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Participant characteristics in the effectiveness of lifestyle interventions to optimize gestational weight gain: a systematic review and meta-analysis

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Abstract

Background Precision prevention involves tailoring interventions to the unique characteristics of a group or individual to maximize their effectiveness. In this study, we examined the role of participant characteristics in the effectiveness of lifestyle interventions to optimize gestational weight gain (GWG).
Methods We searched Medline, Embase, and PubMed, from inception up to March 2025, to identify randomized and non-randomized controlled trials of lifestyle interventions (diet, physical activity, or combined) commencing before or during pregnancy. Participant characteristics, including age, race/ethnicity, body mass index (BMI), employment status, fasting low- and high-density lipoprotein cholesterol (HDL-C) were assessed. Mean differences (MD) in GWG were pooled using the random-effect model. Meta-regression and subgroup analysis were conducted by participant characteristics (e.g., BMI).
Results A total of 86 studies with 28,270 participants were included in this systematic review and meta-analysis. All lifestyle intervention types significantly reduced GWG. Combined lifestyle interventions initiated at first (MD −0.68; 95% confidence interval [CI]: −1.28, −0.07) and early second (13–17 weeks) trimester (MD −0.83; 95% CI: −1.46, −0.20) provide better effectiveness in optimizing GWG. Diet-only interventions significantly reduced GWG only in participants with normal BMI (MD −1.33 kg; CI: −1.75, −1.91) compared to the other BMI categories. Combined diet and physical activity interventions reduce excessive GWG in women with higher baseline HDL-C (β −0.04; 95% CI −0.06, −0.01).
Conclusions Lifestyle interventions reduced excessive GWG, with possible differential effects by intervention initiation time, BMI, and HDL-C. Future studies should consider physiological as well as social characteristics, in line with a holistic framework for precision medicine.

Plain language summary

A growing body of evidence underscores the pivotal role of lifestyle intervention in reducing the risk of excessive weight gain during pregnancy and associated maternal and child health complications. However, instead of a one-size-fits-all approach, further research is needed to help differentiate how to optimize the effectiveness of these interventions based on individual physiological and social determinants. This study found that lifestyle interventions reduce excessive weight gain during pregnancy, with greater benefits for certain women, including those with a normal body mass index and higher high-density lipoprotein cholesterol (good cholesterol) levels at the beginning of lifestyle interventions. Non-stratified data reporting prevented us from examining other pertinent participant characteristics, and future studies are required to inform precision intervention approaches that benefit all women.

The preconception and pregnancy periods are critical stages in reproductive life during which lifestyle modifications to diet and physical activity, as well as changes in weight can impact maternal health and subsequent pregnancy and offspring outcomes[1–4]. There is evidence that excessive gestational weight gain (GWG) across pregnancy increases the risk for gestational diabetes[5–8], and GWG below or above recommendations is associated with adverse neonatal outcomes, including increased risk for small-for-gestational age, preterm birth, and large-for-gestational age[9].

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To support healthy GWG and mitigate the risks of excessive GWG, numerous antenatal interventions, including dietary, physical activity, or a combination of both, have been evaluated. Analysis of individual participant data from 36 randomized trials ($n = 12{,}526$ women) showed diet and physical activity-based interventions reduced GWG by a mean difference of −0.70 kg, compared to control[10]. Further investigation into diet and/or physical activity interventions (117 trials, $n = 34{,}546$ women) demonstrated that dietary interventions led to a greater reduction in GWG compared to physical activity or diet plus physical activity interventions, along with a remarkable reduction in risks for gestational diabetes and other maternal and neonatal outcomes[4]. However, there were inconsistencies between the studies, where many trials failed to find a noticeable benefit from lifestyle interventions on these outcomes[4]. As lifestyle interventions are generally complex and multi-component, the variability in effectiveness could stem from differences in intervention characteristics, including delivery methods[11,12]. In addition, response heterogeneity in lifestyle interventions may also be due to individual differences. For example, physiological factors indicated by BMI, blood pressure or biomarkers such as lipids may serve as predictors of treatment responsiveness[13]. Social determinants of health, such as socioeconomic status, education and employment, may also influence behavioral intervention outcomes[14]. Considering such sources of heterogeneity, lifestyle interventions to support appropriate GWG are unlikely to be effective for every individual as a 'one-size-fits-all' approach. Precision medicine emphasizes the need to tailor interventions to the unique needs of a particular population group to maximize effectiveness in preventing or managing disease[15,16]. To date, no comprehensive meta-analysis has investigated the differential responses to various lifestyle intervention types by participant characteristics in optimizing GWG. This evidence will be important to better understand demographic factors, physiological or clinical traits that might predict the effectiveness of excess GWG prevention programs.

