Effect of digital health applications with or without gamification on physical activity and cardiometabolic risk factors: a systematic review and meta-analysis of randomized controlled trials

Stephanie K. Nishi,[a,b,c,d,e,*] Meaghan E. Kavanagh,[a,f] Kimberly Ramboanga,[a] Sabrina Ayoub-Charette,[a,f] Sébastien Modol,[g] Goretty M. Dias,[g] Cyril W. C. Kendall,[a,f,j] John L. Sievenpiper,[a,f,h,i,k] and Laura Chiavaroli[a,f,h]

[a]Toronto 3D Knowledge Synthesis and Clinical Trials Unit, Clinical Nutrition and Risk Factor Modification Center, St. Michael's Hospital, Unity Health Toronto, Toronto, ON M5B 1W8, Canada
[b]Universitat Rovira i Virgili, Departament de Bioquímica i Biotecnologia, Unitat de Nutrició, Reus, Spain
[c]Institut d'Investigació Sanitària Pere Virgili (IISPV), Reus 43201, Spain
[d]Centro de Investigación Biomédica en Red Fisiopatología de la Obesidad y la Nutrición (CIBEROBN), Institute of Health Carlos III, Madrid 28029, Spain
[e]School of Nutrition, Faculty of Community Services, Toronto Metropolitan University, Toronto, ON, Canada
[f]Department of Nutritional Sciences, Temerty Faculty of Medicine, University of Toronto, Toronto, ON M5S 1A8, Canada
[g]School of Environment, Enterprise and Development, University of Waterloo, Waterloo, ON N2L 3G1, Canada
[h]Li Ka Shing Knowledge Institute, St. Michael's Hospital, Unity Health Toronto, Toronto, ON M5B 1W8, Canada
[i]Division of Endocrinology and Metabolism, St. Michael's Hospital, Unity Health Toronto, Toronto, ON M5B 1W8, Canada
[j]College of Pharmacy and Nutrition, University of Saskatchewan, Saskatoon, SK S7N 5E5, Canada
[k]Department of Medicine, Temerty Faculty of Medicine, University of Toronto, Toronto, ON M5S 1A8, Canada

eClinicalMedicine 2024;76: 102798

Published Online 25 September 2024
https://doi.org/10.1016/j.eclinm.2024.102798

Summary

Background Use of health applications (apps) to support healthy lifestyles has intensified. Different app features may support effectiveness, including gamification defined as the use of game elements in a non-game situation. Whether health apps with gamification can impact behaviour change and cardiometabolic risk factors remains unknown. We conducted a systematic review and meta-analysis to determine the effect of health apps with gamification compared to non-gamified apps (control) on physical activity and cardiometabolic risk factors.

Methods MEDLINE, EMBASE, and Cochrane library databases were searched through May 21st, 2024. We included controlled trials in adults (≥1 years) of all health backgrounds, with intervention periods ≥8-weeks, assessing the effect of gamification strategies used in health behaviour apps on adherence, cardiometabolic risk factors, total energy, and dietary nutrients of concern. Independent reviewers extracted relevant data and assessed risk of bias. Outcomes included physical activity and cardiometabolic risk factors (adiposity, glycemia, lipids, blood pressure and dietary factors). Data were pooled using the inverse variance method and expressed as mean differences (MD) with 95% confidence intervals (CI). Certainty of evidence was assessed using Grading of Recommendations Assessment, Development, and Evaluation (GRADE). Protocol registration was on ClinicalTrials.gov (NCT04633070).

Findings 36 trials (49 trial comparisons, n = 10,079) met eligibility criteria; most targeted physical activity or weight loss. Use of gamification in apps compared to non-gamified interventions resulted in trivial increases in steps (489 steps/day [64 to 914]; high), and reductions in body mass index (–0.28 kg/m^2 [–0.44 to –0.12]; moderate) and body weight (–0.70 kg [–1.18 to –0.22]; moderate), and small important reductions in body fat (–1.92% [–2.71 to –1.14]; high) and waist circumference (–1.16 cm [–1.93 to –0.39]; moderate). No differences were observed for other outcomes (very low-to-high).

Interpretation Current evidence provides a good indication that gamification features in apps targeting physical activity or measures of adiposity results in slight improvements in these outcomes compared to non-gamified versions. Recommendations to use an app for increasing physical activity or targeting weight loss should consider those with gamification features.

*Corresponding author. School of Nutrition, Faculty of Community Services, Toronto Metropolitan University, Toronto, ON, Canada.
E-mail address: snishi@torontomu.ca (S.K. Nishi).

Funding None.

Keywords: Systematic review; Mobile app; mHealth; Gamification; Behavioural change; Cardiovascular health

Research in context

Evidence before this study

Digital applications (apps) have emerged as a potential tool to aid in healthy behaviour change. However, there are inconsistencies in the evidence of whether apps with gamification result in improvements in health outcomes. To understand the role of gamification in health apps, we conducted a systematic review and meta-analysis to assess the effect of gamification as an app feature. We searched MEDLINE, Embase, and the Cochrane Central Register of Controlled Trials from inception to May 21, 2024, for papers with no language restrictions, using terms related to digital health intervention and gamification with a focus on apps targeting physical activity and cardiometabolic risk factors. Our search yielded 20,276 reports.

Added value of this study

This is the first systematic review and meta-analysis to provide a comprehensive overview of the effectiveness of using health apps with gamification to support behaviour change and health in adults. Our systematic search yielded 36 eligible randomized controlled trials assessing the effect of gamified vs. non-gamified apps, which predominantly targeted physical activity and weight loss. The use of gamification in apps compared to non-gamified app interventions resulted in increased physical activity (steps per day), as well as decreased body weight, body mass index, body fat percentage, and waist circumference. No significant effects were observed on blood pressure, lipids, glycemic control, and dietary factors. In general, the certainty of evidence was low to high for outcomes of physical activity and adiposity and very low to high for other outcomes, generally owing to downgrades for indirectness and imprecision.

Implications of all the available evidence

Findings from this systematic review and meta-analysis provide good indication that when apps are targeting physical activity or weight loss, the use of gamification improves the effectiveness of these lifestyle interventions compared to apps without gamification. Future high-quality studies investigating health apps with gamification designed to target cardiometabolic risk factors for a variety of populations are warranted. Recommendations to use an app to improve physical activity or weight loss should consider those with gamification features.

Introduction

Cardiovascular disease (CVD) remains a leading cause of death in Canada and globally.[1] Yet approximately 80% of CVD events could be prevented by a healthy lifestyle.[2] To support sustained behaviour change, interventions that can empower and engage populations are needed. Digital health applications (referred to as "apps") have the potential to deliver effective behaviour change interventions. However, the incorporation of different app features may influence the effectiveness of app interventions.

There is a limited understanding of which app features are necessary for producing sustained behaviour change, from commonly used features which provide educational materials and allow for self-monitoring, to less common features such as gamification or providing a platform for social support.[3] Most health apps incorporate a mix of features, each potentially offering varying levels of benefit. The use of different features, as well as varied controls, might explain discordant findings in previous assessments of the effectiveness of health apps on health outcomes.[4] A recent systematic review and meta-analysis of randomized controlled trials found mobile health app interventions had a weak advantage over standard of care for promoting health behaviour change and disease management.[3] Conversely, another systematic review and meta-analysis showed mobile health app interventions were associated with significant weight loss[5] and another umbrella review and meta-analysis showed eHealth and mHealth interventions compared to varied controls resulted in improvements in lifestyle behaviours, including physical activity, dietary intake, body weight, and sleep quality.[6] Identifying mechanisms in health apps which foster sustained behaviour change has been a challenge and is a current knowledge gap.

Studies on health behaviours, including physical activity and smoking cessation, have indicated that gamification may be an effective tool for engagement and behaviour change.[7–9] Gamification employs game design elements, mechanics, and principles with the objective of engaging the user and motivating behaviour change in a non-game environment.[10–13] While there are various definitions of what is considered a gamification-related element,[13] based on the literature, for the purposes of this study, gamification will refer to incorporating

'gaming elements' such as goal setting, feedback, badges, leaderboards, competitions, rewards, use of social networks, and avatars to engage and motivate individuals to change their behaviour.[10–12] If properly designed and implemented, gamification can overlap with established behaviour change strategies,[11] such as those defined by Michie and colleagues.[14–16]

Much of the current research on apps does not discern the effect of gamification as an added feature in health apps due to inadequate control groups.[10] Therefore, we conducted a systematic review and meta-analysis of randomized controlled trials to investigate the effect of health apps with and without gamification on behaviour change with a specific focus on physical activity and established targets of CVD in adults.

Methods

Design

A systematic review and meta-analysis was conducted according to the Cochrane handbook for systematic reviews and interventions (version 6.3),[17] with results following the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA)[18,19] guidelines. The study was originally registered at ClinicalTrials.gov (NCT04633070) with revisions to protocol noted in the Supplemental Methods. Given the systematic review and meta-analysis study design, which synthesizes and analyses previously published content, ethical approval was not required.

Data sources and search strategy

Supplemental Tables S1a and b and S2 show the systematic search strategy based on the population, intervention, comparator, outcome, time, and study design (PICOTS)[19] framework without language restrictions. We conducted a systematic search in MEDLINE, Embase, and the Cochrane Central Register of Controlled Trials from inception to May 21, 2024. The initial search covered database inception to December 11, 2020, and an updated search extended to May 21, 2024. Manual searches supplemented database searches. Due to the substantial increase in telehealth and digital health intervention related publications between 2020 and 2024, the search strategy was modified slightly to better reflect a focus on apps targeting physical activity and CVD specific risk factors (Supplemental Table S1b).

Study selection

We included controlled trials in adults (≥18 years) of all health backgrounds, with intervention periods ≥8-weeks assessing the effect of gamification strategies used in health behaviour apps on adherence, cardiometabolic risk factors, total energy, and dietary nutrients of concern as indicated by Health Canada (total sugars, sodium, saturated fat).[20] For the purposes of this analysis, gamification referred to the inclusion of one or more of the following elements: goal setting, personalized feedback, badges, leaderboards, competitions and challenges, rewards, avatars, as well as the use of social teams, point systems, and social support features.[10–12] Reports were excluded if the intervention was a non-health behaviour application, if the intervention included human support (but the control did not), if they lacked a suitable control (i.e., a suitable active control being comparator (i.e., an app without gamification components), or if they lacked viable outcome data. Reports were initially excluded based on a review of their titles and abstracts (SKN, MK, and/or KR). Remaining reports were reviewed in full by at least two reviewers (SKN, MK, and/or KR), leaving the final set of reports to be included in our syntheses. In reports containing more than one eligible trial comparison, we included each available trial comparison separately.

Data extraction

At least two reviewers (SKN, MK, KR, or SA-C) independently extracted the data from each included trial. Relevant information included number of participants, setting, participant health status, study design, comparator, gamification type, app purpose, behaviour targeted, follow-up duration, funding source, and outcome data. The authors were contacted for missing outcome data when it was indicated that an outcome was measured but not reported. Graphically presented data was extracted from figures using Plot Digitizer.[21]

Risk of bias assessment

At least two reviewers (SKN, SAC, or KR) independently assessed risk of bias (ROB) for each included trial using the Cochrane risk of bias tool 2.0.[22] This tool was used to assess bias across six domains (randomization process, deviations from the intended intervention, missing outcome data, measurement of outcome, reported results, and for crossover trials, bias arising from period and carryover effects). Reviewer discrepancies were resolved by consensus or arbitration by a senior author (LC).

Outcomes

The primary outcomes were markers of adherence (physical activity (moderate-to-vigorous physical activity [MVPA] and steps) and body weight). The secondary outcomes were blood lipids (low-density lipoprotein-cholesterol [LDL-C], non-high-density lipoprotein-cholesterol [non-HDL-C], high-density lipoprotein-cholesterol [HDL-C], triglycerides [TG], apolipoprotein B [apoB]); adiposity (body mass index [BMI], body fat, waist circumference, waist-to-hip ratio [WHR]); blood pressure (systolic blood pressure [SBP] and diastolic blood pressure [DBP]); glucose control (fasting glucose, haemoglobin A1c [HbA1c]); and dietary factors (total energy, total sugars, sodium, saturated fat). Mean differences (MDs)

between the intervention and control arms and their standard errors (SEs) were extracted for each eligible trial comparison. Mean pairwise differences in change-from-baseline values were preferred over end values, when available. Missing SEs were derived from available data using published formulae.[23] When median data was provided, they were converted to mean data with corresponding variances using methods developed by McGrath et al.[24] When no variance data was available, the standard deviation of the MDs was borrowed from a trial with similar size, participants, and nature of intervention. When an outcome was not reported, but the variables to calculate that outcome were, the outcome was calculated using a standard formula (body weight and height were used to calculate BMI; BMI and height were used to calculate the body weight; body fat mass (in kilograms) and total body weight (in kilograms) were used to calculate percentage body fat; waist and hip measurements were used to calculate the WHR; total cholesterol and HDL-C were used to calculate non-HDL-C; and total cholesterol, HDL-C and triglycerides were used to calculate LDL-C[25]). SEs for the calculated outcome were derived from the original variables using the inverse variance law.[26] All disagreements were reconciled by consensus or arbitration by a senior author (LC).

