Evaluating Effectiveness of mHealth Applications for Older Adults with Diabetes: Meta-Analysis of Randomized Controlled Trials

Renato Ferreira Leitao Azevedo, Michael Varzino, Erika Steinman, Wendy A. Rogers

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Evaluating Effectiveness of mHealth Applications for Older Adults with Diabetes: Meta-Analysis of Randomized Controlled Trials

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Abstract

Background: The global population is aging rapidly, with projections indicating a doubling of older adults by 2050. Among the chronic conditions affecting this demographic, diabetes stands out due to its prevalence and impact on health. Mobile health (mHealth) app interventions show promise in improving health outcomes, leveraging the widespread adoption of smartphones among older adults.

Objective: This meta-analysis aimed to evaluate the effectiveness of mHealth apps specifically tested for older adults with diabetes. It addresses the gap in existing literature by focusing on this age group, aiming to provide insights into the benefits and challenges of these technologies.

Methods: A meta-analysis of randomized controlled trials (RCTs) was conducted, across major databases using PRISMA guidelines, to examine the effectiveness of mHealth apps for improving older adults' diabetes outcomes. Primary outcomes included changes in glycated hemoglobin (HbA1c), fasting blood sugar (FBS), and medication adherence levels. We retrieved of 4247 papers, of which 257 were moved to full review, and 7 identified following our criteria. Papers were excluded if the study was not an RCT, did not examine the effect of mHealth apps, or was not conducted with older adults. We provide a mixed-methods perspective, pairing the effect sizes in the literature with a review of features included in these apps, allowing for a more comprehensive comparison and reference for future RCT interventions with similar technologies designed for older adults.

Results: Overall, our results indicated that mHealth app interventions can be effective for managing blood glucose in older adult populations. Seven RCTs met the inclusion criteria, involving a total of 490 participants. The meta-analysis revealed a significant reduction in glycated hemoglobin (HbA1c) levels (Hedge's g: -0.40, 95% CI [-0.75 to -0.06]) among older adults using mHealth apps. Limited data on fasting blood sugar (FBS) and medication adherence showed positive trends, echoing the main HbA1c findings.

Conclusions: mHealth apps demonstrate effectiveness in improving glycemic control among older adults with diabetes, highlighting their potential as tools for health management in this demographic. Our effect sizes were comparable with other meta-analyses conducted across different aging groups, suggesting that diabetes mHealth apps can be as effective for older adults compared to younger cohorts. Some of our data suggests that the effectiveness of mHealth apps might decrease over trial time. These findings underscore the need for further research to refine these interventions and optimize their impact on older adults' health outcomes. We describe each RCT intervention and evaluate the risk of bias and the app components that could relate to the app effectiveness to inform the design of other diabetes management RCT interventions, and more broadly, the design of other mHealth tools for older adults.

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Keywords: mHealth apps; diabetes; older adults; RCT; meta-analysis; gerontechnology

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Introduction

As of 2024, there are 8.1 billion people living on the planet. The good news is that people worldwide are living longer and life expectancy has roughly tripled over the course of human history [1]. Improvements in hygiene and sanitation, immunization programs, and other healthcare and medical advancements, as well as healthier lifestyles have contributed to human longevity. Presently, most people are expected to live into their sixties and beyond. The World Health Organization (WHO) estimates that every country in the world is experiencing growth in both the proportion of older adults and the population size. By 2030, 1 in 6 people are projected to be aged 60 years or over, and by 2050, the global population of older adults is expected to double (2.1 billion) [2].

The bad news is that with increased longevity the prevalence of chronic conditions, commonly linked with advancing age, has become a significant public health concern. For example, diabetes is increasingly becoming a prevalent health concern among older adults. In 2019, it is estimated, globally, that 19.3% of people aged 65-99 years (135.6 million) live with diabetes [3]. This number is projected to reach 195.2 million by 2030 and double by 2045; approximately 276.2 million older adults with diabetes [3, 4, 5]. In the US, 38.4 million people have diabetes and 97.6 million have prediabetes (11.6% and 38.0% of the country population respectively) [4, 6]. Furthermore, diabetes is one of the top five most common chronic conditions impacting older adults (~27% of adults 65+) [7]. Hence, amongst various chronic conditions affecting older adults, diabetes stands out as one of the most pervasive, highly prevalent comorbidity among patients, and significantly compromising the health and wellness of a large segment of the aging population.

Potential for mobile health (mHealth) interventions

Most forms of diabetes are chronic but all forms are manageable with medications and/or lifestyle changes [8, 9). Moreover, diabetes is considered one of the major controllable risk factors for cardiac, brain, eye, and kidney diseases [9, 10]. With the continuous advances of technology, the use of mobile health (mHealth) tools to facilitate the attainment of health objectives (i.e., continuous glucose monitoring, medication adherence) is increasing, and holds the potential to revolutionize healthcare delivery worldwide [11; 12; 13], see also [14]. This transformative shift is leveraged and propelled by advancements and wide availability in mobile technologies and applications, the emergence of opportunities for integrating mobile health into existing eHealth services, and the ongoing expansion of coverage in mobile cellular networks.