This review is written on behalf of the American Diabetes Association (ADA)/European Association for the Study of Diabetes (EASD) Precision Medicine in Diabetes Initiative (PMDI) as part of a comprehensive evidence evaluation in support of the 2nd International Consensus Report on Precision Diabetes Medicine[17]. As part of the series, the current author group recently published a systematic review and meta-analysis examining the contributions of participant characteristics to the effectiveness of interventions employing lifestyle modification for the primary outcome of gestational diabetes[18]. In this study, we conducted an additional analysis on the secondary outcome of GWG and examined whether specific participant characteristics impact the effectiveness of lifestyle interventions in relation to optimizing GWG.

Methods

The systematic review and meta-analysis were conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Statement[19]. The protocol was registered in the PROSPERO International Prospective Register of Systematic Reviews (CRD42022320513). Further to our primary aim[18], we conducted a secondary analysis to examine whether participant characteristics also impacted the effectiveness of lifestyle interventions for reducing GWG, thereby broadening the scope of our research. We included studies involving diet-only, physical activity-only, and combined diet and physical activity as intervention strategies to test their effect on optimizing GWG. We followed the Population, Comparison, Outcomes, and Study framework to set the inclusion criteria (Supplementary Table 1).

Search strategy

A comprehensive search strategy of the literature was developed by a research librarian (AF) in consultation with the authors (SL, LR, KV, JJ). The search strategy included keywords and Medical Subject Headings, such as pregnancy, antenatal, behavior therapy, diet, intervention, and GWG, as shown in our previous publication[18] and was aimed at comprehensive inclusion of lifestyle interventions that assessed the outcomes of gestational diabetes and GWG. The following databases were searched: Embase (Elsevier), Medline (Ovid), and PubMed from inception to May 24, 2022, updated on September 19, 2023, and then again on March 20, 2025. Results from the literature search were limited to human studies and articles published in the English language. EndNote (Clarivate) was used to compile the references from the literature search and remove duplicates. These references were uploaded into Covidence (Veritas Health Innovation, Melbourne, Australia) and then used for title/abstract screening and full-text review. Hand-searches, including the reference list of related reviews, were also examined for additional eligible trials.

Selection criteria

Randomized and non-randomized controlled trials (RCTs and non-RCTs) in women of childbearing age (including preconception cohorts) investigating the effects of lifestyle interventions (diet, physical activity, or both) on the risk of gestational diabetes were included, and that included the outcome of GWG. Control conditions included usual care or minimal intervention, defined as no more than a single intervention session for diet and physical activity interventions. Studies without a control group (usual care or placebo), as well as editorials, commentaries, and conference abstracts, were excluded. Titles and abstracts were independently evaluated (SL, JJ, KV, NH, GGU, AQ, SC, JAG, WWT) and in duplicate to identify articles for full-text review. Full-text review was conducted independently and in duplicate, with reasons for exclusion recorded. Discrepancies were resolved by consensus by JAG and SL.

Data extraction

We extracted data on study characteristics (author names, year of publication, country, setting, sample size [in the control and intervention groups], study design, time of intervention commencement [before or during pregnancy], intervention type (diet-only, physical activity-only, combined) and outcome of interest (GWG [continuous]). Similarly, we extracted participant characteristics data, including age, race/ethnicity, BMI, educational status, employment status, parity, prior gestational diabetes, smoking status, systolic blood pressure, high-density lipoprotein cholesterol (HDL-C), low-density lipoprotein cholesterol (LDL-C), triglycerides, and fasting blood glucose levels. One author performed the data extraction, while a second author conducted a 10% sub-sample data extraction to establish reliability.

Risk of bias assessment

The quality of the included studies was critically appraised using the appropriate tool for each study design. The Revised Cochrane Risk of Bias Tool for Randomized Trials (RoB 2.0) was used for RCTs to assess bias arising from the randomization process, deviations from the protocol, missing data, measurement of the outcome and selective reporting[20]. For the non-RCTs, the ROBINS-I tool was used to assess bias from confounding, participant selection, classification of interventions, missing data, deviations from intended interventions, measurement of outcomes, and selection of reported results[21]. Two reviewers independently assessed the methodological quality and risk bias assessment for each study, with any disagreements resolved by consensus.

Evaluation of evidence certainty

The strength and certainty of evidence were examined using the Grading of Recommendations, Assessment, Development, and Evaluation (GRADE) system using GRADEpro GDT software. The evidence was assessed using critical domains, namely consistency, directness, risk of bias, and precision. The level of certainty was interpreted based on the GRADE guideline[22]. The assessment was done for the three lifestyle intervention types separately.