Data synthesis and analysis

We used Stata software, version 16.1 (StataCorp, College Station, TX, USA) for all analyses. The principal effect measures were the mean pairwise differences in changes from baseline (or alternatively, end differences) between the gamification intervention and non-gamified control arm (significance at $P < 0.05$). Results are reported as MDs with 95% confidence intervals (CIs). Data were analysed using the generic inverse variance method with a DerSimonian and Laird random-effects model.[27] Fixed-effects models were used when fewer than five trial comparisons were available.[28] To mitigate a unit-of-analysis error, when arms of trials with multiple intervention or control arms were used more than once, the corresponding sample size was divided by the number of times it was used for a calculation of the SE.[23] Each pairwise trial comparison was considered a separate trial for the purpose of this analysis.

Inter-study heterogeneity was estimated using the Cochran Q statistic and quantified using the I^2 statistic.[29] An $I^2 \geq 50\%$ and $P_Q < 0.10$ was considered as evidence of substantial heterogeneity.[23]

Sources of heterogeneity were explored by sensitivity and subgroup analyses. We conducted sensitivity analyses by influence analysis in which each trial was systematically removed from the meta-analysis with recalculation of the summary effect estimate. A trial whose removal explained the heterogeneity or changed the significance, direction, or magnitude of the effect by more than the minimally important difference (MID) for harm or benefit for each outcome (set as ± 30 min/week for MVPA,[30,31] ±2000 steps/day for steps,[32] ±1 kg for body weight, ±0.4 kg/m^2 for BMI, ±2% for body fat percentage,[33,34] ±1 cm for waist circumference,[35] ±0.02 for waist-to-hip ratio,[35,36] ±0.1 mmol/L for LDL-C, non-HDL-C, HDL-C, triglycerides and apoB,[37–39] ±0.3% for HbA1c,[40] ±0.5 mmol/L for fasting glucose,[40,41] ±2 mmHg for SBP and DBP,[42] ±500 kcals/day for total energy,[43] ±5 g/day for total sugars,[44,45] ±115 mg/day for sodium intake,[44,45] and ±1 g/day for saturated fat intake[44,45]) was considered an influential trial. Furthermore, for trials which reported outcomes using more than one assessment method, we performed sensitivity analyses where meta-analysed results were re-calculated using alternative the method. If ten or more trial comparisons were available,[23] we conducted subgroup analyses using meta-regression (significance at $P_Q < 0.05$). Subgroup analyses were conducted by participant health status, included participant sex (women or men only, or mixed), participant age, study design, randomization (yes, no), tool type, gamification type, whether the intervention was described as being based on behavioural change theory (yes, no), study purpose, behaviour targeted, intervention duration (follow-up <6 months, or ≥ 6 months), continent where the study was conducted, setting (professional or community), funding, whether the outcome was objectively measured or self-reported, type of analysis (completers/per-protocol or intention-to-treat (ITT)/modified ITT (mITT)), type of imputation performed for deriving variances (change from the baseline and end differences), data source (published/reported or calculated) and ROB domains. Meta-regression analyses were used to assess the significance of each subgroup categorically and, when applicable, continuously.

If ten or more trial comparisons were available, we assessed the presence of small-study effects (publication bias)[46] by visual inspection of funnel plots and formal testing by the Egger's and Begg's tests (significant at $P < 0.10$).[46–48] If there was evidence of small-study effects (publication bias), we quantified the size of the potential publication bias or other causes of asymmetry by adjusting for the funnel plot asymmetry and assessing the effect of small-study effects using the trim-and-fill method of Duval and Tweedie.[49]

Certainty of the evidence assessment

The certainty of the evidence was assessed using the Grading of Recommendations Assessment, Development, and Evaluation (GRADE) approach[50] and software (GRADEpro GDT, McMaster University and Evidence Prime Inc.).[51] The assessments were conducted by two independent reviewers (LC, SA-C), and discrepancies were resolved by consensus. The certainty of evidence was rated as high, moderate, low, or very low certainty. The included randomized controlled trials were initially rated as high certainty by default and then downgraded

or upgraded based on prespecified criteria. Reasons for downgrading the evidence included ROB (assessed by the Cochrane ROB 2.0 Tool),[52] inconsistency (substantial unexplained interstudy heterogeneity: $I^2 > 50\%$ and $P_Q < 0.10$), indirectness (presence of factors that limit the generalizability of the results), imprecision (the 95% CI for effect estimates overlap the MID for benefit or harm), and the presence of publication bias (significant evidence of small-study effects). The importance of the magnitude of the pooled estimates was assessed using prespecified MIDs and the effect size categories according to the GRADE guidance[53–55] as follows: large effect (≥5X MID); moderate effect (≥2X MID); small but important effect (≥1X MID); and trivial/unimportant effect (<1X MID).

Role of the funding source

There was no funding source for this specific study. Further, none of the authors' affiliated funding sources had any role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Results

Search results

Fig. 1 shows the results of the literature search. The search identified 20,276 reports from databases, of which 15,196 were excluded based on title and abstract. Of the 911 reports reviewed in full text, 36 randomized controlled trials (49 trial comparisons, n = 10,079) met the eligibility criteria.[7,56–88] Out of the 12 authors who were contacted for additional relevant information,[60,89–99] four responded, yet the applicable information was not available[90,100] or the trial was determined as not eligible.[91,93] Included trials reported 19 relevant outcomes with the number of trial comparisons per outcome ranging from one to 34.

Trial characteristics

Table 1 and Supplemental Table S3 along with Supplemental Fig. S1 show the summary and full individual trial characteristics, respectively. Trial sizes ranged from a median of 59 participants in the sodium intake analysis to 195 (36–301) participants in the MVPA analysis. Participants were adults, predominantly free from disease, but with a mix of participants including those with overweight/obesity, CVD, and type 2 diabetes. The majority of participants were women, middle-aged adults, with median proportions of women ranging from 40 to 100%, and ages ranging from a median of 36.0 (27.8–48.9) years to 55.4 (23.4–60.4) years. Most trials were conducted in the United States (40% on average), in the general community (69%) vs. professional (31%) settings (i.e., recommended by a health care professional within a health practice), and all were randomized and parallel in design. Objective measurements were utilized in 100% of the steps, blood lipids, and blood glucose trials, and most of the blood pressure and adiposity trials, whereas the dietary assessments were self-reported. The duration of trials ranged from a median of 3.0 to 12.0 (2.0–32.5) months. For each outcome, the study purpose of each of the included trials were predominantly to increase mobility/physical activity followed by weight loss, with fewer relating to disease prevention or management, dietary habits, or mixed purposes; while targeted behaviours comprised of physical activity, diet, mixed, or other behaviours. The intervention tool tended to be a mobile-app (14%–100%) or mobile and web-based app combined (23%–100%), most incorporating a mix of gamification types (up to 84%). The matched control most often being the equivalent tool without gamification (56%–100%). A behaviour change theory was noted as informing a median of 62% of the intervention developments. Most trials were funded by agency sources (33%–100%).

Risk of bias

Supplemental Figs. S2–S20 summarize the ROB assessments of the included trial comparisons by outcome. Across outcomes, excluding those with only one comparison, most trials were assessed as having low risk among all domains: randomization process (20%–100%), deviations from intended interventions (40%–100%), missing outcome data (50%–100%), measurement of the outcome (0%–100%), and selection of the reported result (50%–100%). Nonetheless, several trial comparisons were assessed as having high risk: for randomization process (0%–40%), deviations from intended interventions (0%–20%), missing outcome data (0%–50%), measurement of the outcome (0%–33.3%), and selection of the reported result (0%–6.25%) domains. Overall, there was no serious ROB in most trial comparisons except for waist-to-hip ratio, non-HDL-C, HDL-C, TG, and SBP, where the overall pooled estimate may be influenced by high ROB trials.

Physical activity markers

Fig. 2 and Supplemental Figs. S21 and S22 present the effect of using gamification in apps compared to non-gamified interventions on MVPA and steps. Use of gamification resulted in trivial increases in steps (34 trials; n = 5119; MD: 489 steps/day; 95% CI: 64, 914 steps/day; $P_{MD} = 0.024$; substantial heterogeneity: $I^2 = 93.8\%$; $P_Q < 0.0001$). No significant effect was observed for MVPA.

Adiposity markers

Fig. 2 and Supplemental Figs. S23–S27 present the effect of using gamification in apps compared to a non-gamified app on body weight and markers of adiposity. Use of gamification resulted in a trivial reduction in body weight (17 trials; n = 6088; MD: –0.70 kg; 95% CI: –1.18, –0.22 kg;

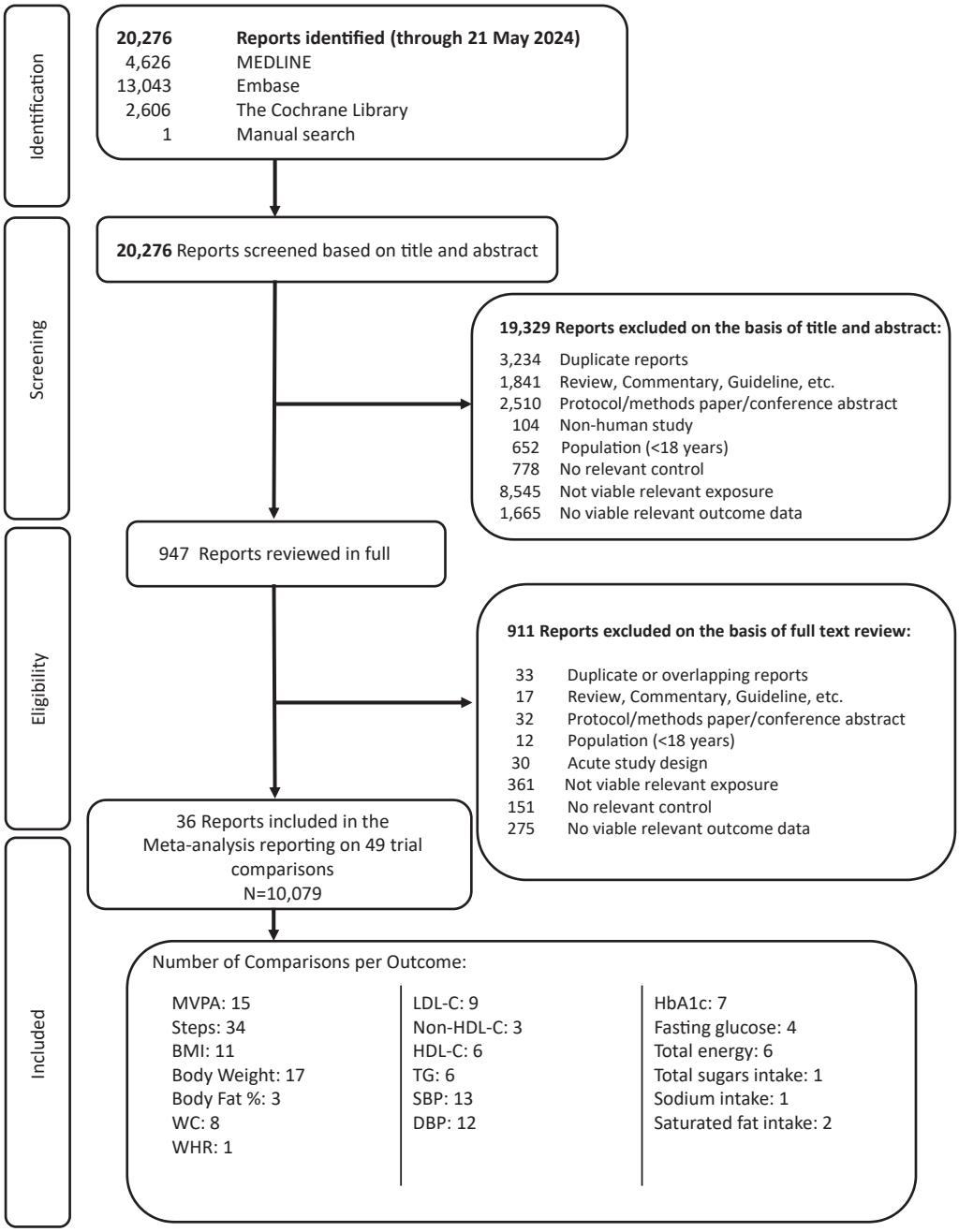

Fig. 1: Summary of evidence search and selection.