These are optimistic times, with advancing technologies becoming increasingly more affordable and smartphone ownership among older adults rising from only 10% in 2011 to 76% in 2023 [15]. Furthermore, relying on smartphones for internet access is notably prevalent among older adult Americans with lower household incomes and individuals with less formal education. Surveys conducted from 2013 to 2023, demonstrated an increased smartphone dependency among older adults, with numbers rising from 3% in 2013 to 16% of users above 65+ depending on their phones for internet access [15]. Therefore, because health information is more often only accessible electronically, such as through Electronic Health Records on patient portals, it is reasonable to conclude that a significant portion of older adults will utilize their smartphones for access to health information. Moreover, a systematic review conducted by [14] indicated that smartphones and tablets were seen by older adults with and without cognitive impairment as acceptable, enjoyable, and valuable alternatives to conventional assistive technology.

As per the data accessible up to 2022, an estimated 41,517 to 54,000 healthcare and medical apps on the Apple App Store [16], and between 54,546 to 65,300 apps available on the Google Play Store [17]. Although mobile apps continue to expand in different markets (e.g., social, communication, health, entertainment, banking, and personal finance), they are not always designed for every age demographic and there is a need to investigate their effectiveness, as well as to advance guidelines for designing these apps specifically for older adults [11, 18, 19, 20].

Existing research and why meta-analysis is important?

Meta-analyses are vital for evidence-based practice and healthcare decision-making because they employ an objective qualitative approach for assembling, arranging, and assessing existing literature in a research domain, which also includes a quantitative approach and statistical analysis of a collection of results from its individual studies for the purpose of integrating findings [21, 22, 23). The process involves thorough searches to identify relevant articles for statistical analysis, aiming to minimize bias and ensure a true representation of available research.

The development of mHealth apps involves a substantial undertaking, requiring a significant allocation of resources, which is also true for researchers conducting randomized controlled trials (RCTs). The development of mHealth apps encompasses not only financial investments but also considerable amounts of time, technical expertise, and interdisciplinary collaborations to ensure that these applications are user-friendly and effective. The complexity of rigorous testing and validation contribute to the resource-intensive nature of mHealth application development. However, the potential benefits in terms of improving healthcare access, patient engagement, and the overall quality of healthcare services make this investment in resources valuable and necessary for the future of healthcare technology.

Hence, conducting a comprehensive meta-analysis is crucial to provide information for cost-benefit analysis and to identify health technology components and features that are effective for the intended users. Given the uncertainty surrounding the efficacy of these applications, particularly for older adults, a gap in consolidating the existing knowledge to propel the field forward is justified. To our knowledge, there has not been a meta-analysis to evaluate the effectiveness of mHealth apps for improving diabetic older adults' health outcomes. The identified meta-analyses evaluated mHealth apps on a wider age spectrum and do not evaluate the effectiveness for older adults [10, 24, 25, 26, 27, 28, 29], but see [30] for eHealth nutrition intervention. Hence, the evidence concerning if mHealth apps are effective for older adults with diabetes is scarce and fragmented, and often extrapolated from studies of younger age groups.

Objective

Our goal was to address the pressing need to evaluate the effectiveness of mHealth applications tailored specifically for older adults with diabetes. The overarching purpose is rooted in the understanding that diabetes not only affects a substantial number of older adults but is intricately linked to other health complications, thereby compromising their overall quality of life. Recognizing a significant research gap in this area, we note that the existing meta-analyses often encompass a broader age range in their evaluations, neglecting the distinct needs and potential barriers faced by older individuals when adopting and using these technologies. We addressed this deficiency by concentrating on the studies conducted exclusively with older adults, with the ultimate goal of shedding light on the potential benefits and challenges associated with mHealth apps, and to evaluate the effectiveness of these promising health technologies on improving older adults' health management and outcomes. The justification for conducting meta-analyses on the effects of mHealth apps on blood sugar control, especially when considering older adults as the target audience, was grounded in the shared health management challenges faced by this demographic. Older adults often struggle with multiple chronic conditions, each demanding careful attention to medication adherence, lifestyle adjustments, and continuous monitoring.

Furthermore, conducting meta-analyses to determine effect sizes in the existing literature – even in the earlier formative stages of accumulated knowledge, when only a restricted number of interventions have been published – is crucial for estimating statistical power in the context of future health technology interventions, because it provides a consolidated understanding of the cumulative evidence at this stage and enables researchers to make informed decisions about the feasibility and potential impact of such interventions in this population. It offers the opportunity for researchers to adapt their ongoing projects based on the anticipated effect sizes and statistical power, allowing them to proactively allocate resources and address potential challenges (e.g., alteration of funding support, recruitment challenges) by determining minimum sample sizes necessary for the planned analyses, ultimately ensuring the success and relevance of these critical health technology projects.