Statistical analysis

Data analysis was conducted by WWT using R statistical software version 4.3.0. Heterogeneity was assessed using the I^2 test. Mean differences (MD) were estimated employing the random-effects model with the restricted

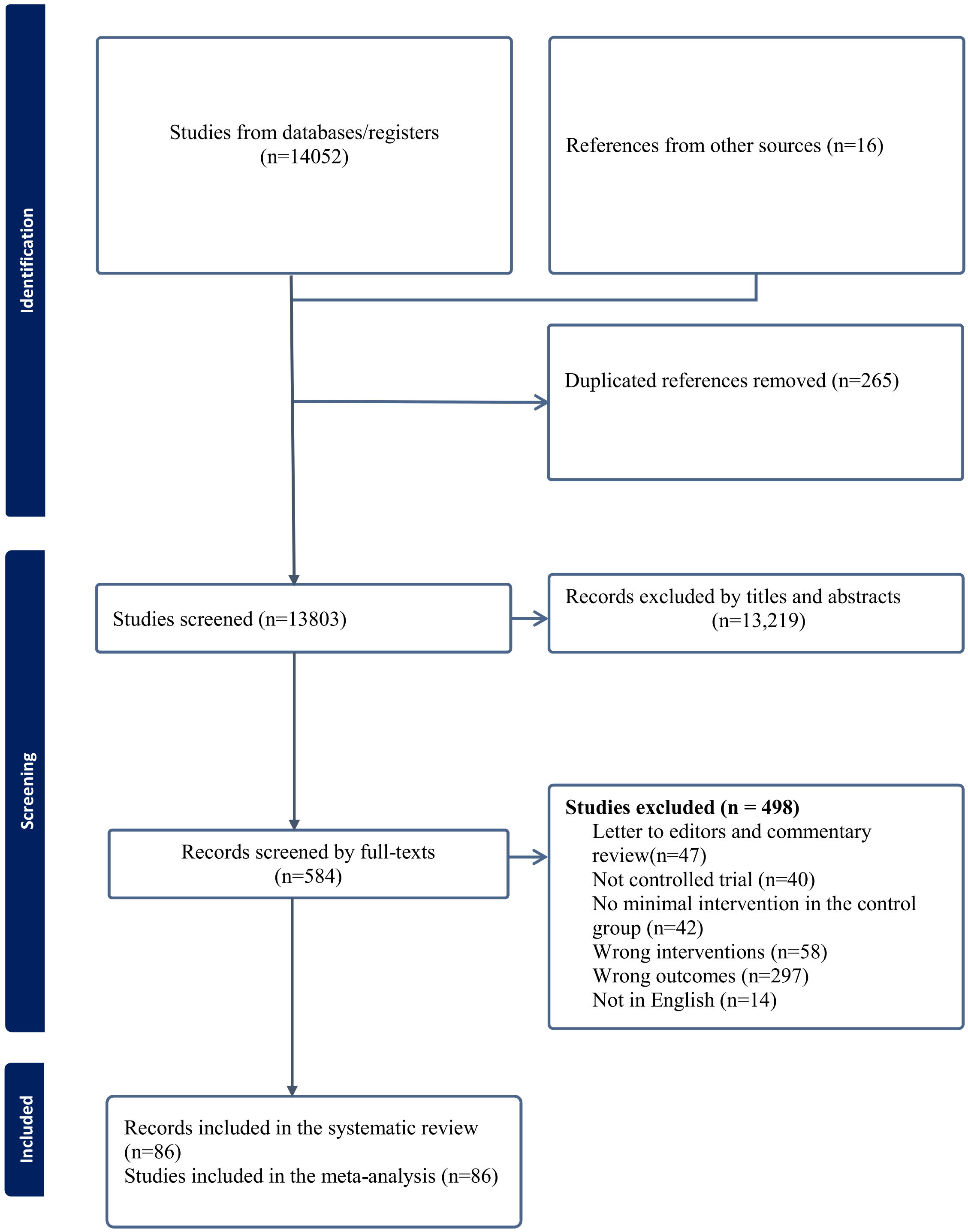

Fig. 1 | PRISMA flow diagram of the study. The diagram illustrates the procedure followed to identify the eligible studies. Studies were excluded in each critical screening step based on the eligibility criteria.

maximum likelihood (REML) estimator. The risk MD, along with the 95% confidence interval, was used to interpret the findings. Influential analysis was performed using the "metainf" function from "meta" package in R to identify outlier studies affecting the pooled estimates. Sensitivity analysis was also carried out by excluding non-RCT studies. Additionally, meta-regression and subgroup analysis were conducted by participant characteristics. Moreover, publication bias was investigated using funnel plots and Egger's regression test. Asymmetric funnel plots and a significant Egger's regression test ($p < 0.05$) were used as suggestive of publication bias.