P_{MD} = 0.0043; no substantial heterogeneity: I^2 = 35.8%; P_Q = 0.071); and small important reductions in BMI (11 trials; n = 1880; MD: –0.28 kg/m^2; 95% CI: –0.44, –0.12 kg/m^2; P_{MD} = 0.00068; no substantial heterogeneity: I^2 = 35.8%; P_Q = 0.27); body fat percentage (3 trials; n = 230; MD: –1.92%; 95% CI: –2.71, –1.14%; P_{MD} < 0.0001; no substantial heterogeneity: I^2 = 0%; P_Q = 0.66); and waist circumference (8 trials; n = 802; MD: –1.16 cm; 95% CI: –1.93, –0.39 cm; P_{MD} = 0.0032; no substantial heterogeneity: I^2 = 44.7%; P_Q = 0.081). No significant effect was observed for waist-to-hip ratio.

Lipid markers

Fig. 2 and Supplemental Figs. S28–S31 present the effect of gamification on blood lipids, LDL-C, non-HDL-C, HDL-C, and triglycerides. No significant effects were observed. No applicable data was identified related to apolipoprotein B.

Trial characteristics	Moderate-to-vigorous physical activity (mins/week)	Steps (steps/day)	BMI (kg/m^2)	Body weight (kg)	Body fat percentage (%)	Waist circumference (cm)	Waist-to-hip ratio
Trials, N	15	34	11	17	3	8	1
Participants, N[a]	195 (36–301)	146 (30–388)	72 (30–890)	156 (35–2991)	66 (56–108)	82 (35–201)	156 (156–156)
Underlying health status, N trials	T2DM = 0; CVD = 5; People with OW/OB = 1; Absence of disease = 9; Other health status = 0; Mixed health status = 0	T2DM = 5; CVD = 7; People with OW/OB = 8; Absence of disease = 11; Other health status = 1; Mixed health status = 2	T2DM = 1; CVD = 3; People with OW/OB = 5; Absence of disease = 1; Other health status = 0; Mixed health status = 1	T2DM = 5; CVD = 2; People with OW/OB = 8; Absence of disease = 1; Other health status = 0; Mixed health status = 1	T2DM = 0; CVD = 0; People with OW/OB = 2; Absence of disease = 0; Other health status = 0; Mixed health status = 1	T2DM = 1; CVD = 2; People with OW/OB = 5; Absence of disease = 0; Other health status = 0; Mixed health status = 0	T2DM = 1; CVD = 0; People with OW/OB = 0; Absence of disease = 0; Other health status = 0; Mixed health status = 0
Sex ratio, %women:men	76: 24	76: 24	56: 44	59: 41	40: 60	55: 45	54: 46
Age, years[a,e]	55.4 (23.4–60.4)	52.3 (23.4–61.5)	50 (26.8–61.54)	52.28 (27.8–61.5)	36 (27.8–48.9)	52.6 (27.8–61.5)	52.3 (52.3–52.3)
Country, N trials	Australia = 1; Brazil = 0; Canada = 2; China = 0; Germany = 0; Netherlands = 2; South Korea = 0; Sweden = 1; Switzerland = 0; UK = 0; USA = 9	Australia = 0; Brazil = 0; Canada = 2; China = 2; Germany = 0; Netherlands = 2; South Korea = 1; Sweden = 0; Switzerland = 1; UK = 1; USA = 25	Australia = 0; Brazil = 1; Canada = 0; China = 2; Germany = 1; Netherlands = 0; South Korea = 2; Sweden = 0; Switzerland = 0; UK = 0; USA = 5	Australia = 0; Brazil = 1; Canada = 0; China = 2; Germany = 3; Netherlands = 0; South Korea = 2; Sweden = 0; Switzerland = 0; UK = 1; USA = 8	Australia = 0; Brazil = 0; Canada = 0; China = 0; Germany = 1; Netherlands = 0; South Korea = 1; Sweden = 0; Switzerland = 0; UK = 0; USA = 1	Australia = 0; Brazil = 0; Canada = 0; China = 2; Germany = 2; Netherlands = 0; South Korea = 1; Sweden = 0; Switzerland = 0; UK = 1; USA = 2	Australia = 0; Brazil = 0; Canada = 0; China = 0; Germany = 0; Netherlands = 0; South Korea = 0; Sweden = 0; Switzerland = 0; UK = 1; USA = 0
Setting ratio, % Community:Professional[b]	93: 7	82: 18	82: 18	88: 12	67: 33	75: 25	0: 100
Randomization ratio, % Yes:No	100: 0	100: 0	100: 0	100: 0	100: 0	100: 0	100: 0
Outcome objectively measured ratio, %No:Yes	7: 7	0: 100	18: 82	12: 88	0: 100	0: 100	0: 100
Follow-up, months[a]	3 (2–32.5)	3.125 (2–12)	3 (3–6)	6 (3–32.5)	3 (3–3)	3 (3–32.5)	12 (12–12)
Study purpose, N trials	Improve dietary habits = 0; Weight loss = 1; Increasing mobility/physical activity = 11; Disease self-management = 1; Disease prevention = 2; Mixed purposes = 0	Improve dietary habits = 0; Weight loss = 2; Increasing mobility/physical activity = 23; Disease self-management = 1; Disease prevention = 3; Mixed purposes = 5	Improve dietary habits = 0; Weight loss = 4; Increasing mobility/physical activity = 4; Disease self-management = 1; Disease prevention = 0; Mixed purposes = 2	Improve dietary habits = 0; Weight loss = 8; Increasing mobility/physical activity = 3; Disease self-management = 0; Disease prevention = 1; Mixed purposes = 5	Improve dietary habits = 0; Weight loss = 1; Increasing mobility/physical activity = 0; Disease self-management = 0; Disease prevention = 0; Mixed purposes = 2	Improve dietary habits = 0; Weight loss = 4; Increasing mobility/physical activity = 2; Disease self-management = 0; Disease prevention = 1; Mixed purposes = 1	Improve dietary habits = 0; Weight loss = 0; Increasing mobility/physical activity = 0; Disease self-management = 0; Disease prevention = 1; Mixed purposes = 0
Behaviour targeted, N trials	Diet = 0; Physical activity = 12; Mixed behaviours = 3; Other behaviours = 0	Diet = 0; Physical activity = 28; Mixed behaviours = 5; Other behaviours = 1	Diet = 1; Physical activity = 4; Mixed behaviours = 6; Other behaviours = 0	Diet = 0; Physical activity = 6; Mixed behaviours = 10; Other behaviours = 1	Diet = 0; Physical activity = 0; Mixed behaviours = 3; Other behaviours = 0	Diet = 0; Physical activity = 2; Mixed behaviours = 6; Other behaviours = 0	Diet = 0; Physical activity = 0; Mixed behaviours = 1; Other behaviours = 0
Control tool type ratio, % Electronic education/ website:Mobile app:Mobile & Web-based app:Physical activity tracking device:Web-based app	20: 33: 0: 20: 27	24: 32: 3: 21: 21	45: 45: 0: 9: 0	47: 29: 0: 6: 18	33: 67: 0: 0: 0	75: 12: 0: 12: 0	100: 0: 0: 0: 0
Intervention tool type ratio, %Mobile app:Web-based app:Web-based & mobile app	60: 40: 0	65: 29: 6	64: 36: 0	41: 53: 6	67: 33: 0	50: 50: 0	100: 0: 0
Intervention gamification type ratio, % PDF:GS:BA:S:SC:M[c]	0: 0: 13: 7: 7: 73	6: 0: 6: 0: 3: 85	18: 0: 9: 0: 0: 73	24: 0: 6: 6: 0: 65	33: 0: 33: 0: 0: 33	12: 0: 12: 12: 0: 62	100: 0: 0: 0: 0: 0
Control gamification type ratio, %PDF:GS:M:No gamification[c]	27: 0: 7: 67	18: 21: 32: 29	0: 18: 0: 82	6: 18: 18: 59	0: 0: 0: 100	0: 25: 0: 75	0: 0: 0: 100
BCT ratio, %Intervention based on a BCT:Intervention not based on a BCT	60: 40	79: 21	73: 27	71: 29	33: 67	62: 38	100: 0
Funding ratio, %A:I:A + I:NR[d]	73: 7: 13: 7	85: 0: 9: 6	55: 9: 18: 18	82: 6: 6: 6	33: 33: 0: 33	75: 12: 12: 0	100: 0: 0: 0
Design ratio, %P:C	100: 0	100: 0	100: 0	100: 0	100: 0	100: 0	100: 0