Among various technological interventions, mHealth applications have emerged as promising tools for diabetes management. We explored the potential of mHealth interventions to empower older adults to effectively manage their blood sugar levels. We aimed to inform guidelines and practices by harnessing the capabilities of smartphones and wearable devices. These applications offer real-time monitoring, personalized feedback, and educational resources, facilitating better self-management practices among older individuals with diabetes. Our analyses provided insights for design and implementation of technology to enhance health management and well-being for older adults. It complements other systematic reviews that focused on psychological techniques implemented in mHealth solutions [31] and design guidelines of mobile applications for older adults [11], providing a perspective of features available in these mHealth app interventions. Thus, we provided a mixed-methods perspective, pairing the effect sizes in the literature with a review of features included in these apps, allowing for a more comprehensive comparison and reference for future RCT interventions with similar technologies designed for older adults.

Research question: Do mobile health apps improve older adults' diabetes management?

Methods

Design, Data Sources, and Literature Search Strategy

In December 2022, we conducted a systematic literature search in Clinical Trials Cochrane Library, EBSCO, ProQuest, PubMed/MEDLINE, ScienceDirect, Scopus, and Web of Science in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) strategy (see Figure 1) [32, 33]. These databases are representative of the health-related literature, and are the largest databases in the field. The search strategy included keywords that combine: a) mobile health applications terms (e.g., app, cell Phone, digital technolog*, etc.), b) age-related terms (e.g., aging, elderly, geriatric*, older adults, etc.), and c) health conditions related terms (e.g., diabet*, gluco*, glycemic*, A1C, etc.). We developed our search strategies in consultation with a search specialist and developed keywords in consultation with a subject matter expert in pharmacy and geriatrics. This list of keywords was cross validated, as a quality control, against the column "Keywords" on the Cochrane Library database to ensure that we were not missing relevant keyword variations. For our general search strategy query strings and complete list of keywords, see Appendix A. In addition, we manually searched reference lists and previous meta-analyses to identify further papers. We employed ascendancy and descendancy approaches on the full papers selected, as quality control, using the sources cited in our included sources, and the Crossref and CoCities systems. The study protocol was registered on OSF Registries and available at http://doi.org/10.17605/OSF.IO/AWVCX.

Inclusion and Exclusion Criteria

Studies were included in the review if they (1) were RCTs; (2) examined the effects of mobile health app-based self-care interventions relative to other control conditions (e.g., usual care) on patient outcomes; (3) included people with diabetes; (4) included older adults (60 years or older); and (5) were published in English-language peer-reviewed journals. We excluded review articles, case reports, book chapters, and studies that only provided an abstract. We further excluded studies that only reported protocols without data or only outcomes on application use (i.e., app satisfaction and utilization rate), as the goal of this meta-analysis was to evaluate direct outcomes related to the effectiveness in improving blood sugar control. Based on the SPIDER framework for qualitative evidence synthesis [34], we outline our inclusion criteria as follows:

Sample: Older adults (60 or older) with diabetes

Phenomenon of Interest: The effect of mHealth app interventions on blood sugar control

Design: RCTs

Evaluation: effectiveness in improving blood sugar control

Research type: Mixed methods (e.g., quantitative: effect sizes of outcome measures; qualitative: features of the mHealth apps that are effective to the target population)

Study screening and selection

We carried out the process of importing and compiling citations using Microsoft Excel for initial selection and screening. Three researchers (RFLA, MV, and ES) were involved in the screening and selection of studies. RFLA removed duplicate entries and provided training to both MV and ES. In the initial phase, MV and ES independently assessed the relevance of study titles. Following the title screening, MV and ES screened the abstracts to identify potentially relevant studies. Any disagreements (5.23%) that arose during these stages were resolved through consensus supervised by RFLA. Subsequently, RFLA and MV retrieved and assessed full texts of potentially relevant papers against the inclusion and exclusion criteria. Any areas of disagreement (22.6% of records) were collective compared and discussed. Additionally, the snowballing method was employed by examining the reference lists of relevant articles and other meta-analyses involving mHealth apps with a broader age range.