Reporting summary
Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Results
A total of 14,052 articles were screened for eligibility of which 584 were reviewed as full texts (Fig. 1). Overall, 86 (79 RCT and 7 non-RCTs) articles were deemed eligible and were included in this study. The screening process and reasons for exclusion are documented in Fig. 1.

Table 1 | Subgroup analysis by lifestyle intervention type

	Number of studies	Mean difference (95%CI)	Heterogeneity (I^2)	*p* value for subgroups
All RCTs and non-RCTs				
Intervention types				0.55
Physical activity-only	16	−1.10 (−1.71, −0.48)	88.8	
Diet-only	17	−1.46 (−2.56, −0.35)	90.7	
Combined (diet and physical activity)	53	−0.82 (−1.45, −0.18)	93.8	
RCTs-only (sensitivity analysis)				
Intervention types				0.26
Physical activity-only	16	−1.10 (−1.71, −0.48)	88.8	
Diet-only	15	1.70 (−2.91, −0.48)	91.8	
Combined (diet and physical activity)	48	−0.66 (−1.32, −0.01)	94.4	

Study characteristics

Supplementary Data 1 describes the characteristics of the included studies, with the first publication published in 2000. The highest number of included studies was from the USA ($n = 21$), China ($n = 14$), Spain ($n = 10$), Australia ($n = 5$), and Germany ($n = 5$), with fewer (<3 each) from other countries. Sample sizes ranged from 32 to 3363 women. Of the included studies, 53 (61.6%) involved combined diet and physical activity interventions, 16 (18.6%) were physical activity-only interventions, and 17 (19.8%) were diet-only interventions. Thirty-five (41.7%) studies reported interventions commencing in the early second (13–17 weeks of gestation) trimester of pregnancy, while six studies (7%) reported starting in the preconception period.

Study quality assessment

Supplementary Data 2 summarizes the risk of bias assessment for the included studies in each intervention type. Of the 86 studies, 32 were classified as having a high risk or having some concerns regarding deviations from intended outcomes. Conversely, 54 studies had a low risk of bias in selecting the reported results, and most had a low risk of bias for missing outcome data or measurement of outcomes. Sixteen studies were assessed as having an overall low risk of bias, and 21 studies were categorized as having an overall high risk of bias.

Evidence certainty assessment

The evidence certainty for all three types of interventions and GWG was deemed "low". The main reason for the downgrade of the strength of evidence was due to the high risk of bias and inconsistency of results (Supplementary Table 2).

Participant characteristics

The definition of the participant characteristics is shown in Supplementary Data 3. Participant characteristics of the included studies are reported in Supplementary Data 4. Three studies focused exclusively on nulliparous women, 41 studies were in women with a BMI in an overweight/obese category or an obese BMI category, 19 studies were among women who were free of hypertension, and 34 studies were in women without prediabetes. The mean age of the participants ranged from 24.0 to 32.3 years, and the mean BMI at baseline ranged from 20.6 to 43.0 kg/m^2. Among the included studies, 24 had mostly participants who were in employed positions, 28 studies included participants with a mixed ethnicity, and 7 studies included predominantly non-White participants.

Meta-analysis

Effect of lifestyle intervention on optimizing GWG. In the overall meta-analysis of all 86 lifestyle intervention studies (combined diet and physical activity interventions; physical activity only; and diet only), GWG was significantly reduced by 1.00 kg (MD −1.00; 95% CI; −1.45, −0.54; $I^2 = 92.8\%$) without significant differences among the intervention types ($p = 0.55$; Table 1). After excluding the seven non-RCTs, lifestyle intervention provided a comparable effect with the finding from all study designs (0.95 kg [MD −0.95; 95% CI; −1.42, −0.47; $I^2 = 93.3\%$]) without differential effect by intervention types ($p = 0.55$; Table 1).

Combined diet and physical activity interventions. Combined diet and physical activity interventions in 53 studies ($n = 17{,}596$) significantly reduced GWG (MD −0.82 kg; 95% CI: −1.45, −0.18). Subgroup analysis by participant characteristics is shown in Table 2. Gestational week at which the combined intervention was initiated was associated with a reduction of weight gain, with a greater reduction in women who started the intervention during the first trimester (MD −0.68 kg; 95% CI: −1.28, −0.07) and early second trimester (12–17) (MD −0.83 kg; 95% CI: −1.46, −0.20; $p = 0.02$). No significant association was found between other participant characteristics and GWG.