Trial characteristics	LDL-C (mmol/L)	non-HDL-C (mmol/L)	HDL-C (mmol/L)	Triglycerides (mmol/L)	HbA1c (%)	Fasting glucose (mg/dL)	SBP (mmHg)	DBP (mmHg)	Total energy intake (kcals/day)	Total sugars intake (g/day)	Sodium intake (mg/day)	Saturated fat intake (g/day)
Trials, N	9	3	6	6	7	4	13	12	6	1	1	2
Participants, N[a]	162 (66–201)	156 (108–162)	132 (66–201)	132 (66–201)	174 (92–182)	143.5 (66–201)	92 (36–201)	82 (36–296)	112.5 (35–201)	117 (117–117)	59 (59–59)	88 (59–117)
Underlying health status, N trials	T2DM = 5; CVD = 0; People with OW/OB = 4; Absence of disease = 0; Other health status = 0; Mixed health status = 0	T2DM = 2; CVD = 0; People with OW/OB = 1; Absence of disease = 0; Other health status = 0; Mixed health status = 0	T2DM = 2; CVD = 0; People with OW/OB = 4; Absence of disease = 0; Other health status = 0; Mixed health status = 0	T2DM = 2; CVD = 0; People with OW/OB = 4; Absence of disease = 0; Other health status = 0; Mixed health status = 0	T2DM = 5; CVD = 0; People with OW/OB = 2; Absence of disease = 0; Other health status = 0; Mixed health status = 0	T2DM = 1; CVD = 0; People with OW/OB = 3; Absence of disease = 0; Other health status = 0; Mixed health status = 0	T2DM = 1; CVD = 5; People with OW/OB = 4; Absence of disease = 2; Other health status = 1; Mixed health status = 0	T2DM = 1; CVD = 4; People with OW/OB = 4; Absence of disease = 2; Other health status = 1; Mixed health status = 0	T2DM = 0; CVD = 0; People with OW/OB = 6; Absence of disease = 0; Other health status = 0; Mixed health status = 0	T2DM = 0; CVD = 0; People with OW/OB = 1; Absence of disease = 0; Other health status = 0; Mixed health status = 0	T2DM = 0; CVD = 1; People with OW/OB = 0; Absence of disease = 0; Other health status = 0; Mixed health status = 0	T2DM = 0; CVD = 1; People with OW/OB = 1; Absence of disease = 0; Other health status = 0; Mixed health status = 0
Sex ratio, % women:men	56: 44	51: 49	55: 45	55: 45	57: 43	50: 50	63: 37	65: 35	73: 27	85: 15	100: 0	92: 8
Age, years[a,e]	52.5 (27.8–57.7)	52.28 (48.92–57.7)	51.14 (27.8–57.7)	51.14 (27.8–57.7)	52.5 (48.92–57.7)	51.41 (27.8–57.7)	53 (27.8–58.9)	52.6 (27.8–58.9)	48.9 (27.8–61.5)	NR	49.9 (49.9–49.9)	49.9 (49.9–49.9)
Country, N trials	Australia = 0; Brazil = 0; Canada = 0; China = 0; Germany = 2; Netherlands = 0; South Korea = 2; Sweden = 0; Switzerland = 0; UK = 1; USA = 4	Australia = 0; Brazil = 0; Canada = 0; China = 0; Germany = 1; Netherlands = 0; South Korea = 1; Sweden = 0; Switzerland = 0; UK = 1; USA = 0	Australia = 0; Brazil = 0; Canada = 0; China = 0; Germany = 2; Netherlands = 0; South Korea = 2; Sweden = 0; Switzerland = 0; UK = 1; USA = 1	Australia = 0; Brazil = 0; Canada = 0; China = 0; Germany = 2; Netherlands = 0; South Korea = 2; Sweden = 0; Switzerland = 0; UK = 1; USA = 10	Australia = 0; Brazil = 0; Canada = 0; China = 0; Germany = 2; Netherlands = 0; South Korea = 0; Sweden = 0; Switzerland = 0; UK = 1; USA = 4	Australia = 0; Brazil = 0; Canada = 0; China = 0; Germany = 1; Netherlands = 0; South Korea = 2; Sweden = 0; Switzerland = 0; UK = 0; USA = 1	Australia = 0; Brazil = 0; Canada = 2; China = 2; Germany = 2; Netherlands = 0; South Korea = 1; Sweden = 0; Switzerland = 0; UK = 1; USA = 5	Australia = 0; Brazil = 0; Canada = 2; China = 2; Germany = 2; Netherlands = 0; South Korea = 1; Sweden = 0; Switzerland = 0; UK = 1; USA = 4	Australia = 1; Brazil = 0; Canada = 0; China = 0; Germany = 1; Netherlands = 0; South Korea = 1; Sweden = 0; Switzerland = 0; UK = 0; USA = 3	Australia = 1; Brazil = 0; Canada = 0; China = 0; Germany = 0; Netherlands = 0; South Korea = 0; Sweden = 0; Switzerland = 0; UK = 0; USA = 0	Australia = 0; Brazil = 0; Canada = 0; China = 0; Germany = 0; Netherlands = 0; South Korea = 0; Sweden = 0; Switzerland = 0; UK = 0; USA = 1	Australia = 1; Brazil = 0; Canada = 0; China = 0; Germany = 0; Netherlands = 0; South Korea = 0; Sweden = 0; Switzerland = 0; UK = 0; USA = 1
Setting ratio, % Community: Professional[b]	78: 22	67: 33	67: 33	67: 33	86: 14	75: 25	62: 38	67: 33	83: 17	100: 0	100: 0	100: 0
Randomization ratio, %Yes:No	100: 0	100: 0	100: 0	100: 0	100: 0	100: 0	100: 0	100: 0	100: 0	100: 0	100: 0	100: 0
Outcome objectively measured ratio, % No:Yes	0: 100	0: 100	0: 100	0: 100	0: 100	0: 100	23: 77	25: 75	100: 0	100: 0	100: 0	100: 0
Follow-up, months[a]	12 (3–32.5)	3 (3–12)	3 (3–32.5)	3 (3–32.5)	12 (3–12)	3 (3–32.5)	3 (2–32.5)	3 (2–32.5)	4.5 (3–32.5)	3 (3–3)	3 (3–3)	3 (3–3)
Study purpose, N trials	Improve dietary habits = 0; Weight loss = 3; Increasing mobility/physical activity = 1; Disease self-management = 0; Disease prevention = 1; Mixed purposes = 4	Improve dietary habits = 0; Weight loss = 1; Increasing mobility/physical activity = 1; Disease self-management = 0; Disease prevention = 1; Mixed purposes = 0	Improve dietary habits = 0; Weight loss = 3; Increasing mobility/physical activity = 1; Disease self-management = 0; Disease prevention = 1; Mixed purposes = 1	Improve dietary habits = 0; Weight loss = 3; Increasing mobility/physical activity = 1; Disease self-management = 0; Disease prevention = 1; Mixed purposes = 1	Improve dietary habits = 0; Weight loss = 2; Increasing mobility/physical activity = 1; Disease self-management = 0; Disease prevention = 1; Mixed purposes = 3	Improve dietary habits = 0; Weight loss = 2; Increasing mobility/physical activity = 1; Disease self-management = 0; Disease prevention = 0; Mixed purposes = 1	Improve dietary habits = 1; Weight loss = 3; Increasing mobility/physical activity = 3; Disease self-management = 2; Disease prevention = 3; Mixed purposes = 1	Improve dietary habits = 1; Weight loss = 3; Increasing mobility/physical activity = 3; Disease self-management = 1; Disease prevention = 3; Mixed purposes = 1	Improve dietary habits = 1; Weight loss = 4; Increasing mobility/physical activity = 0; Disease self-management = 0; Disease prevention = 0; Mixed purposes = 1	Improve dietary habits = 1; Weight loss = 0; Increasing mobility/physical activity = 0; Disease self-management = 0; Disease prevention = 0; Mixed purposes = 0	Improve dietary habits = 1; Weight loss = 0; Increasing mobility/physical activity = 0; Disease self-management = 0; Disease prevention = 0; Mixed purposes = 0	Improve dietary habits = 2; Weight loss = 0; Increasing mobility/physical activity = 0; Disease self-management = 0; Disease prevention = 0; Mixed purposes = 0
Behaviour targeted, N trials	Diet = 0; Physical activity = 4; Mixed behaviours = 5; Other behaviours = 0	Diet = 0; Physical activity = 1; Mixed behaviours = 2; Other behaviours = 0	Diet = 0; Physical activity = 1; Mixed behaviours = 5; Other behaviours = 0	Diet = 0; Physical activity = 1; Mixed behaviours = 5; Other behaviours = 0	Diet = 0; Physical activity = 4; Mixed behaviours = 3; Other behaviours = 0	Diet = 0; Physical activity = 1; Mixed behaviours = 3; Other behaviours = 0	Diet = 1; Physical activity = 5; Mixed behaviours = 7; Other behaviours = 0	Diet = 1; Physical activity = 5; Mixed behaviours = 6; Other behaviours = 0	Diet = 1; Physical activity = 0; Mixed behaviours = 5; Other behaviours = 0	Diet = 1; Physical activity = 0; Mixed behaviours = 0; Other behaviours = 0	Diet = 1; Physical activity = 0; Mixed behaviours = 0; Other behaviours = 0	Diet = 2; Physical activity = 0; Mixed behaviours = 0; Other behaviours = 0

(Table 1 continues on next page)

Trial characteristics	LDL-C (mmol/L)	non-HDL-C (mmol/L)	HDL-C (mmol/L)	Triglycerides (mmol/L)	HbA1c (%)	Fasting glucose (mg/dL)	SBP (mmHg)	DBP (mmHg)	Total energy intake (kcals/day)	Total sugars intake (g/day)	Sodium intake (mg/day)	Saturated fat intake (g/day)
(Continued from previous page)												
Control tool type ratio, %Electronic education/ website:Mobile app:Mobile & Web-based app:Physical activity tracking device:Web-based app	44: 22: 0: 0: 33	67: 33: 0: 0: 0	67: 33: 0: 0: 0	67: 33: 0: 0: 0	43: 14: 0: 0: 43	50: 50: 0: 0: 0	62: 38: 0: 0: 0	67: 33: 0: 0: 0	50: 33: 0: 17: 0	100: 0: 0: 0: 0	0: 100: 0: 0: 0	50: 50: 0: 0: 0
Intervention tool type ratio, % Mobile app:Web-based app:Web-based & mobile app	33: 67: 0	67: 33: 0	50: 50: 0	50: 50: 0	29: 71: 0	50: 50: 0	77: 23: 0	75: 25: 0	33: 67: 0	0: 100: 0	100: 0: 0	50: 50: 0
Intervention gamification type ratio, % PDF:GS:BA:S:SC:M[c]	11: 0: 11: 11: 0: 67	33: 0: 0: 0: 0: 67	17: 0: 17: 17: 0: 50	17: 0: 17: 17: 0: 50	14: 0: 0: 0: 0: 86	0: 0: 25: 25: 0: 50	15: 0: 23: 8: 0: 54	17: 0: 25: 8: 0: 50	0: 17: 17: 17: 0: 50	0: 100: 0: 0: 0: 0	100: 0: 0: 0: 0: 0	50: 50: 0: 0: 0: 0
Control gamification type ratio, % PDF:GS:M:No gamification[c]	0: 0: 33: 67	0: 0: 0: 100	0: 0: 0: 100	0: 0: 0: 100	0: 0: 43: 57	0: 0: 0: 100	0: 15: 8: 77	0: 17: 8: 75	0: 0: 17: 83	0: 0: 0: 100	0: 0: 0: 100	0: 0: 0: 100
BCT ratio, % Intervention based on a BCT:Intervention not based on a BCT	56: 44	33: 67	33: 67	33: 67	57: 43	25: 75	69: 31	67: 33	67: 33	100: 0	0: 100	50: 50
Funding ratio, % A:I:A + I:NR[d]	78: 11: 11: 0	67: 33: 0: 0	67: 17: 17: 0	67: 17: 17: 0	71: 14: 14: 0	75: 25: 0: 0	54: 23: 23: 0	58: 17: 25: 0	67: 17: 0: 17	0: 0: 0: 100	100: 0: 0: 0	50: 0: 0: 50
Design ratio, %P:C	100: 0	100: 0	100: 0	100: 0	100: 0	100: 0	100: 0	100: 0	100: 0	100: 0	100: 0	100: 0

A = agency funding; BA = badges, achievements, levels, rewards; BCT = behaviour change theory; BMI = body mass index; C = crossover trial; C = challenges; CU = customizable avatars and environments; CVD = cardiovascular disease; DBP = diastolic blood pressure; Edu-web = electronic education/website; GS = heal goal setting; HbA1c = haemoglobin A1c; HDL-C = high-density lipoprotein cholesterol; I = industry funding; kcals = kilocalories; LDL-C = low-density lipoprotein cholesterol; M = multiple forms of gamification; N = number; non-HDL-C = non-high-density lipoprotein cholesterol; NR = not reported; OW/OB = overweight/obese body mass index; P = parallel trial; PB = point-based system; PFD = personalized feedback; S = social support feature; SBP = systolic blood pressure; SC = social competitive; ST = social team; T2DM = type 2 diabetes mellitus; UK = United Kingdom; USA = United States of America; Web-app = web-based app. Trials refer to trial comparisons. [a]Data presented as Median (Range). [b]Professional settings includes interventions recommended by a health care professional, within the health practice setting. Community settings includes interventions administered in the general community. [c]Types of gamification include Personalized Feedback (PFD), Health goal setting (GS), Point-based system (PB), Badges, achievements, levels, rewards (BA), Social support feature (S), Social competitive (SC), Social team (ST), Challenges (C) and/or Customizable avatars and environments (CU) or multiple forms of gamification (M). Types of gamifications in the control groups are also present in the intervention groups as uniform background app features. [d]Agency funding included government, not-for-profit health agencies or University sources. [e]Age measured in participants at baseline.

