9 (0.9%) 6 (0.6%) 3 (0.3%) 40 (3.9%)	5 (1.6%) 3 (0.9%) 2 (0.6%) 18 (5.7%)	4 (0.6%) 3 (0.4%) 1 (0.1%) 22 (3.1%)	2.81 (0.76 to 10.40)	p=0.121
Illness category	**Fluid and electrolyte disorders**	22 (2.1%)	12 (3.8%)	10 (1.4%)	2.70 (1.18 to 6.18)	p=0.019*
	Muscular: pain, soreness and/or mild exercise-associated cramping	20 (1.9%)	8 (2.5%)	12 (1.7%)	1.50 (0.62 to 3.63)	p=0.370
	Gastrointestinal: nausea/vomiting, abdominal pain	18 (1.7%)	10 (3.2%)	8 (1.1%)	2.81 (1.12 to 7.06)	p=0.028*
	Exercise-associated postural hypotension	16 (1.5%)	9 (2.8%)	7 (1.0%)	2.89 (1.09 to 7.70)	p=0.034*
	Thermoregulatory: hypothermia/cold intolerance	14 (1.4%)	8 (2.5%)	6 (0.8%)	2.99 (1.05 to 8.57)	p=0.040*
	Respiratory: wheeze, and/or shortness of breath	2 (0.2%)	1 (0.3%)	1 (0.1%)	2.25 (0.14 to 35.85)	p=0.566
	Neurologic: peripheral numbness or tingling	2 (0.2%)	1 (0.3%)	1 (0.1%)	2.25 (0.14 to 35.85)	p=0.566
	Dermatologic: blisters, abrasions	4 (0.4%)	1 (0.3%)	3 (0.4%)	0.75 (0.08 to 7.18)	p=0.803
Injury category	**Gradual onset overload injury**	1 (0.1%)	1 (0.3%)	0	6.74 (0.28 to 164.91)	p=0.242
	Sudden onset traumatic injury	0	0	0		

*p<0.05, **p<0.01, ***p<0.001.
LEA-I, low energy availability indicators.

weekly running distance and illnesses causing time away from training within the last 6 months were significant covariates. Training and performance tier[17] was a significant covariate for males, but not female participants. Sudden onset traumatic injuries with time away from training during the last 6 months was a significant covariate for female participants, but not for males. No other covariates were significantly associated with performance. Of the 1030 starters in the cohort, 9 (0.9%) did not finish, all due to medical reasons (table 4).

Intra-event medical encounters

Medical encounter incidence in this study cohort was 47.6 per 1000 starters (table 4). Compared with non-LEA-I athletes, LEA-I athletes had approximately twice the risk of an intra-event medical encounter of any severity level (relative risk (RR)=1.99, 95% CI: 1.15 to 3.43, p=0.013; table 4). LEA-I athletes had 2.86-times increased risk of a major medical encounter (RR=2.86, 95% CI: 1.31 to 6.24, p=0.008) (table 4). However, there was no significant difference in RR for minor medical encounters between LEA-I and non-LEA-I athletes (RR=1.35, 95% CI: 0.59 to 3.05, p=0.471; table 4). Athletes with LEA-I demonstrated increased risk for medical encounters involving exercise-associated postural hypotension (RR=2.89, 95% CI: 1.09 to 7.70, p=0.034); fluid and electrolyte derangements (RR=2.70, 95% CI: 1.18 to 6.18, p=0.019); gastrointestinal issues (RR=2.81, 95% CI: 1.12 to 7.06, p=0.028); and impaired thermoregulation (ie, hypothermia/cold intolerance) (RR=2.99, 95% CI: 1.05 to 8.57, p=0.040) compared with non-LEA-I athletes (table 4). The full logistic regression model for medical encounter incidence was statistically significant, (χ^2 (6, N=1030)= 12.72, p=0.048) and LEA-I was found to be the only significant predictor (OR: 2.43, 95% CI: 1.30 to 4.52, p=0.005) of respondents experiencing an intra-event medical encounter (table 5).