Meta-regression (Supplementary Table 3) suggested that, for each one-unit increase in HDL-C, for participants receiving combined diet and physical activity interventions, there was a 0.04 kg reduction in GWG (MD −0.04 kg; 95% CI: −0.06, −0.01; $p = 0.01$). There was no effect of BMI, systolic blood pressure, LDL-C, triglyceride, or fasting blood glucose on GWG. Influential analysis suggested no single study affected the pooled estimates. Further sensitivity analysis after excluding five non-RCTs maintained the significance of combined lifestyle interventions in reducing GWG (MD −0.67 kg; 95% CI; −1.32, −0.01; $I^2 = 94.3\%$; low quality evidence). The Egger's test ($p = 0.69$) and funnel plot (Supplementary Fig. 1) suggest the absence of publication bias.

Physical activity-only intervention. Physical activity-only interventions significantly reduced GWG (MD −1.10 kg; 95% CI; −1.71, −0.48; $I^2 = 88.8\%$; low quality evidence) in 16 studies involving 4049 participants (Supplementary Fig. 2). Differences in intervention effect by participant characteristics are reported in Table 3. These interventions resulted in significant GWG reduction across all BMI categories except in a study that included only individuals with obesity. However, this non-significant finding was based on a single study (MD 0.60 kg; 95% CI: −1.24, 2.44). Meta-regression (Supplementary Table 4) showed no effect of age, sample size, or BMI on GWG associated with physical activity interventions. There was no influential study identified. Egger's test ($p = 0.78$) and funnel plot (Supplementary Fig. 3) suggested no publication bias.

Diet-only intervention. Diet-only interventions significantly reduced GWG (MD −1.46 kg; 95% CI; −2.56, −0.35; $I^2 = 90.7\%$) across 17 studies with 6,625 participants (Supplementary Fig. 4). Subgroup analysis by participant characteristics is shown in Table 4. Diet-only interventions were only significant in reducing GWG in studies involving participants within the normal BMI category compared with other categories (MD −1.33 kg; 95% CI; −1.75, −0.1.91; $p = 0.02$). In the meta-regression, age, sample size, and BMI did not affect the effectiveness of these interventions (Supplementary Table 5). There was no influential study identified. After excluding two non-

Table 2 | Summary of subgroup analysis by participant characteristics combined (diet and physical activity)

Variables	Number of studies	Mean difference	Confidence interval	Heterogeneity (I^2) (%)	*p* value for subgroups
Gestational week, baseline					0.02
Preconception	3	1.82	−1.50, 5.15	59.0	
First trimester	14	−0.68	−1.28, −0.07	74.1	
Early second trimester	21	−0.83	−1.46, −0.20	69.5	
Late second trimester	14	−0.50	−2.30, 1.29	94.5	
BMI					0.99
Overweight/obese	21	−0.81	−1.68, −0.04	91.1	
Obese	7	−1.02	−5.64, 3.60	95.3	
All BMIs	25	−0.88	−1.61, −0.15	95.1	
Educational status					0.77
No tertiary-level education	21	−0.94	−1.73, −0.16	90	
Attended tertiary level	13	−0.58	−1.34, 0.18	70.9	
Unspecified	19	−0.89	−2.950, 0.73	96.7	
Employment status					0.16
Employed	14	−0.88	−1.54, −0.22	63.6	
Unemployed	1	−2.76	−4.71, −0.81	-	
Unspecified	38	−0.70	−1.56, 0.187	95.4	
Hypertension at baseline					0.73
Without	11	−0.52	−3.11, −2.06	91.9	
Unspecified	42	−0.94	−1.52, −0.35	94.2	
Prediabetes at entry					0.99
Without	21	−0.69	−1.18, −0.19	61.6	
Unspecified	32	−0.70	−1.68, 0.30	96	
Parity					0.49
Nulliparous	2	−0.21	−13.04, 12.62	90.9	
Not nulliparous	1	0.52	−1.28, 2.34	-	
Mixed	31	−1.01	−1.99, −0.03	95.3	
Unspecified	19	−0.73	−1.62, −0.16	88.8	
PCOS					0.40
With	1	0.07	−1.19, 1.33	-	
Without	2	−1.18	−12.52, 10.15	85	
Unspecified	50	−0.82	−1.49, −0.14	94.1	
Ethnicity					0.15
White	4	0.41	−2.30, 3.12	77.8	
Non-White	5	−1.93	−5.61, 1.75	81.3	
Mixed	18	−0.17	−1.52, 1.17	90.6	
Unspecified	26	−1.28	−2.06, −0.49	95.7	
History of GDM					0.73
Without	5	−0.55	−2.68, 1.58	77.5	
Unspecified	48	−0.84	−1.53, −0.15	94.3	
History of CVD					0.81
Without	5	−0.94	−2.38, 0.49	39.8	
Unspecified	48	−0.79	−1.49, −0.09	94.4	
Risk of bias					0.29
High/moderate	18	−0.98	−1.84, −0.14	87.1	
Some concern/low	35	−0.37	−1.20, 0.46	77.3	

BMI body mass index, *PCOS* polycystic ovary syndrome, *GDM* gestational diabetes, *LGA* large for gestational age, *CVD* cardiovascular disease.