Table 1: **Summary of main characteristics of included studies.**

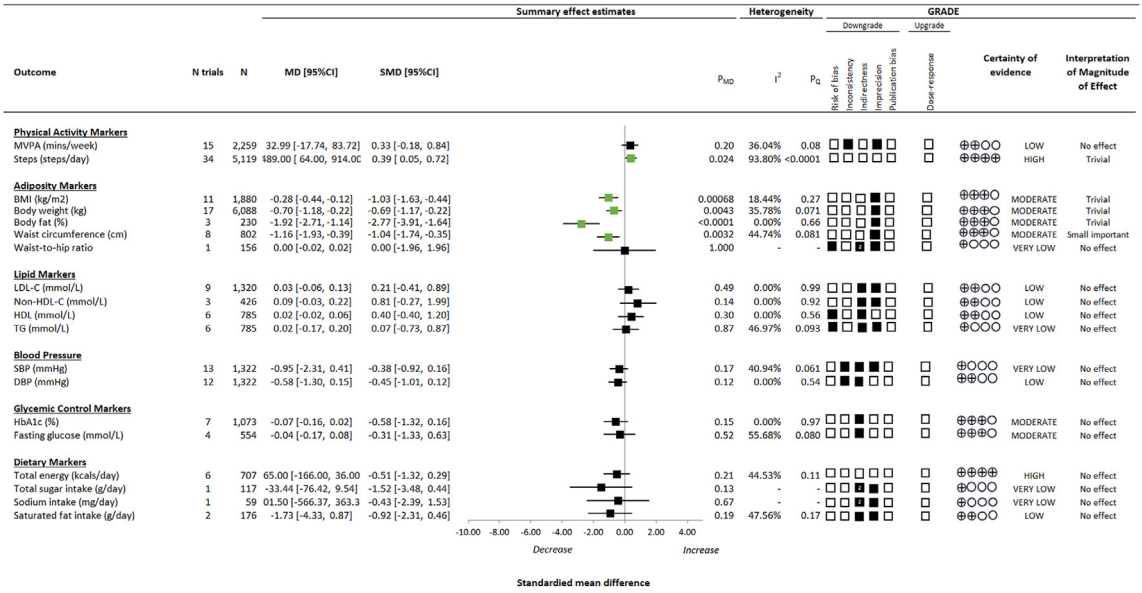

Fig. 2: Summary plot for the effect of using gamification in health applications on physical activity and cardiovascular disease risk factors. Data are weighted mean differences (MD) [95% confidence intervals (CI)] and standardized mean differences (SMD). Analyses were conducted by generic, inverse variance random effects models (when ≥ five trial comparisons available) or fixed effects models (when <five trial comparisons available). Between study heterogeneity was assessed by the Cochran Q statistic, where $P_Q < 0.100$ is considered statistically significant, and quantified by the I^2 statistic, where $I^2 \geq 50\%$ is considered evidence of substantial heterogeneity. Any statistically significant beneficial effects are highlighted in green and significant harm in red. The GRADE of randomized controlled trials are rated as "high" certainty of evidence and can be downgraded by five domains and upgraded by one domain. The white squares represent no downgrades, the filled black squares indicate a single downgrade or upgrades for each outcome, and the black square with a white "2" indicates a double downgrade for each outcome. Criteria for downgrades included risk of bias (downgraded if the majority of trials were considered to be at high risk of bias); inconsistency (downgraded if there was substantial unexplained heterogeneity [$I^2 \geq 50\%$, $P < 0.10$]; indirectness (downgraded if there were factors absent or present relating to the participants, interventions, or outcomes that limited the generalizability of the results); imprecision (downgraded if the 95% confidence interval crossed the minimally important difference [MID] for harm or benefit set as ± 30 min/week for MVPA,[29,30] ±2000 steps/day for Steps,[31] ±0.1 mmol/L for LDL-C, non-HDL-C, HDL-C and triglycerides,[32–34] ±0.3% for HbA1c,[35] ±0.5 mmol/L for fasting glucose,[35,36] ±2 mmHg for SBP and DBP,[37] ±0.4 kg/m^2 for BMI, ±1 kg for body weight, ±2% for body fat percentage[38,39]), ±1 cm for waist circumference,[40] ±0.02 for waist-to-hip ratio,[40,41] ±500 kcals/day for total energy,[42] ±5 g/day for total sugars,[43,44] ±115 mg/day for sodium intake,[43,44] and ±1 g/day for saturated fat intake[43,44]); and publication bias (downgraded if there is evidence of publication bias based on funnel plot asymmetry and/or significant Egger's or Begg's tests ($P < 0.10$) with confirmation by adjustment by Duval and Tweedie trim-and-fill analysis). Criteria for upgrades included a significant dose–response gradient. [a]For the interpretation of the magnitude, we used the MIDs (see above) to assess the importance of magnitude of our pooled estimates using the effect size categories according to new GRADE guidance. We then used the MIDs to assess the importance of the magnitude of our point estimates using the effect size 82 categories according GRADE guidance[52–54] as follows: large effect (≥5x MID); moderate effect (≥2x MID); small important effect (≥1x MID); and trivial/unimportant effect (<1 MID). Abbreviations: BMI = body mass index; CI = confidence interval; DBP = diastolic blood pressure; GRADE = Grading of Recommendations, Assessment, Development and Evaluation; HbA1c = haemoglobin A1c; HDL-C = high-density lipoprotein-cholesterol; LDL-C = low-density lipoprotein-cholesterol; MD = mean difference; MID = minimally important difference; N = number; non-HDL-C = non-high-density lipoprotein-cholesterol; SBP = systolic blood pressure; SMD = standardized mean difference; TG = triglycerides.

Blood pressure

Fig. 2 and Supplemental Figs. S32 and S33 present the effect of gamification on systolic and diastolic blood pressure. No significant effects were observed.

Glycemic control markers

Fig. 2 and Supplemental Figs. S34 and S35 present the effect of gamification on HbA1c and fasting glucose. No significant effects were observed.

Dietary markers

Fig. 2 and Supplemental Figs. S36–S39 present the effect of gamification on dietary intake for nutrients of concern, as assessed by intakes of total energy, sugars, sodium, and saturated fat. No significant effects were observed.

Sensitivity analyses

Supplemental Figs. S40–S54 present the influence analyses for each outcome. Among the physical activity

markers, the removal of the study by either King et al.,[60] or Monroe et al.[101] or Willms et al.,[87] (self-funded investment incentive) resulted in a gain in significance for MVPA. Whereas the systematic removal of each trial did not significantly impact the effect estimate of gamification related to steps; however, the removal of the study by Francis et al.[74] provided an explanation of the evidence of substantial heterogeneity.

Of the adiposity markers, systematic removal of individual studies did not modify the observed significant effectiveness of gamification in reducing BMI, body weight, body fat percentage, or waist circumference. For fasting glucose, an explanation of substantial heterogeneity was provided by the removal of Kim et al.[102] without impacting the significance of the effect.

Systematic removal of individual studies did not impact the effect estimates nor provide explanations for heterogeneity where it was observed in the analyses of LDL-C, HDL-C, fasting glucose, HbA1c, or total energy intake.

Supplemental Table S4 presents a summary of sensitivity analyses for the MVPA and step assessments as there were trial comparisons that reported outcomes using more than one assessment method. MVPA was determined using both the Behavioural Risk Factor Surveillance System (BRFSS) and actigraph methods in one report.[59] Regardless of whether actigraph or BRFSS measurements were utilized, the effect remained non-significant for MVPA. Three trial comparisons assessed steps using two different methods (actigraph and Fitbit).[77,101] Regardless of whether actigraph or Fitbit measurements were utilized, the effectiveness of gamification increasing steps/day remained.

Subgroup analyses

Supplemental Figs. S55–S67 present the subgroup analyses of the effect of gamification on outcomes with >10 trial comparisons. While there were no significant effect modification for any subgroups for steps; for MVPA, there was significant effect modification by study purpose (P = 0.028; where a greater increase were seen for gamified apps targeting increasing mobility/physical activity), and funding source (P = 0.028; where a greater increase was seen for studies funded from agency sources).

For BMI, there was significant effect modification BCT (P = 0.008; where there was a greater decrease for interventions with no mention BCT) and by follow-up (P = 0.036; where a greater decrease was seen for studies), and continent (P = 0.042; where a greater decrease was seen for studies from Europe and South America). For body weight, there was significant effect modification by funding source (P = 0.003; where a greater decrease was seen for studies funded from agency, agency–industry sources and for studies with no reported funding). Additionally, there was significant effect modification by follow-up duration (P = 0.039; where a greater decrease was seen for studies <6 months in duration).

No effect modifications were observed for diastolic blood pressure; however, for systolic blood pressure, there was a significant effect modification by the control group's tool type (P = 0.049) and setting (P = 0.043), where studies comparing gamified vs. non-gamified mobile apps and apps delivered through professional setting showed reductions, and ROB domains 2 (deviations from the intended interventions) (P = 0.042; decreasing effect of some concerns and high ROB) and 4 (measurement of the outcome) (P = 0.030; decreasing effect of low ROB).

Supplemental Figs. S67–S72 present the continuous meta-regression analyses. No associations were observed except for a positive association between follow-up duration and BMI (P = 0.038) and body weight (P = 0.035).

Publication bias

Supplemental Figs. S73–S81 present the funnel plots, and trim-and-fill (where applicable) to assess small study effects for the effect of gamification on MVPA, steps, BMI, body weight, and blood pressure. Formal testing with Egger's and Begg's tests revealed significant publication bias for MVPA, steps, and DBP. The trim-and-fill assessments did not suggest evidence of small study effects across these outcomes as there was no influence on significance or magnitude of effect.

No publication bias analyses were undertaken for body fat percentage, waist circumference, waist-to-hip ratio, nor for assessed lipid, glycemic control, and dietary markers as fewer than ten trial comparisons were available.

GRADE assessment

Fig. 2 and Supplemental Table S5 present the GRADE assessments. The certainty of evidence for the effect of gamification on the primary outcomes of interest ranged from low to high, with steps presenting with a high certainty of evidence (trivial increase), while body weight was considered to have moderate certainty (trivial decrease), owing to a downgrade for imprecision, and MVPA presented with low certainty (no effect).

The certainty of evidence for the effect of gamification on secondary outcomes of interest was moderate for body fat percentage (trivial decrease) and total energy intake (no effect); moderate for BMI (trivial decrease), waist circumference (small important decrease), and glucose control (no effect) measures owing to downgrades for imprecision or indirectness; low for LDL-C (no effect), HDL-C (no effect), diastolic blood pressure (no effect), and saturated fat (no effect) intake owing to downgrades for inconsistency, indirectness, and/or imprecision; and very low for waist-to-hip ratio (no effect), non-HDL-C (no effect), triglycerides (no effect), systolic blood pressure

(no effect), total sugar (no effect), and sodium intake (no effect) owing to downgrades for risk of bias, inconsistency, indirectness, and/or imprecision.

Discussion

To our knowledge, this is the first systematic review and meta-analysis to assess the effect of gamification in digital health apps compared to non-gamified counterparts on physical activity and cardiometabolic risk factors. Most health apps targeted physical activity measures or weight loss. Gamified interventions compared to a non-gamified control resulted in trivial increases in steps, and reductions in BMI and body weight, and small important reductions in body fat and waist circumference, with no change in other outcomes assessed.

Health apps with the use of gamification to support physical activity has been the most researched.[103] The significant improvement effect on a measure of physical activity in the form of steps found in the present study is similar to that found in a previously conducted systematic review and meta-analysis. Mazeas et al. found that apps using gamification targeting physical activity led to significant increases in physical activity compared to non-gamified app controls.[104] Given that this field is rapidly emerging, their search date in 2020 resulted in its inclusion of only 7 trials compared to the 34 included for steps and 15 for MVPA in the present study. Furthermore, their study combined both adolescents and adults, as well as various measures of physical activity as their outcome. Interestingly, while gamification significantly impacted step count, it was not observed to significantly affect MVPA in the present analysis. This may be because the interventions were not targeting moderate or vigorous physical activity. Furthermore, it may be more challenging to encourage MVPA as it is a more complex and less understood metric compared to steps to the general public.[105] It may also be challenging to increase the intensity of physical activity among low-active, sedentary, and/or older adults, and there may be less barriers to incorporating lower-intensity physical activity, such as walking, into daily activities.[106] No other systematic reviews and meta-analyses have been conducted on exploring other health outcomes comparing gamified mobile health interventions to non-gamified versions. However, one systematic review of health apps with gamification elements compared to a non-app control found improvements in medication adherence[107] and another that gamified apps compared to usual care or other non-app controls resulted in greater improvements in behaviours and health outcomes, such as diabetes and heart failure self-management and medication adherence, in secondary prevention patients.[108]

Various systematic reviews and meta-analyses have been conducted exploring a variety of digital interventions without consideration of gamification and have demonstrated inconsistent effects on cardiometabolic health outcomes. Zheng et al. showed significant weight loss (9 trials) but no change in physical activity (6 trials) when comparing health apps to any control in healthy participants.[5] In another recent umbrella meta-analysis, Singh et al. observed that interventions involving mobile apps, web- and short message service (SMS)-based strategies compared to various controls increase steps (5 trials), MVPA (3 trials), sleep quality (2 trials), along with fruit and vegetable consumption (3 trials), while reducing sedentary behaviour (2 trials), energy (4 trials) and saturated fat (1 trial) intake, as well as body weight (11 trials).[6] There is limited research on health apps targeting CVD risk factors. This may explain the lack of effect observed in the present analyses on established CVD risk factors since the majority of trials assessed health apps targeting physical activity or weight loss. A systematic review and meta-analysis of digital interventions targeting CVD risk factors included a broad definition of eligible interventions spanning telehealth to self-management websites with healthcare provider support.[109] This study of 47 randomized controlled trials demonstrated significant yet modest improvements across CVD risk factors, however, effects were larger when combined with human support and effects declined over time.[109] The scalability of interventions requiring the support of allied health professionals is limited due to cost. However, health apps with engagement features such as gamification have the potential to provide interventions with broader reach.