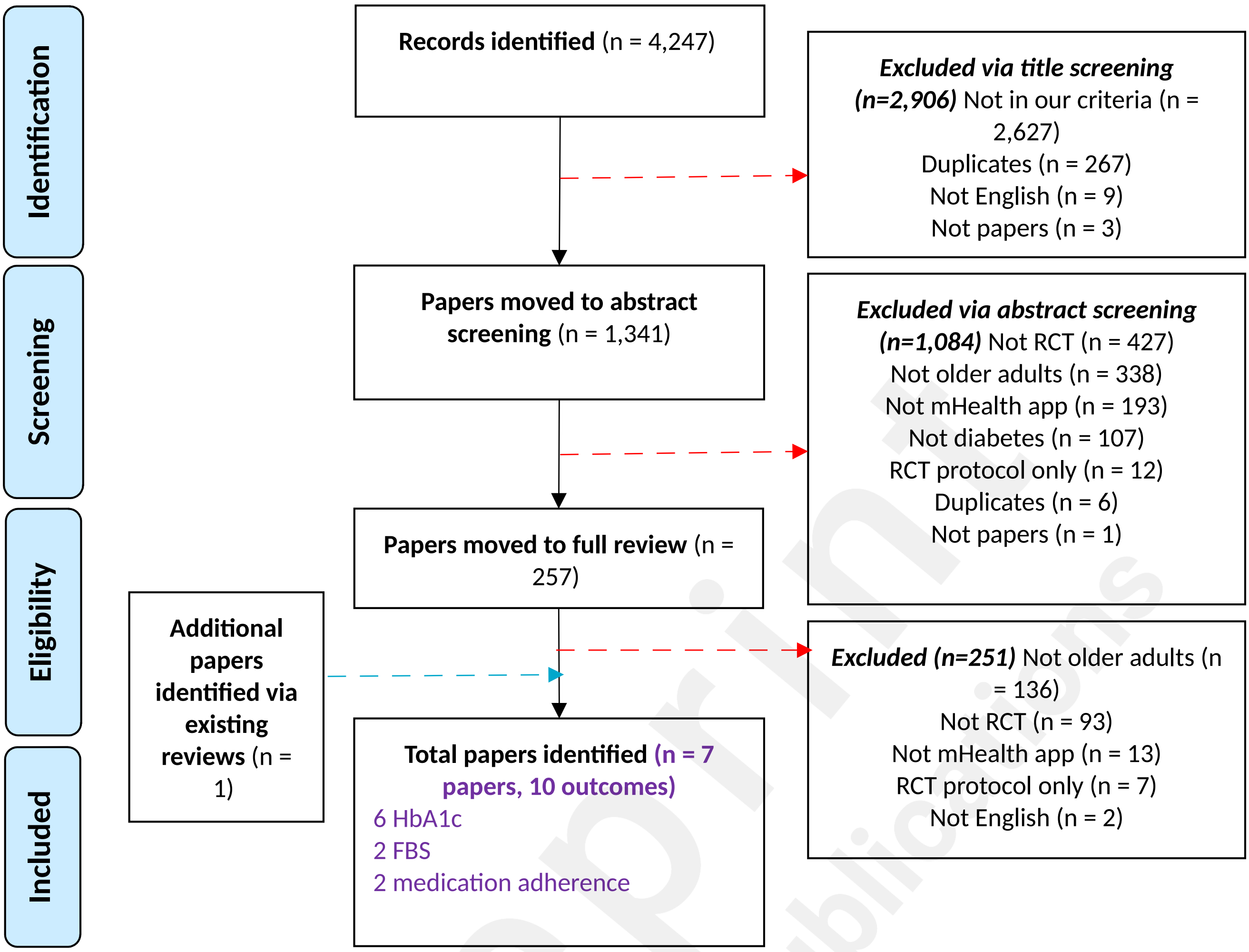

Figure 1. PRISMA flowchart of studies included in the review

Throughout the screening process, we relied solely on information from the title and abstract fields for classification. Author names, publication year, and journal information were available for reference if needed to retrieve missing abstracts or confirm duplicates for removal but were not actively used for screening purposes to mitigate biases.

Outcome measures

The following outcome measures are most usually reported in the diabetes literature:
(1) glycated hemoglobin (HbA1c), also referred to as A1c.
(2) fasting blood sugar (FBS)
(3) medication adherence

When available, we reported other secondary outcome measures, such as measures of diabetes knowledge to provide a comprehensive perspective of the impact and efficacy of mHealth apps in the management of diabetes for older adults.

Data extraction, synthesis, and analysis

We extracted the following information about each study: author, publication year, study location, intervention and control groups, baseline and follow-up outcome variable values (i.e., HbA1c, FBS, medication adherence), sample size, mean age of participants, sex ratio, trial duration length, mHealth app features, and main findings related to the outcomes of interest.

We synthesized the studies based on their outcomes, as the clinical approach prioritizes enhancing outcomes for older adults through mHealth RCT interventions. We conducted a meta-analysis to assess the impact of the interventions on the participants' blood sugar levels and diabetes medication adherence. To assess changes in blood sugar levels and medication adherence, we combined the identified studies featuring intervention groups (utilizing mHealth applications) and control groups (receiving usual care). We computed the mean differences, accompanied by a 95% confidence interval and effect sizes (Hedges' g) in R 4.2.1, with the packages *meta* [35] and *esc* [36]. Data comprised studies reporting modifications in HbA1c, FBS, and medication adherence, comparing baseline values to the conclusion of the study for both intervention and control groups. HbA1c is the most important and most studied clinical outcome related to diabetes management [24]. Plots were created with the packages *meta* [35] and *robvis* [37, 38].