Table 3 | Summary of subgroup analysis by participant characteristics for physical activity-only interventions

Variables	Number of studies	MD	Confidence interval	Heterogeneity (I^2) (%)	*p* value for subgroups
Gestational week at baseline					0.33
Preconception	1	3.20	−6.54, 12.94	-	
First trimester	6	−1.40	−1.88, −0.93	10.2	
Early second trimester	6	−0.6	−2.05, 0.85	92.1	
Late second trimester	3	−1.08	−2.03, 1.13	0	
BMI					0.002
Overweight/obese	5	−2.09	−2.67, −1.49	0	
Obese	1	0.60	−1.24, 2.44	-	
All BMIs	10	−0.99	−1.79, −0.19	90.0	
Educational status					0.81
No tertiary-level education	6	−1.3	−1.78, −0.82	13.4	
Attended tertiary level	3	−0.59	−5.28, 4.09	94.2	
Unspecified	7	−1.27	−2.0, 0.07	75.3	
Employment status					0.46
Employed	8	0.73	−1.51, 0.04	89.7	
Unemployed	2	−2.14	−48.86, 44.59	55.8	
Unspecified	6	−1.36	−2.42, −0.31	80.6	
Hypertension at baseline					0.85
Without	5	−1.20	−2.54, 0.14	54.5	
Unspecified	11	−1.09	−1.93, −0.25	89.3	
Prediabetes at entry					0.88
Without	6	−1.07	−2.06, −0.08	77.9	
Unspecified	10	−1.15	−2.14, −0.16	89.3	
Parity					0.68
Not nulliparous	1	3.2	−6.54, 12.94	0	
Mixed	8	−1.16	−2.30, −0.03	75	
Unspecified	7	−1.08	−1.99, −0.18	93.2	
Ethnicity					0.002
White	1	0.30	−0.44, 1.03	-	
Mixed	4	−0.39	−1.85, 1.06	0	
Unspecified	11	−1.42	−2.13, −0.7	92.3	
History of GDM					0.002
With	1	0.30	−0.44, 1.04	-	
Without	2	−1.11	−3.32, 1.09	0	
Unspecified	13	−1.27	−1.98, −0.56	90.4	
History of CVD					0.22
Without	4	−1.64	−2.86, −0.42	5.1	
Unspecified	12	−0.99	−1.78, −0.20	90.0	
Risk of bias					0.06
High/moderate	6	−0.39	−1.53, 0.76	64.6	
Some concern/low	10	−1.43	−2.17, −0.69	71.6	

BMI body mass index, *GDM* gestational diabetes mellitus, *CVD* cardiovascular disease.

RCTs, the diet-only interventions remained significant in reducing GWG (MD −1.71 kg; 95% CI: −2.92, −0.50; I^2 = 91.7%; low quality evidence). According to Egger's test (p = 0.21) and funnel plot (Supplementary Fig. 5), publication bias was not detected. Moreover, studies with some concern/low risk of bias (vs high risk) exhibited better effectiveness in limiting excessive GWG (MD −3.33; 95% CI: −6.37, 0.30).

Discussion

The current meta-analysis reveals that diet, physical activity or combined diet and physical activity interventions, commencing in the preconception period or during pregnancy, reduce GWG by ~1 kg, with no differences between intervention types. The current exploratory analysis suggests that the effectiveness of combined lifestyle interventions in limiting excessive GWG may vary according to baseline gestational week at which interventions were initiated, BMI, and HDL-C. The available data are limited due to the inadequate reporting of these characteristics in fully assessing the impact of several individual characteristics on the effectiveness of lifestyle interventions.