Mobile health interventions with gamification may be an effective tool for supporting cardiometabolic health for several reasons related to intrinsic motivation, goal setting and progress tracking, provision of feedback, social interaction and support, personalization, and adaptation.[13,110] Gamification elements such as points, badges, leaderboards, and challenges can tap into individuals' intrinsic motivation, making tasks more engaging and enjoyable.[13] This could be particularly effective for younger individuals who are more accustomed to digital technologies and game-like experiences. However, older individuals may also respond positively to well-designed gamified interventions that provide clear benefits and feedback.[110,111] Gamification provides mechanisms for goal setting and progress tracking, which can enhance individuals' sense of accomplishment and self-efficacy. By breaking down health-related tasks into smaller, achievable, time-specific steps, gamified interventions can help individuals stay motivated and committed to their health goals.[112] This aspect can be beneficial for individuals of all ages, especially those managing chronic conditions or seeking to adopt healthier lifestyles. Gamified app interventions incorporating social elements, such as peer competitions, collaboration, and social support networks, can foster a sense of community and

accountability, encouraging individuals to engage more actively in their health behaviours.[113] For instance, younger individuals may be motivated by friendly competition and social recognition, while older individuals may value the opportunity to connect with peers facing similar health challenges. Gamified app interventions leveraging principles of personalization and adaptation to tailor the experience to individual preferences, needs, and capabilities may enhance relevance and effectiveness across diverse user populations.[114] For example, individuals with specific health conditions may benefit from personalized health education content and tailored behaviour change strategies. When gamified app interventions integrate evidence-based behaviour change techniques, such as goal setting, self-monitoring, feedback, rewards, and social support, they are designed to promote positive behaviour change by targeting key psychological mechanisms and cognitive processes.[11,89,115] Depending on the target population and context, certain techniques may be more effective than others as motivational factors may vary across age groups,[116,117] or according to individual intrinsic and extrinsic factors.[118] Thus, there are several reasons why gamified apps may be effective for various individuals. However, an important aspect to consider is the possible additional burden or distraction that gamification may add to app interventions.[13] The present study included trials which were all in young to middle aged adults and there was no effect modification demonstrated by age in continuous subgroup analyses. Thus, future trials are needed in various age groups to understand whether health apps with gamification is uniformly effective across ages or whether they may vary by type of gamification. Determining the appropriate use and combination of approaches, where applicable would be an important future step in optimizing the potential use of gamification in health apps.

The present systematic review and meta-analysis has several strengths. It reports on a comprehensive search and selection process to identify eligible trials. The totality of available evidence from eligible intervention trials with a suitable active control group were collated and synthesized, giving greater protection against bias. Possible sources of heterogeneity were methodically explored. Finally, the GRADE approach was utilized to assess the overall certainty of evidence.

This study is not without limitations. First, despite the inclusion of randomized controlled trials, waist-to-hip ratio, non-HDL-C, triglycerides, and HDL-C, meta-analyses were downgraded for serious ROB, largely due to missing data. Second, there was evidence of unexplained inconsistency for MVPA, SBP, and DBP. Third, there was evidence of serious to very serious indirectness for the majority (10/19) of outcomes due to a small number of trial comparisons, the inclusion of participants with specific health conditions, or app interventions targeting intermediate cardiometabolic outcomes, limiting generalizability of results. Fourth, there was evidence of imprecision in the majority (10/19) of pooled analyses, such that the prespecified MID was crossed indicating clinically important benefit could not be confirmed and/or harm could not be ruled out. Fifth, subgroup and publication bias analyses were unable to be conducted for many of the outcomes owing to the small number of available trials (<10 trials).

Our research holds significant implications for the design of effective health apps by optimizing the delivery of health interventions. Our work supports the use of gamification in health apps targeting increased physical activity and weight loss. Given that a broad review of the health app space found only 64 of 1680 (4%) of health apps included gamification[119] there is an opportunity to improve effectiveness of health apps. Furthermore, there was a lack of apps targeting cardiometabolic outcomes, calling for more work in this area. Novel findings include the lack of effect modification by follow-up duration in physical activity outcomes, where studies ≥6-months saw similar effects compared to those <6-months. Thus, gamification features in health apps may be effective in supporting sustained behaviour change to increase physical activity. For adiposity outcomes, there was a tendency for a greater reduction in shorter follow-up (<6 months) vs. longer follow-ups (≥6 months), which indicates that, gamification may not be a sole feature to guarantee success. Future works should include developing and assessing health apps for usability and effectiveness in their target population.[120] However, assessment is severely lacking, given over 300,000 health apps may be found in app stores, yet most are untested.[121] Furthermore, future health apps should be assessed for quality to explore important aspects from reliability of information to safety[122] and consideration of mapping app features to behaviour change theories[15] to enhance effectiveness.[115]

In conclusion, current evidence provides a good indication that gamification features in apps targeting physical activity or weight loss result in trivial improvements in steps per day, BMI, and body weight, and small important improvements in body fat and waist circumference, compared to non-gamified apps. No effects were observed for other cardiometabolic risk factors or dietary markers. More high-quality studies investigating health apps with gamification designed to target cardiometabolic risk factors for a variety of populations is warranted.

Contributors

Conceptualization: SKN, MK, JLS, LC; methodology: SKN, JLS, LC; acquisition of data: SKN, MK, KR; formal analysis, SKN, MK, KR, SAC; Drafting the manuscript: SKN, MK; review and editing, SKN, MK, KR, SAC, SM, GD, CWCK, JLS, LC. All authors had access to the data for verification and have read and agreed to the published version of the manuscript.

Data sharing statement

The data described in the manuscript and analytic code may be made available upon on request.

Declaration of interests

SKN was supported by a postdoctoral fellowship from the Canadian Institutes of Health Research (CIHR, MFE-171207) and is a volunteer member of the not-for profit group Plant-Based Canada. MEK and SA-C are funded by a CIHR Canadian Graduate Scholarship Doctoral Award (funding reference number 181403 and 476,251, respectively). S.A.-C. has received an honorarium from the international food information council (IFIC) for a talk on artificial sweeteners, the gut microbiome, and the risk for diabetes. CWCK has received grants or research support from the Advanced Food Materials Network, Agriculture and Agri-Foods Canada (AAFC), Almond Board of California, Barilla, Canadian Institutes of Health Research (CIHR), Canola Council of Canada, International Nut and Dried Fruit Council, International Tree Nut Council Research and Education Foundation, Loblaw Brands Ltd, the Peanut Institute, Pulse Canada and Unilever. He has received in-kind research support from the Almond Board of California, Barilla, California Walnut Commission, Kellogg Canada, Loblaw Companies, Nutrartis, Quaker (PepsiCo), the Peanut Institute, Primo, Unico, Unilever, WhiteWave Foods/Danone. He has received travel support and/or honoraria from the Barilla, California Walnut Commission, Canola Council of Canada, General Mills, International Nut and Dried Fruit Council, International Pasta Organization, Lantmannen, Loblaw Brands Ltd, Nutrition Foundation of Italy, Oldways Preservation Trust, Paramount Farms, the Peanut Institute, Pulse Canada, Sun-Maid, Tate & Lyle, Unilever and White Wave Foods/Danone. He has served on the scientific advisory board for the International Tree Nut Council, International Pasta Organization, McCormick Science Institute and Oldways Preservation Trust. He is a founding member of the International Carbohydrate Quality Consortium (ICQC), Executive Board Member of the Diabetes and Nutrition Study Group (DNSG) of the European Association for the Study of Diabetes (EASD), is on the Clinical Practice Guidelines Expert Committee for Nutrition Therapy of the EASD and is a Director of the Toronto 3D Knowledge Synthesis and Clinical Trials foundation. JLS has received research support from the Canadian Foundation for Innovation, Ontario Research Fund, Province of Ontario Ministry of Research and Innovation and Science, Canadian Institutes of health Research (CIHR), Diabetes Canada, American Society for Nutrition (ASN), National Honey Board (U.S. Department of Agriculture [USDA] honey "Checkoff" program), Institute for the Advancement of Food and Nutrition Sciences (IAFNS), Pulse Canada, Quaker Oats Center of Excellence, INC International Nut and Dried Fruit Council Foundation, The United Soybean Board (USDA soy "Checkoff" program), Protein Industries Canada (a Government of Canada Global Innovation Cluster), Almond Board of California, European Fruit Juice Association, The Tate and Lyle Nutritional Research Fund at the University of Toronto, The Glycemic Control and Cardiovascular Disease in Type 2 Diabetes Fund at the University of Toronto (a fund established by the Alberta Pulse Growers), The Plant Protein Fund at the University of Toronto (a fund which has received contributions from IFF among other donors), The Plant Milk Fund at the University of Toronto (a fund established by the Karuna Foundation through Vegan Grants), and The Nutrition Trialists Network Fund at the University of Toronto (a fund established by donations from the Calorie Control Council and Physicians Committee for Responsible Medicine). He has received food donations to support randomized controlled trials from the Almond Board of California, California Walnut Commission, Danone, Nutrartis, Soylent, and Dairy Farmers of Canada. He has received travel support, speaker fees and/or honoraria from Danone, FoodMinds LLC, Nestlé, Abbott, General Mills, Nutrition Communications, International Food Information Council (IFIC), Arab Beverages, International Sweeteners Association, Association Calorie Control Council, and Phynova. He has or has had ad hoc consulting arrangements with Perkins Coie LLP, Tate & Lyle, Ingredion, and Brightseed. He is on the Clinical Practice Guidelines Expert Committees of Diabetes Canada, European Association for the study of Diabetes (EASD), Canadian Cardiovascular Society (CCS), and Obesity Canada/Canadian Association of Bariatric Physicians and Surgeons. He serves as an unpaid member of the Board of Trustees of IAFNS. He is a Director at Large of the Canadian Nutrition Society (CNS), founding member of the International Carbohydrate Quality Consortium (ICQC), Executive Board Member of the Diabetes and Nutrition Study Group (DNSG) of the EASD, and Director of the Toronto 3D Knowledge Synthesis and Clinical Trials foundation. His spouse is an employee of AB InBev. LC has received research support from the Canadian Institutes of health Research (CIHR), Protein Industries Canada (a Government of Canada Global Innovation Clusters), The United Soybean Board (USDA soy "Checkoff" program), and the Alberta Pulse Growers Association.

Acknowledgements

We wish to thank the authors of the included reports, especially those who shared additional information from their work.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.eclinm.2024.102798.

References

1 Roth GA, Mensah GA, Johnson CO, et al. Global burden of cardiovascular diseases and risk factors, 1990–2019. *J Am Coll Cardiol*. 2020;76(25):2982–3021.
2 Mozaffarian D, Benjamin EJ, Go AS, et al. Heart disease and stroke statistics—2016 update. *Circulation*. 2016;133(4).
3 Iribarren SJ, Akande TO, Kamp KJ, Barry D, Kader YG, Suelzer E. Effectiveness of mobile apps to promote health and manage disease: systematic review and meta-analysis of randomized controlled trials. *JMIR Mhealth Uhealth*. 2021;9(1):e21563.
4 Cucciniello M, Petracca F, Ciani O, Tarricone R. Development features and study characteristics of mobile health apps in the management of chronic conditions: a systematic review of randomised trials. *NPJ Digit Med*. 2021;4(1):144.
5 Zheng S, Edney SM, Goh CH, et al. Effectiveness of holistic mobile health interventions on diet, and physical, and mental health outcomes: a systematic review and meta-analysis. *EClinicalMedicine*. 2023;66:102309.
6 Singh B, Ahmed M, Staiano AE, et al. A systematic umbrella review and meta-meta-analysis of eHealth and mHealth interventions for improving lifestyle behaviours. *NPJ Digit Med*. 2024;7:179. Nature Research.
7 Patel MS, Small DS, Harrison JD, et al. Effectiveness of behaviorally designed gamification interventions with social incentives for increasing physical activity among overweight and obese adults across the United States: the STEP UP randomized clinical trial. *JAMA Intern Med*. 2019;179(12):1624–1632.
8 Marin-Gomez FX, Garcia-Moreno Marchán R, Mayos-Fernandez A, et al. Exploring efficacy of a serious game (tobbstop) for smoking cessation during pregnancy: randomized controlled trial. *JMIR Serious Games*. 2019;7(1):e12835.
9 El-Hilly AA, Iqbal SS, Ahmed M, et al. Game on? Smoking cessation through the gamification of mHealth: a longitudinal qualitative study. *JMIR Serious Games*. 2016;4(2):e18.
10 King D, Greaves F, Exeter C, Darzi A. 'Gamification': influencing health behaviours with games. *J R Soc Med*. 2013;106(3):76–78.
11 Cugelman B. Gamification: what it is and why it matters to digital health behavior change developers. *JMIR Serious Games*. 2013;1(1):e3.
12 Cotton V, Patel MS. Gamification use and design in popular health and fitness mobile applications. *Am J Health Promot*. 2019;33(3):448–451.
13 Liu D, Santhanam R, Webster J. Toward meaningful engagement: a framework for design and research of gamified information systems. *MIS Q*. 2017;41(4):1011–1034. Available from: https://misq.org/toward-meaningful-engagement-a-framework-for-design-and-research-of-gamified-information-systems.html.
14 Michie S, van Stralen MM, West R. The behaviour change wheel: a new method for characterising and designing behaviour change interventions. *Implement Sci*. 2011;6(1):42.
15 Michie S, Wood CE, Johnston M, Abraham C, Francis JJ, Hardeman W. Behaviour change techniques: the development and evaluation of a taxonomic method for reporting and describing