Critical Appraisal (Assessment of Quality of Evidence and Risk of Biases)

Based on the Cochrane Risk of Bias 2.0 tool for randomized trials (RoB 2) [39], two researchers (RFLA and MV) evaluated the risks of biases in included RCTs across 5 specific dimensions: D1 – Randomization process, D2 – Deviations from intended interventions, D3 – Missing outcome data, D4 – Outcome measurement, and D5 – Selection of reported results. Risk ratings of "low", "some concerns", and "high" were assigned to each bias (see also Guyatt et al., 2008, and Figure 3 for a global risk assessment across all identified studies). In Appendix B, we provide additional information concerning publication bias and sensitivity analysis.

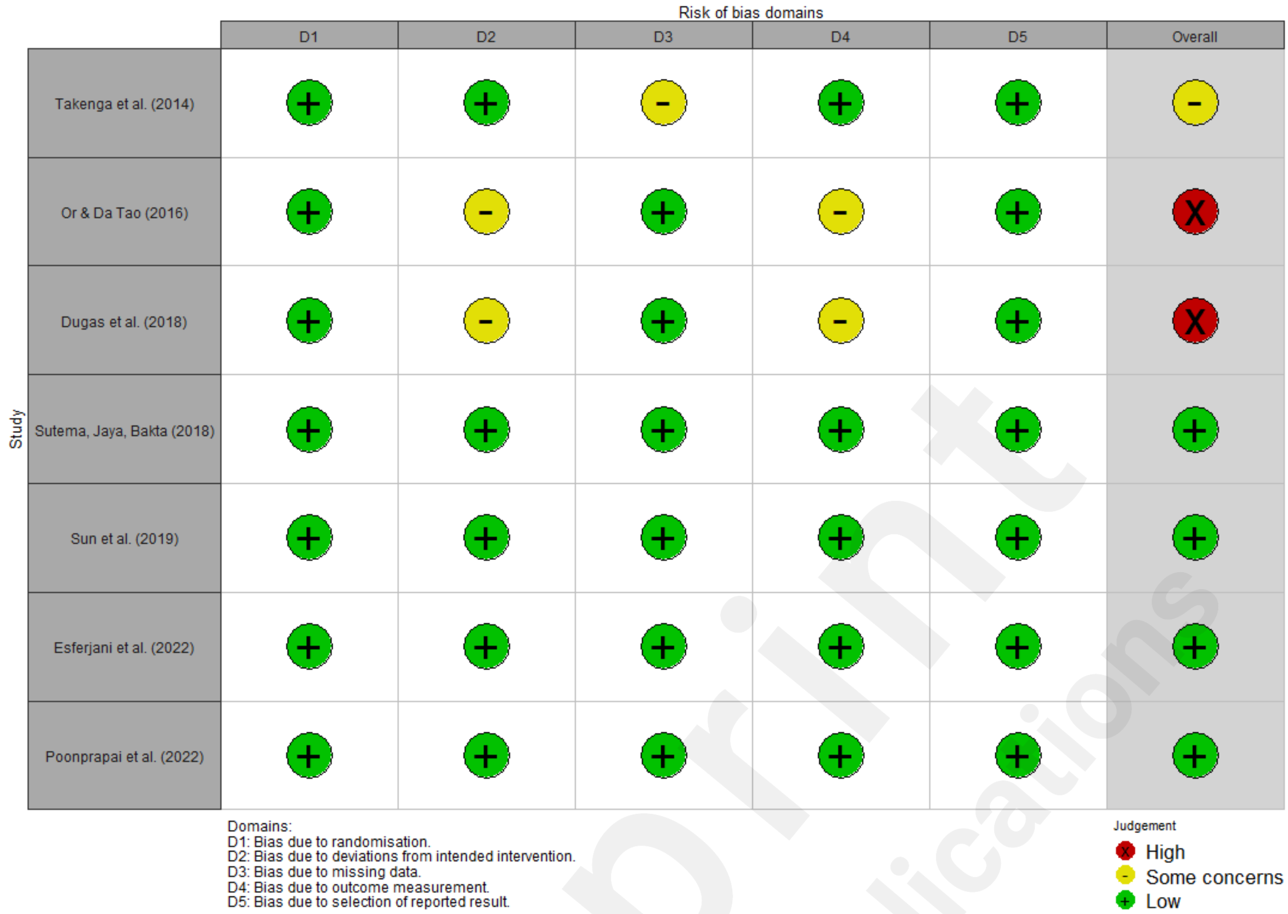

Figure 2. Risk of bias assessment summary (RoB 2.0)