Although all three intervention types demonstrated a noticeable benefit in GWG, this was not different between intervention types in head-to-

Table 4 | Summary of subgroup analysis by participant characteristics, diet-only interventions

Variables	Number of studies	MD	95% confidence interval (CI)	Heterogeneity (I^2) (%)	*p* value for subgroups
Gestational week at baseline					0.47
Preconception	2	−0.37	−4.18, 3.42	60.8	
First trimester	1	−0.40	−0.75, −0.05	-	
Early second trimester	8	−1.06	−2.20, 0.08	75.2	
Late second trimester	5	−1.29	−3.89, 1.31	90.3	
BMI					0.02
Normal weight	4	−1.33	−1.75, −1.91	0	
Overweight/obese	3	−2.71	−13.17, 7.75	95.9	
Obese	4	−2.96	−8.13, 2.20	83.5	
All BMIs	6	−0.51	−1.09, 0.07	60.6	
Educational status					0.14
No tertiary-level education	5	−0.58	−1.41, 0.25	72.8	
Attended tertiary level	3	−1.02	−1.43, −0.62	-	
Unspecified	7	−2.83	−5.73, 0.08	91.2	
Employment status					0.02
Employed	2	−0.54	−3.49, 2.40	0.0	
Unemployed	2	−0.12	−2.14, 1.89	0.0	
Unspecified	13	−1.81	−3.28, −0.34	92.2	
Hypertension at baseline					0.67
Without	5	−1.120	−3.20, 0.80	95.8	
Unspecified	12	−1.64	−3.22, 0.05	85.4	
Prediabetes at entry					0.08
Without	7	−0.67	−1.29, 0.06	28.6	
Unspecified	10	−2.18	−4.06, −0.30	94.5	
Parity					0.88
Not nulliparous	1	−1.50	−2.16, −0.84	0	
Mixed	11	−1.30	−2.81, 0.19	93.7	
Unspecified	6	−1.93	−5.03, 1.16	62.1	
Race					0.74
White	2	−3.10	−45.55, 39.35	92.2	
Non-White	6	−1.03	−2.67, 0.61	94.8	
Mixed	6	−2.14	−5.02, 0.75	90	
Unspecified	3	−0.94	−3.49, 1.61	40.6	
Risk of bias					0.02
High/Moderate	11	−0.49	−0.85, 0.12	42.5	
Some concern/Low	6	−3.34	−6.37, −0.30	91.5	

BMI body mass index.

head comparisons. This may reflect overlapping mechanisms and shared behavioral targets across the interventions, such as improved energy balance, increased awareness of weight-related goals, and engagement with health professionals, as observed in other interventions for limiting GWG[1] or in the general population for reducing body weight[23]. Additionally, the high between-study heterogeneity ($I^2 > 88\%$ across comparisons) likely contributed to limited power to detect subgroup differences. This could be due to variability in intervention adherence[10,24] or differences in frequency or intensity of the interventions among studies[25]. Future research should consider the role of delivery methods, adherence or intervention intensity in optimizing these interventions.

The evidence on the effect of lifestyle interventions on optimizing weight gain during pregnancy in the current study aligns with findings from a recent meta-analysis[4]. Our study extends those findings by investigating differential intervention effects by a range of participant characteristics, including demographic and physiological markers. We found that lifestyle interventions may be more effective in mitigating excessive GWG in individuals with normal BMI. Further studies are needed to confirm the variations in the effectiveness of lifestyle interventions in optimizing GWG among individuals with overweight or obesity. Recommended GWG varies by pre-pregnancy BMI category, with women with a BMI ≥ 30 kg/m^2 suggested to gain the least amount of weight[26]. Yet, only about one in four women with obesity gain within the Institute of Medicine recommended range, and most women with obesity gain in excess[27]. Contrastingly, women with normal weight are more than 1.5 times as likely to meet GWG recommendations compared to those with obesity[27]. Lower baseline BMI has also been shown to be a predictor of adherence to lifestyle interventions in a systematic review in the general population with obesity[28]. However, it is worth noting that the characteristics of other interacting participants and interventions may play a role in the effectiveness of interventions. For example, equal intervention dose to all participants regardless of women's BMI may primarily benefit the normal BMI groups than others. Hence, future studies are recommended to consider intervention duration and dose.

Meta-regression by participant characteristics revealed no clinically relevant impact on GWG based on sample size, age, or cardiometabolic variables that were assessed for each of the intervention types, except for higher baseline HDL-C, having a small effect on lowering GWG with combined diet and physical activity interventions. Higher HDL-C likely reflects better diet quality of the participants prior to the intervention[29]. The National Health Survey in Australia (2011-13) indicated that lower HDL-C was associated with dietary patterns characterized by higher intakes of added sugars and tropical fruits[30]. Past intervention studies have reported that participants with greater dietary restraint and healthier dietary behaviors before treatment were more likely to experience weight loss through lifestyle intervention[31]. Further, HDL cholesterol is implicated in insulin resistance measures such as triglyceride/HDL ratio and C-reactive protein/HDL ratio[32,33]. It is unclear if the current findings imply greater effectiveness of lifestyle intervention among those who are less insulin resistant. The role of HDL-C as a predictive marker of intervention response is to be confirmed in further studies.