behaviour change interventions (a suite of five studies involving consensus methods, randomised controlled trials and analysis of qualitative data). *Health Technol Assess*. 2015;19(99):1–188.
16 Michie S, Richardson M, Johnston M, et al. The behavior change technique taxonomy (v1) of 93 hierarchically clustered techniques: building an international consensus for the reporting of behavior change interventions. *Ann Behav Med*. 2013;46(1):81–95.
17 Cumpston M, Li T, Page MJ, et al. Updated guidance for trusted systematic reviews: a new edition of the cochrane handbook for systematic reviews of interventions. *Cochrane Database Syst Rev*. 2019;10(10):ED000142.
18 Page MJ, McKenzie JE, Bossuyt PM, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ*. 2021;372:n71.
19 Moher D, Liberati A, Tetzlaff J, Altman DG. Preferred reporting Items for systematic reviews and meta-analyses: the PRISMA statement. *PLoS Med*. 2009;6(7):e1000097.
20 Government of Canada HC. *Nutrition labelling: front-of-package nutrition symbol*; 2024 [cited 2024 Mar 9]. Available from: https://www.canada.ca/en/health-canada/services/food-nutrition/nutrition-labelling/front-package.html.
21 Porbital. *PlotDigitizer*; 2023 [cited 2023 Sep 21]. Available from: https://plotdigitizer.com/app.
22 Higgins JPT, Altman DG, Gøtzsche PC, et al. The Cochrane Collaboration's tool for assessing risk of bias in randomised trials. *BMJ*. 2011;343:d5928.
23 Higgins J, Thomas J, Chandler J, et al., eds. *Cochrane handbook for systematic reviews of interventions version 6.3 (updated February 2022)*. Cochrane; 2022. [cited 2023 Sep 21]. Available from: www.training.cochrane.org/handbook, 2022 Feb.
24 McGrath S, Sohn H, Steele R, Benedetti A. Meta-analysis of the difference of medians. *Biom J*. 2020;62(1):69–98.
25 Friedewald WT, Levy RI, Fredrickson DS. Estimation of the concentration of low-density lipoprotein cholesterol in plasma, without use of the preparative ultracentrifuge. *Clin Chem*. 1972;18(6):499–502.
26 Ku HH. Notes on the use of propagation of error formulas. *J Res Natl Bur Stand (1934)*. 1966;70C(4):263.
27 DerSimonian R, Laird N. Meta-analysis in clinical trials. *Control Clin Trials*. 1986;7(3):177–188.
28 Tufanaru C, Munn Z, Stephenson M, Aromataris E. Fixed or random effects meta-analysis? Common methodological issues in systematic reviews of effectiveness. *Int J Evid Based Healthc*. 2015;13(3):196–207.
29 Higgins JPT. Measuring inconsistency in meta-analyses. *BMJ*. 2003;327(7414):557–560.
30 Center for Disease Control and Prevention. *How much physical activity do adults need?*; 2022 [cited 2024 Jan 9]. Available from: https://www.cdc.gov/physicalactivity/basics/adults/index.htm.
31 Government of Canada. *Physical activity tips for adults (18-64 years)*; 2018 [cited 2023 Oct 19]. Available from: https://www.canada.ca/en/public-health/services/publications/healthy-living/physical-activity-tips-adults-18-64-years.html.
32 Sigal RJ, Armstrong MJ, Bacon SL, et al. Physical activity and diabetes. *Can J Diabetes*. 2018;42:S54–S63.
33 Johnston BC, Kanters S, Bandayrel K, et al. Comparison of weight loss among named diet programs in overweight and obese adults. *JAMA*. 2014;312(9):923.
34 Ge L, Sadeghirad B, Ball GDC, et al. Comparison of dietary macronutrient patterns of 14 popular named dietary programmes for weight and cardiovascular risk factor reduction in adults: systematic review and network meta-analysis of randomised trials. *BMJ*. 2020;369:m696.
35 Sacks FM, Bray GA, Carey VJ, et al. Comparison of weight-loss diets with different compositions of fat, Protein, and Carbohydrates. *N Engl J Med*. 2009;360(9):859–873.
36 Molarius A, Seidell J, Sans S, Tuomilehto J, Kuulasmaa K. Waist and hip circumferences, and waist-hip ratio in 19 populations of the WHO MONICA Project. *Int J Obes*. 1999;23(2):116–125.
37 Cannon CP, Blazing MA, Giugliano RP, et al. Ezetimibe added to statin therapy after acute coronary syndromes. *N Engl J Med*. 2015;372(25):2387–2397.
38 Ference BA, Cannon CP, Landmesser U, Lüscher TF, Catapano AL, Ray KK. Reduction of low density lipoprotein-cholesterol and cardiovascular events with proprotein convertase subtilisin-kexin type 9 (PCSK9) inhibitors and statins: an analysis of FOURIER, SPIRE, and the Cholesterol Treatment Trialists Collaboration. *Eur Heart J*. 2018;39(27):2540–2545.
39 Cholesterol Treatment Trialists' (CTT) Collaboration. Efficacy and safety of more intensive lowering of LDL cholesterol: a meta-analysis of data from 170 000 participants in 26 randomised trials. *Lancet*. 2010;376(9753):1670–1681.
40 European Medicines Agency. *Guideline on clinical investigation of medicinal products in the treatment or prevention of diabetes mellitus*; 2024 [cited 2024 Jan 8]. Available from: https://www.ema.europa.eu/en/clinical-investigation-medicinal-products-treatment-or-prevention-diabetes-mellitus-scientific-guideline.
41 Nathan DM, Kuenen J, Borg R, Zheng H, Schoenfeld D, Heine RJ. Translating the A1C assay into estimated average glucose values. *Diabetes Care*. 2008;31(8):1473–1478.
42 Lewington S, Clarke R, Qizilbash N, Peto R, Collins R, Prospective Studies Collaboration. Age-specific relevance of usual blood pressure to vascular mortality: a meta-analysis of individual data for one million adults in 61 prospective studies. *Lancet*. 2002;360(9349):1903–1913.
43 Wharton S, Pedersen SD, Lau DCW, Sharma AM. Weight management in diabetes. *Can J Diabetes*. 2018;42:S124–S129.
44 Health Canada. *Nutrition labelling: nutrition facts table*; 2024 [cited 2024 Jan 9]. Available from: https://www.canada.ca/en/health-canada/services/food-nutrition/nutrition-labelling/nutrition-facts-tables.html.
45 Health Canada. *Nutrition labelling – table of daily values*; 2022 [cited 2024 Jan 9]. Available from: https://www.canada.ca/en/health-canada/services/technical-documents-labelling-requirements/table-daily-values/nutrition-labelling.html.
46 Sterne JA, Gavaghan D, Egger M. Publication and related bias in meta-analysis: power of statistical tests and prevalence in the literature. *J Clin Epidemiol*. 2000;53(11):1119–1129.
47 Egger M, Davey Smith G, Schneider M, Minder C. Bias in meta-analysis detected by a simple, graphical test. *BMJ*. 1997;315(7109):629–634.
48 Begg CB, Mazumdar M. Operating characteristics of a rank correlation test for publication bias. *Biometrics*. 1994;50(4):1088–1101.
49 Duval S, Tweedie R. Trim and fill: a simple funnel-plot-based method of testing and adjusting for publication bias in meta-analysis. *Biometrics*. 2000;56(2):455–463.
50 Schünemann H, Brożek J, Guyatt G, Oxman A. *GRADE handbook*; 2013 [cited 2023 Sep 21]. Available from: https://gdt.gradepro.org/app/handbook/handbook.html.
51 GRADEpro GDT. *GRADEpro guideline development tool [Software]. McMaster University*. Evidence Prime, Inc.; 2020. Available from: https://gradepro.org.
52 The Cochrane Collaboration. *RoB 2: a revised Cochrane risk-of-bias tool for randomized trials* 2024 [cited 2023 Nov 18]. Available from: RoB 2: A revised Cochrane risk-of-bias tool for randomized trials.
53 Guyatt G, Oxman AD, Akl EA, et al. GRADE guidelines: 1. Introduction-GRADE evidence profiles and summary of findings tables. *J Clin Epidemiol*. 2011;64(4):383–394.
54 Johnston BC, Ebrahim S, Carrasco-Labra A, et al. Minimally important difference estimates and methods: a protocol. *BMJ Open*. 2015;4:7953. Available from: http://bmjopen.bmj.com/.
55 Schünemann HJ, Wiercioch W, Brozek J, et al. GRADE Evidence to Decision (EtD) frameworks for adoption, adaptation, and de novo development of trustworthy recommendations: GRADE-ADOLOPMENT. *J Clin Epidemiol*. 2017;81:101–110.
56 Ambeba EJ, Ye L, Sereika SM, et al. The use of mHealth to deliver tailored messages reduces reported energy and fat intake. *J Cardiovasc Nurs*. 2015;30(1):35–43.
57 Beleigoli A, Andrade AQ, De Fatima Diniz M, Ribeiro AL. Personalized web-based weight loss behavior change program with and without dietitian online coaching for adults with overweight and obesity: randomized controlled trial. Available from: https://clinicaltrials.gov/ct2/show/NCT03435445.
58 Edney SM, Olds TS, Ryan JC, et al. A social networking and gamified app to increase physical activity: cluster RCT. *Am J Prev Med*. 2020;58(2):e51–e62.
59 Hageman PA, Pullen CH, Hertzog M, Pozehl B, Eisenhauer C, Boeckner LS. Web-based interventions alone or supplemented with peer-led support or professional email counseling for weight loss and weight maintenance in women from rural communities: results of a clinical trial. *J Obes*. 2017;2017:1–21.
60 King AC, Hekler EB, Grieco LA, et al. Effects of three motivationally targeted mobile device applications on initial physical activity and sedentary behavior change in midlife and older adults: a randomized trial. *PLoS One*. 2016;11(6):e0156370.