A total of 25 (2.4%) study participants experienced major medical encounters, including 19 (1.9%) moderate and 6 (0.6%) severe medical encounters (online supplemental table 6). Moderate medical encounters predominantly involved gastrointestinal issues (ie, nausea/vomiting), exercise-associated postural hypotension, fluid and electrolyte disorders (ie, mild dehydration) and thermoregulatory problems (ie, hypothermia/cold intolerance). All severe medical encounters involved athletes with fluid and electrolyte disorders including moderate/severe dehydration, hyponatraemia and/or acute kidney injury (online supplemental table 6).

DISCUSSION

In this cohort of Boston Marathon athletes, worse endurance race performance and increased intra-event medical encounter risk were associated with LEA-I. Athletes with LEA-I had an increased risk of intra-event medical encounters, including major medical encounters, compared with non-LEA-I athletes. Our findings align with the REDs models, supporting the association between LEA-I and negative performance outcomes and increased intra-event medical risk in the sport setting.[1]

Performance

The observed performance deficits among study participants with LEA-I likely have multifactorial aetiologies. Although the mechanism was not specifically assessed, several possibilities warrant consideration. Prior research has established that marathoners' foundation of training influences race performance.[28] Reduced training availability due to injuries and illnesses has been shown to be a determinant of athletes' performance goal success

Table 5 Association of intra-event medical encounters with athlete demographics, anthropometrics, low energy availability indicators status and training and performance classification tier

	B	SE	Wald	Df	OR (95% CI)	P value
Age (years)	0.01	0.01	0.85	1	1.01 (.99 to 1.04)	0.357
Sex						
Male (n=484)					Reference	
Female (n=546)	0.44	0.32	1.97	1	1.56 (0.84 to 2.89)	0.161
BMI (kg/m^2)	0.02	0.05	0.21	1	1.02 (0.93 to 1.12)	0.649
LEA-I group classification						
Non-LEA-I (n=713)					Reference	
LEA-I (n=317)	0.89	0.32	7.79	1	2.43 (1.30 to 4.52)	0.005**
Training and performance tier*						
Tier ≤2					Reference	
Tier ≥3	0.29	0.38	0.56	1	0.75 (0.36 to 1.59)	0.455
Training days in last 6 months impacted by injury or illness	−0.02	0.02	1.25	1	0.98 (0.94 to 1.02)	0.263

*p<0.05, **p<0.01, ***p<0.001.
*Training and performance classification tier.[17]
BMI, body mass index; LEA-I, low energy availability indicators.

or failure.[29] Boston Marathon athletes with LEA-I had higher odds of lost/modified training days due to illnesses and overload injuries (bone and soft tissue) within the preceding 6 months. Prior studies have demonstrated an association between LEA and reduced training availability from overload injuries[30 31] and illnesses.[32] Our data on pre-race injury/illness prevalence are consistent with these prior studies, and highlight reduced training availability due to illness as a significant covariate in the performance outcomes observed in those with LEA-I.

LEA has been proposed to affect performance through indirect pathways that impair recovery and reduce muscle mass and function.[33 34] Early research showed female endurance athletes with amenorrhoea demonstrated reduced isokinetic lower extremity strength.[35] When compared with elite eumenorrhoeic female runners, elite amenorrhoeic runners were found to have significantly lower haemoglobin mass,[36] suggesting a reduced oxygen-carrying capacity as a potential mediator for reduced athletic performance. A recent study of endurance athletes exposed to a short-term LEA diet noted reduced perceived recovery and fitness, and increased subjective fatigue, burnout, whole-body physical complaints and perceived vulnerability to injury.[37] Thus, the impaired Boston Marathon race performance outcomes observed in the LEA-I group may have been due to multifactorial biopsychosocial mechanisms, however this warrants further study.