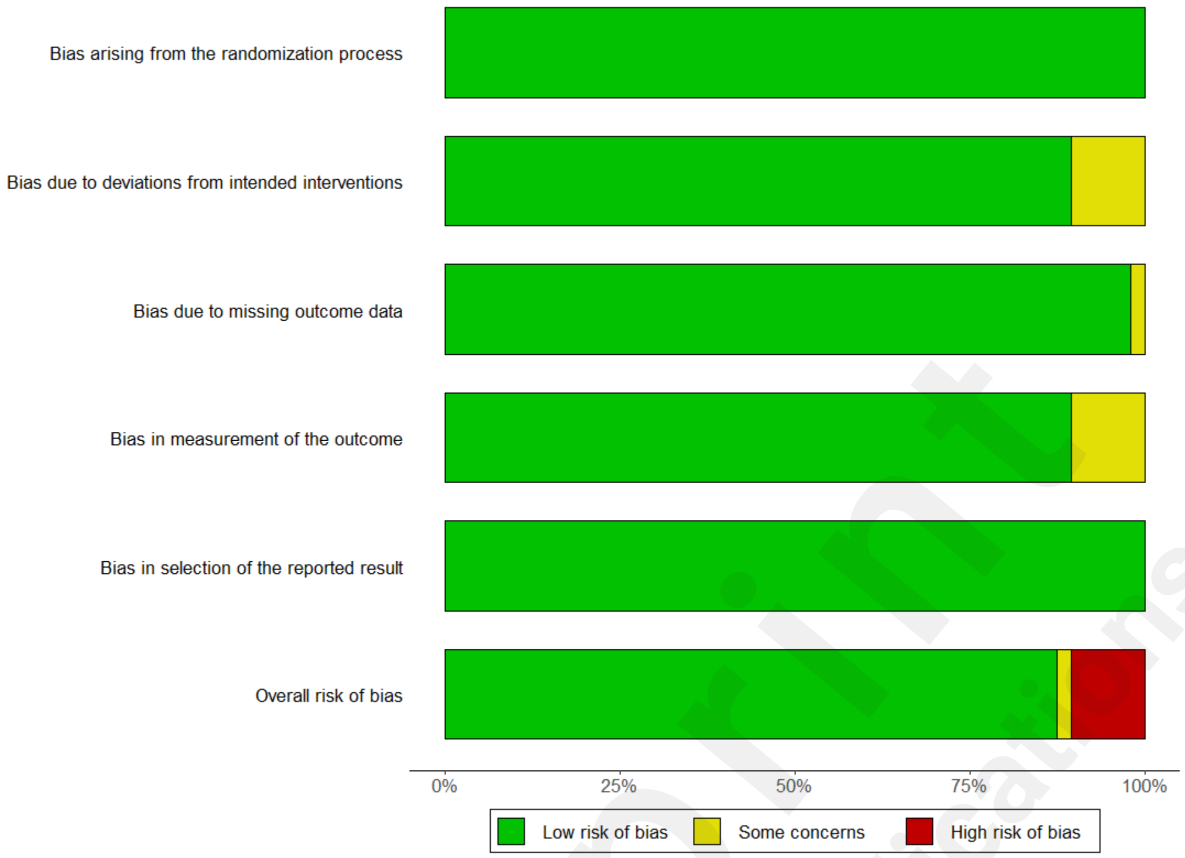

Figure 3. Bias appraisal across domains

App feature analysis

To offer a comprehensive analysis of the identified mHealth apps, we supplemented the quantitative assessment, as demonstrated by the calculation of effect sizes, with a qualitative exploration of the most prevalent components and features comprising these app interventions. Our mix methods approach aimed to contribute to future design and recommendations by identifying crucial components and comparing the effect size findings with an understanding of which features may explain the success of these interventions. Conversely, the absence of a feature could potentially account for the lack of success observed in certain apps and RCT interventions. The categories for this analysis were formulated by adapting the conclusions drawn from the research conducted by [26, 40, 41, 42]. Table 2 presents a summary of all features identified across the seven papers and respective studies.

Results

Study selection

We retrieved 4,247 papers and two reviewers (MV and ES) completed a full screen review of 257. We excluded papers if the study was not a RCT, did not examine the effect of mHealth apps, or was not conducted with older adults, resulting in 7 papers included in the final analysis (see Figure 1). The meta-analysis incorporated a total of 490 participants from these seven papers. Characteristics of the included studies are presented in Table 1. These studies were undertaken in the China, Hong Kong, Indonesia, Iran, Republic of Congo, Thailand, and USA, and were published from 2014 to 2022. During this period, there was an upward trend in sample sizes (see Table 1) and studies enhanced their methodologies, as indicated by our Cochrane assessment (Figure 2).

Out of these papers, [40] had four different app interventions, testing the use of their app without clinician or peer engagement, with only clinician engagement, with only peer engagement, and with both clinician and peer engagement. Note that [43] extended their study to encompass a broader age spectrum. Nonetheless, because the authors provided effects for each participant, we computed the appropriate effect sizes specifically for the older adults within their sample, enabling us to include the study in our meta-analysis.