61 Kurtzman GW, Day SC, Small DS, et al. Social incentives and gamification to promote weight loss: the LOSE IT randomized, controlled trial. *J Gen Intern Med*. 2018;33(10):1669–1675.
62 Patel MS, Asch DA, Rosin R, et al. Individual versus team-based financial incentives to increase physical activity: a randomized, controlled trial. *J Gen Intern Med*. 2016;31(7):746–754.
63 Patel MS, Benjamin EJ, Volpp KG, et al. Effect of a game-based intervention designed to enhance social incentives to increase physical activity among families: the BE FIT randomized clinical trial. *JAMA Intern Med*. 2017;177(11):1586–1593.
64 Shin DW, Yun JM, Shin JH, et al. Enhancing physical activity and reducing obesity through smartcare and financial incentives: a pilot randomized trial. *Obesity*. 2017;25(2):302–310.
65 Staite E, Bayley A, Al-Ozairi E, et al. A wearable technology delivering a web-based diabetes prevention program to people at high risk of type 2 diabetes: randomized controlled trial. *JMIR Mhealth Uhealth*. 2020;8(7):e15448.
66 Zhang J, Jemmott JB. Mobile app-based small-group physical activity intervention for young african American women: a pilot randomized controlled trial. *Prev Sci*. 2019;20(6):863–872.
67 Agarwal AK, Waddell KJ, Small DS, et al. Effect of gamification with and without financial incentives to increase physical activity among veterans classified as having obesity or overweight. *JAMA Netw Open*. 2021;4(7):e2116256.
68 Brame J, Kohl J, Wurst R, et al. Health effects of a 12-week web-based lifestyle intervention for physically inactive and overweight or obese adults: study protocol of two randomized controlled clinical trials. *Int J Environ Res Public Health*. 2022;19(3):1393.
69 Browne JD, Boland DM, Baum JT, et al. Lifestyle modification using a wearable biometric ring and guided feedback improve sleep and exercise behaviors: a 12-month randomized, placebo-controlled study. *Front Physiol*. 2021;12:777874.
70 Burke LE, Sereika SM, Bizhanova Z, et al. The effect of tailored, daily, smartphone feedback to lifestyle self-monitoring on weight loss at 12 Months: the SMARTER randomized clinical trial. *J Med Internet Res*. 2022;24(7):e38243.
71 Ek A, Alexandrou C, Söderström E, et al. Effectiveness of a 3-month mobile phone–based behavior change program on active transportation and physical activity in adults: randomized controlled trial. *JMIR Mhealth Uhealth*. 2020;8(6):e18531.
72 Ferrante JM, Devine KA, Bator A, et al. Feasibility and potential efficacy of commercial mHealth/eHealth tools for weight loss in African American breast cancer survivors: pilot randomized controlled trial. *Transl Behav Med*. 2020;10(4):938–948.
73 Fichtner UA, Armbruster C, Bischoff M, et al. Evaluation of an interactive web-based health program for weight loss—a randomized controlled trial. *Int J Environ Res Public Health*. 2022;19(22):15157.
74 Francis SL, Simmering JE, Polgreen LA, et al. Gamifying accelerometer use increases physical activity levels of individuals predisposed to type II diabetes. *Prev Med Rep*. 2021;23:101426.
75 Greysen SR, Changolkar S, Small DS, et al. Effect of behaviorally designed gamification with a social support partner to increase mobility after hospital discharge. *JAMA Netw Open*. 2021;4(3):e210952.
76 Lewey J, Murphy S, Zhang D, et al. Effectiveness of a text-based gamification intervention to improve physical activity among postpartum individuals with hypertensive disorders of pregnancy. *JAMA Cardiol*. 2022;7(6):591.
77 Middelweerd A, Mollee J, Klein MM, Manzoor A, Brug J, te Velde SJ. The use and effects of an app-based physical activity intervention "Active2Gether" in young adults: quasi-experimental trial. *JMIR Form Res*. 2020;4(1):e12538.
78 Mönninghoff A, Fuchs K, Wu J, Albert J, Mayer S. The effect of a future-self avatar mobile health intervention (FutureMe) on physical activity and food purchases: randomized controlled trial. *J Med Internet Res*. 2022;24(7):e32487.
79 Patel MS, Small DS, Harrison JD, et al. Effect of behaviorally designed gamification with social incentives on lifestyle modification among adults with uncontrolled diabetes. *JAMA Netw Open*. 2021;4(5):e2110255.
80 Patel MS, Bachireddy C, Small DS, et al. Effect of goal-setting approaches within a gamification intervention to increase physical activity among economically disadvantaged adults at elevated risk for major adverse cardiovascular events. *JAMA Cardiol*. 2021;6(12):1387.
81 Persell SD, Peprah YA, Lipiszko D, et al. Effect of home blood pressure monitoring via a smartphone hypertension coaching application or tracking application on adults with uncontrolled hypertension: a randomized clinical trial. *JAMA Netw Open*. 2020;3(3):e200255.
82 Radhakrishnan K, Julien C, Baranowski T, et al. Feasibility of a sensor-controlled digital game for heart failure self-management: randomized controlled trial. *JMIR Serious Games*. 2021;9(4):e29044.
83 Steinberg DM, Kay MC, Svetkey LP, et al. Feasibility of a digital health intervention to improve diet quality among women with high blood pressure: randomized controlled feasibility trial. *JMIR Mhealth Uhealth*. 2020;8(12):e17536.
84 Cáceres NA, Yu Q, Lauzon M, et al. Supplementing a widely available weight loss program with gamified inhibitory control training: a randomized pilot study. *Obes Sci Pract*. 2022;8(6):775–783.
85 Kohl J, Brame J, Centner C, et al. Effects of a web-based lifestyle intervention on weight loss and cardiometabolic risk factors in adults with overweight and obesity: randomized controlled clinical trial. *J Med Internet Res*. 2023;25:e43426.
86 Rahimi-Ardabili H, Reynolds RC, Zwar N, Briggs N, Vartanian LR. The efficacy of an online behavioural intervention for improving dietary habits with a focus on self-compassion, goal-setting and self-monitoring: a randomised controlled trial. *medRxiv preprint*. 2023. https://doi.org/10.1101/2023.04.18.23288716, 1–28.
87 Willms A, Rhodes RE, Liu S. Effects of mobile-based financial incentive interventions for adults at risk of developing hypertension: feasibility randomized controlled trial. *JMIR Form Res*. 2023;7:e36562.
88 Xu L, Tong Q, Zhang X, et al. Smartphone-based gamification intervention to increase physical activity participation among patients with coronary heart disease: a randomized controlled trial. *J Telemed Telecare*. 2023. https://doi.org/10.1177/1357633X221150943.
89 Dickinson WP, Glasgow RE, Fisher L, et al. Use of a website to accomplish health behavior change: if you build it, will they come? And will it work if they do? *J Am Board Fam Med*. 2013;26(2):168–176.
90 Graham AL, Papandonatos GD, Cha S, et al. Improving adherence to smoking cessation treatment: intervention effects in a web-based randomized trial. *Nicotine Tob Res*. 2017;19(3):324–332.
91 Mailey EL, Huberty J, Irwin BC. Feasibility and effectiveness of a web-based physical activity intervention for working mothers. *J Phys Act Health*. 2016;13(8):822–829.
92 Mason D, Gilbert H, Sutton S. Effectiveness of web-based tailored smoking cessation advice reports (iQuit): a randomized trial. *Addiction*. 2012;107(12):2183–2190.
93 Mora-Gonzalez J, Pérez-López IJ, Esteban-Cornejo I, Delgado-Fernández M. A gamification-based intervention program that encourages physical activity improves cardiorespiratory fitness of college students: 'the matrix refvolution program'. *Int J Environ Res Public Health*. 2020;17(3):877.
94 Riva S, Camerini AL, Allam A, Schulz PJ. Interactive sections of an Internet-based intervention increase empowerment of chronic back pain patients: randomized controlled trial. *J Med Internet Res*. 2014;16(8):e180.
95 Robertson MC, Lyons EJ, Liao Y, Baum ML, Basen-Engquist KM. Gamified text messaging contingent on device-measured steps: randomized feasibility study of a physical activity intervention for cancer survivors. *JMIR Mhealth Uhealth*. 2020;8(11):e18364.
96 Severson H, Gordon J, Danaher B, Akers L. ChewFree.com: evaluation of a web-based cessation program for smokeless tobacco users. *Nicotine Tob Res*. 2008;10(2):381–391.
97 Patnaik L, Panigrahi SK, Sahoo AK, Mishra D, Muduli AK, Beura S. Effectiveness of mobile application for promotion of physical activity among newly diagnosed patients of type II diabetes -A randomized controlled trial. *Int J Prev Med*. 2022;13(1):54.
98 Okaniwa F, Yoshida H. Evaluation of dietary management using artificial intelligence and human interventions: nonrandomized controlled trial. *JMIR Form Res*. 2022;6(6):e30630.
99 Pritschmann R, Jake-schoffman D, Monroe C. Moderators of physical activity and sedentary behavior changes in an e/mHealth intervention. *Obesity*. 2020;28(52):40–187.
100 Bernstein MA, Tucker KL, Ryan ND, et al. Higher dietary variety is associated with better nutritional status in frail elderly people. *J Am Diet Assoc*. 2002;102:1096–1104.
101 Monroe CM, Cai B, Edney S, et al. Harnessing technology and gamification to increase adult physical activity: a cluster randomized controlled trial of the Columbia Moves pilot. *Int J Behav Nutr Phys Activ*. 2023;20(1):129.

102 Kim G, Kim S, Lee Y Bin, Jin SM, Hur KY, Kim JH. A randomized controlled trial of an app-based intervention on physical activity and glycemic control in people with type 2 diabetes. *BMC Med*. 2024;22(1):185.
103 Johnson D, Deterding S, Kuhn KA, Staneva A, Stoyanov S, Hides L. Gamification for health and wellbeing: a systematic review of the literature. *Internet Interv*. 2016;6:89–106.
104 Mazeas A, Duclos M, Pereira B, Chalabaev A. Evaluating the effectiveness of gamification on physical activity: systematic review and meta-analysis of randomized controlled trials. *J Med Internet Res*. 2022;24(1):e26779.
105 Hamaya R, Shiroma EJ, Moore CC, Buring JE, Evenson KR, Lee IM. Time- vs step-based physical activity metrics for health. *JAMA Intern Med*. 2024;184(7):718–725.
106 Lewis BA, Napolitano MA, Buman MP, Williams DM, Nigg CR. Future directions in physical activity intervention research: expanding our focus to sedentary behaviors, technology, and dissemination. *J Behav Med*. 2017;40:112–126. Springer New York LLC.
107 Tran S, Smith L, El-Den S, Carter S. The use of gamification and incentives in mobile health apps to improve medication adherence: scoping review. *JMIR Mhealth Uhealth*. 2022;10(2):e30671.
108 Davis AJ, Parker HM, Gallagher R. Gamified applications for secondary prevention in patients with high cardiovascular disease risk: a systematic review of effectiveness and acceptability. *J Clin Nurs*. 2021;30(19–20):3001–3010.
109 Beishuizen CR, Stephan BC, van Gool WA, et al. Web-based interventions targeting cardiovascular risk factors in middle-aged and older people: a systematic review and meta-analysis. *J Med Internet Res*. 2016;18(3):e55.
110 Krukowski RA, Denton AH, König LM. Impact of feedback generation and presentation on self-monitoring behaviors, dietary intake, physical activity, and weight: a systematic review and meta-analysis. *Int J Behav Nutr Phys Activ*. 2024;21:3. BioMed Central Ltd.
111 Koivisto J, Malik A. Gamification for older adults: a systematic literature review. *Gerontologist*. 2021;61(7):e360–e372.
112 White ND, Bautista V, Lenz T, Cosimano A. Using the SMART-EST goals in lifestyle medicine prescription. *Am J Lifestyle Med*. 2020;14(3):271–273.
113 Latkin CA, Knowlton AR. Social network assessments and interventions for health behavior change: a critical review. *Behav Med*. 2015;41(3):90–97.
114 Chen J, Mullins CD, Novak P, Thomas SB. Personalized strategies to activate and empower patients in health care and reduce health disparities. *Health Educ Behav*. 2016;43(1):25–34.
115 Webb TL, Joseph J, Yardley L, Michie S. Using the internet to promote health behavior change: a systematic review and meta-analysis of the impact of theoretical basis, use of behavior change techniques, and mode of delivery on efficacy. *J Med Internet Res*. 2010;12(1):e4.
116 Sigmundsson H, Haga M, Elnes M, Dybendal BH, Hermundsdottir F. Motivational factors are varying across age groups and gender. *Int J Environ Res Public Health*. 2022;19(9):5207.
117 Brown-Crowder RR. *Work motivation theory: identifying multigenerational values in the workplace*. Walden University; 2017 [cited 2024 Apr 24]. Available from: https://scholarworks.waldenu.edu/dissertations/4043.
118 Cote R. Motivating multigenerational employees: is there a difference? *J Leadersh Account Ethics*. 2019;16.
119 Edwards EA, Lumsden J, Rivas C, et al. Gamification for health promotion: systematic review of behaviour change techniques in smartphone apps. *BMJ Open*. 2016;6(10):e012447.
120 König LM, Attig C, Franke T, Renner B. Barriers to and facilitators for using nutrition apps: systematic review and conceptual framework. *JMIR Mhealth Uhealth*. 2021;9(6):e20037.
121 Bates DW, Landman A, Levine DM. Health apps and health policy. *JAMA*. 2018;320(19):1975.
122 Roberts AE, Davenport TA, Wong T, Moon HW, Hickie IB, LaMonica HM. Evaluating the quality and safety of health-related apps and e-tools: adapting the Mobile App Rating Scale and developing a quality assurance protocol. *Internet Interv*. 2021;24:100379.