Our findings suggest that the timing of lifestyle intervention initiation may be important in its effectiveness. Combined diet and physical activity interventions that commenced in the first trimester or early in the second trimester (13–17 weeks' gestation) were associated with greater reductions in GWG compared to those initiated later in pregnancy. This aligns with the physiological trajectory of pregnancy, where earlier interventions may better influence behavioral patterns before high GWG occurs[1,34,35]. Early initiation may also allow more time for behavior change to take effect and for women to engage with the intervention throughout a larger proportion of the pregnancy. These findings support recommendations for antenatal care models to identify and engage women at risk of excess GWG as early as possible, ideally before or soon after conception.

Finally, the effectiveness of lifestyle interventions to optimize GWG appears to be shaped by complex interactions between intervention type and participant characteristics. Our review found that physical activity interventions were effective across all BMI categories, including among women with overweight or obesity, whereas diet-only interventions appeared more effective in women with normal BMI. While our analysis focused on intervention effectiveness, the importance of participant characteristics is also reflected in observational studies. For example, Zhou et al. conducted a meta-analysis of 77 observational studies involving over 3.3 million women and identified pre-pregnancy overweight or obesity, high dietary energy intake, and pregnancy complications such as gestational diabetes mellitus as major determinants of excessive GWG, while physical activity was protective[36]. A retrospective cohort study also found several sociodemographic and clinical factors, such as race, pre-pregnancy overweight or obesity, and mood disorders, were associated with higher GWG[37]. These findings suggest that the underlying behavioral and metabolic risk profile of individuals entering pregnancy may influence their GWG outcomes and, by extension, their responsiveness to lifestyle interventions.

Although our meta-regression did not identify a clear association between continuous BMI and GWG outcomes, this may reflect methodological limitations such as subgroup misclassification, but may also underscore the deeper issue of inequitable access and engagement with interventions. We found that combined interventions were most effective when initiated in the first or early second trimester, likely benefiting from greater behavioral receptivity and longer duration of exposure[38]. While some reviews suggest diet and lifestyle interventions are beneficial across populations[10], intervention success is not uniform. Adherence-enhancing strategies[39,40], as well as attention to social factors such as education, socioeconomic status, language, and support systems[41], are essential to improving both the effectiveness and equity of lifestyle interventions to optimize GWG. Further research towards understanding how biological and social characteristics interact with intervention components is critical for tailoring approaches that are both effective and equitable.

Strengths of this review include a comprehensive assessment of how participant characteristics influence different lifestyle interventions to optimize GWG, with the aim of identifying populations who might benefit the most from each intervention type. Overall, we found that while there are many studies that have conducted interventions in different settings, the data available to thoroughly assess how participant characteristics impact the effectiveness of the interventions are limited. Where possible, participant subgroups were coded according to the inclusion and exclusion criteria to allow for group comparisons. However, most studies were conducted in mixed populations and did not report outcomes according to subgroup characteristics. Future studies should not only design clear interventions specific to population characteristics, but also report outcomes stratified by a priori groups, such as different BMI groups and metabolic status, to allow a more thorough comparison and understanding of participant characteristics associated with the effectiveness of lifestyle interventions in supporting recommended GWG. As this is a secondary analysis of a systematic review and meta-analysis on the prevention of gestational diabetes[18], only studies reporting gestational diabetes as one of the outcomes were included in this review. However, the GWG change reported in this meta-analysis is similar to other reviews focusing on GWG as the primary outcome[4].

Conclusions

Lifestyle interventions (diet, physical activity, or both) reduce GWG with no difference in effectiveness between intervention types; however, there may be possible differential effects by intervention initiation time, BMI, and HDL-C. Future studies should consider physiological as well as social characteristics in line with a holistic framework for precision medicine.

Data availability

All data used to produce this study were gathered from published studies. The list of included studies is available in Supplementary Data 1. All other relevant data that support the study's findings are available from the corresponding author upon reasonable request.

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S.L., J.J., L.R., and K.V. conceptualized the research question. A.F. contributed to the article searching. S.L., M.C., J.A.G., N.H., L.R., J.J., K.V., W.W.T., K.L., G.G.U., E.G.M., and S.C. screened the original studies. J.A.G., N.H., W.W.T., G.G.U., S.J.Z., R.T., M.P., K.L., M.B., A.Q., and H.W. appraised the studies and extracted the data. W.W.T conducted the data processing and analysis. K.V, W.W.T, S.L, and J.A.G have interpreted the findings. All authors contributed to the manuscript editing and proofreading.

Competing interests

The authors declare no competing interests.

Additional information

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