Intra-event medical encounters

Boston Marathon athletes with LEA-I had an increased risk for intra-event medical encounters involving physiological systems prone to dysfunction in LEA, including gastrointestinal issues, thermoregulatory dysfunction, exercise-associated postural hypotension and electrolyte imbalances. Although the mechanisms cannot be determined from this study, certain known physiological effects of LEA may overlap with common exercise-associated medical conditions. Gastrointestinal problems are commonly reported in endurance athletes[38] and may be exacerbated in the setting of LEA[39] as demonstrated by the increased prevalence of elevated LEAF-Q gastrointestinal subscale scores and intra-event medical encounters for gastrointestinal problems. Hypothermia/cold intolerance is another common issue treated at endurance events.[14] Thermoregulatory dysfunction has been described among individuals with EDs, thought to be related to impaired heat retention from reduced vasoconstriction and noradrenergic activity in the central and peripheral nervous system.[40 41] Exercise-associated postural hypotension is a prevalent problem at endurance running events,[42] and LEA is associated with impaired blood pressure regulation.[43] Further research is needed to elucidate mechanisms for the intra-event medical problems observed.

Body mass index

For both male and female athletes, there was no significant difference in BMI between LEA-I and non-LEA-I athletes. In prior studies, survey data demonstrated BMI was higher among both female and male athletes with LEA surrogates compared with those without.[44 45] These findings highlight the importance of screening all athletes for LEA-I, not just those below a specific BMI or weight threshold; athletes with LEA are at risk of REDs at any BMI. Additionally, there was no relationship between calculated BMI and marathon performance outcomes observed in this 2022 Boston Marathon cohort. This observation is consistent with recent data from recreational runners participating in a large marathon event in Ireland where there was no significant association between BMI and performance.[46] Although we do not have specific body composition data, our findings support the importance of adequate fuelling over calculated BMI targets in order to optimise athletic performance, contradicting the commonly held sport-cultural assumption that 'lighter is faster', which has historically contributed to motivations to obtain/maintain a small/lean physique.[6]

LEA indicators

Most participants meeting our LEA-I definitions were identified using questions from the LEAF-Q or LEAM-Q alone, with no indication of ED/DE diagnosis, suggesting unintentional inadequate energy intake. Past studies have described unintended LEA in athletes due to appetite suppression post-exercise,[47] low-energy dense diets,[48] gaps in knowledge regarding sports nutrition[49] and/or lack of awareness about LEA and related signs/symptoms.[50] However, other participants were identified to have elevated EDE-Q scores indicative of ED features. These findings highlight the potential relationship between LEA-I and behavioural and mental health factors among female and male endurance athletes.

Clinical implications

The key clinical implication of our findings is the significant negative effect on marathon performance as well as the increased intra-event medical risk associated with LEA-I. Our findings may

help promote athlete awareness and education around LEA and the potential associated negative performance outcomes and increased risk of intra-event medical encounters. Prevention strategies advocating for appropriate energy availability may help preserve athletes' health during training, maintain planned training schedules and reduce the risk of medical compromise during endurance events.

LIMITATIONS

The survey-based design of the study lends itself to certain limitations. First, there may be volunteer bias in self-selection for participation and recall bias regarding training and injury history. Additionally, self-reported height and weight may limit accuracy, although large population studies have demonstrated reasonably reliable and accurate weight and height reporting among survey respondents with normal-range BMI.[51] Our data are limited in the assessment of certain characteristics of LEA exposure (eg, duration, frequency and severity) which may, in conjunction with individual athletes' moderating factors, affect short, medium and long-term outcomes.[1] Given the large scale of this study, we did not include direct physiological data and biomarkers to diagnose athletes with LEA or explain pathophysiological mechanisms. However, the survey instruments selected for use in this study have previously demonstrated construct validity in prior investigations assessing LEA and associated signs/symptoms in athletes.[18–20 22 23] Future investigations utilising biomarkers may further elucidate underlying pathophysiology. Current limitations in screening tools for LEA-I among athletes in the post-menopause or post-andropause age range likely limited the sensitivity of LEA-I identification in these groups, potentially contributing to the observed difference in median age between EA groups, highlighting the need for the development of effective screening tools in these populations.

CONCLUSION

With 1030 Boston Marathon athlete participants, this is the first large study conducted at a mass-endurance event linking athletic performance and medical risk to self-reported problematic LEA-I in a free-living non-randomised cohort. Both male and female athletes with LEA-I demonstrated worse marathon performance. Moreover, athletes with LEA-I had an increased risk of experiencing intra-event medical encounters. Our novel findings support the negative athletic performance outcomes and increased medical risks associated with LEA-I in both female and male marathon athletes.

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