Table 1. Study Characteristics and Demographics

Study ID	Sample of older adults [a] (n, age)	Country	Diabetes eligibility	Duration	Data collection assessments	Intervention	Control	Outcome
Takenga et al. (2014) [43]	Control: n = 5 (5 male), age = 65.8 (60-75) Intervention: n = 5 (4 male) age = 62.8 (60-70)	Democratic Republic of Congo	Type 2 diabetes diagnosis	60 days	Baseline & 60 days	Treatment with the use of the telemedicine “Mobil Diab” app	Conventional therapy without the use of telemedicine	HbA1c, Blood Glucose (BG)
Or & Tao (2016) [44]	Control: n = 11 age = 69.7 +- 10.2 SD Intervention: n=14 age = 69.3 +- 9.7 SD	Hong Kong	Diabetes diagnosis	3 months	Baseline & 3 months	Interactive tablet computer-based system with a 2-in-1 blood glucose and blood pressure monitor device	A log book for manually recording reading and a 2-in-1 blood glucose and blood pressure monitor device	HbA1c, FBG, Diabetes knowledge
Dugas et al. (2018) [40]	Control: n = 5, age = 66.40 +- 4.93 SD	USA	Type 2 diabetes > 3-year diagnosis HbA1c > 7.9	13 weeks	Baseline & 90 days	N/A	Usual care	HbA1c
	Intervention 1: n = 5, age = 65.40 +- 4.72 SD					Using the app without clinician or peer engagement		
	Intervention 2: n = 5,					Using the app with clinician		

	age = 72.00 +- 9.30 SD Intervention 3: n = 6, age = 66.0 +- 5.18 SD Intervention 4: n = 6, age = 68.17 +- 3.66 SD					engagement features Using the app with peer engagement features Using the app with both clinician engagement and peer engagement features		
Sutema, Jaya, Bakta (2018) [45]	Control: n = 31 (17 male) age = 63.48 +- 3.57 SD Intervention: n = 31 (20 male) age = 62.97 +- 4.94 SD	Indonesia	Diabetes diagnosis Undergoing diabetic neuropathy therapy	4 weeks	4 weeks	Neuropathic pain therapy usual care & Medicine Reminder app	Neuropathic pain therapy usual care	Medication adherence
Sun et al. (2019) [46]	Control: n = 47 (18 male) age = 67.9 (66-71) Intervention: n = 44 (19 male) age = 68.04 (66-72)	China	Diabetes diagnosis HbA1c > 7% & <10%	6 months	Baseline, 3 months, & 6 months	A mHealth management app and glucometer to aid data transmission from the user to the dietitian. Once-monthly dietary recommendations based on app information.	Dietary guidance from dietitians in person at baseline and at the conclusion of the study procedures.	HbA1c, FBG, & Postprandial Blood Glucose (PBG)
Esferjani et al. (2022) [47]	Control: n = 59 age = 60 to 64 (67.8%) 65 to 70 (32.2%) Intervention: n = 59 age = 60 to 64 (62.7%) 65 to 70 (37.3%)	Iran	Diabetes diagnosis	3 months	Baseline & 3 months	Three sessions of educational content delivered via a WhatsApp group app on mobile devices, and printed booklet containing health information	Routine care from the Health Center (A ~20 minutes visit every 3 months) with a doctor, a dietitian and a nurse.	HbA1c
Poonprapai et al. (2022) [48]	Control: n= 79 (40.5% male) age = 67.80 +- 6.18 SD Intervention: n =78 (39.7% male) age = 67.36 +- 5.72 SD	Thailand	Diabetes diagnosis HbA1c > 7% or 53 mmol/mol.	9 months	Baseline, 3 months, 6 months, & 9 months	A mobile app to deliver diabetes care information to family caregivers of a diabetes patient	Usual care	HbA1c, Medication adherence, Diabetes knowledge

Glycated Hemoglobin (HbA1c)

The estimated effect sizes indicated that mHealth apps can be effective for older adults managing diabetes, with significant reductions in glycated hemoglobin (HbA1c) (Hedge's g: -0.40, 95% CI [-0.75 to -0.06]). This effect size is comparable with other meta-analyses conducted across different aging groups (HbA1c effect (mean difference: -0.63, 95% CI [-0.93 to -0.32, for type 1 diabetes, and -0.54, 95% CI [-0.80 to -0.28], for type 2 diabetes[24]); HbA1c effect (g: -0.44, 95% CI [-0.59 to -0.29] [27]); HbA1c (weighted mean difference: -0.39, 95% CI, [-0.50 to -0.29] [10]); HbA1c effect (g: -0.48, 95% CI [-0.66 to -0.29] [28]), and HbA1c effect (g: -0.37, 95% CI [-0.43 to -0.31] [29])).

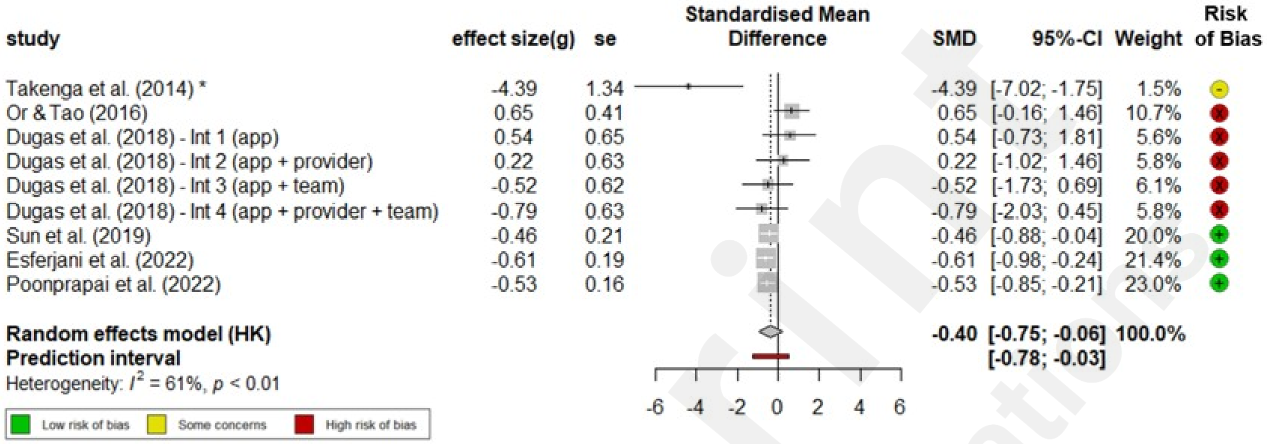

Figure 4. Forest plot of standardized mean differences of mHealth apps on HbA1c reduction

Furthermore, a decrease of -0.40 on the HbA1c scale could be deemed clinically significant, given that 0.5 marks the threshold difference between normal (below 6.0%) and diabetic ranges (6.5% or above) for diagnosis. For instance, in the pre-diabetic stage, which falls between 6.0 to 6.4%, a reduction of 0.4 would transition a patient diagnosis from pre-diabetic to normal.

Fasting Blood Sugar (FBS)

Only two of the identified studies reported fasting blood sugar (FBS) as an outcome measure, namely Or and Tao [44] and Sun et al. [45]. Echoing the findings on HbA1c, our estimated effect size similarly suggested that mHealth apps may contribute to a significant reduction in fasting blood sugar (FBS) levels (g: -0.29, 95% CI [-1.52 to 0.42]). Nevertheless, the scarcity of studies assessing this outcome measure and the wide confidence interval estimate do not provide us a conclusive picture. Although [44] observed a decline in FBS, [45] did not report significant results for that measure.

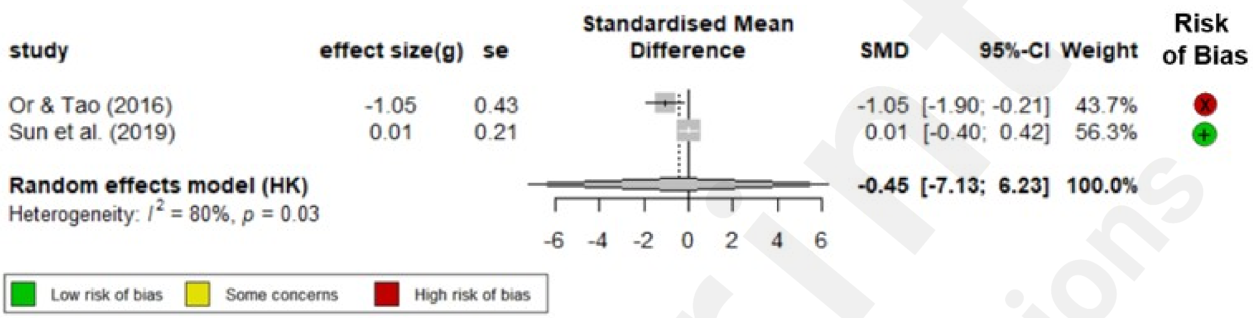

Figure 5. Forest plot of standardized mean differences of mHealth apps on FBS reduction

Medication adherence

Medication adherence is a crucial element in managing chronic conditions but only two studies, namely Sutema, Jaya, Bakta [45] and Poonprapai et al. [48], assessed that outcome. These RCT studies were well designed, with a low risk of biases, and indicated that mHealth apps could support improvements in medication adherence (g: 1.06, 95% CI [-1.14 to 3.26]). Although Dugas et al., [40] presented some medication adherence data, we were unable to calculate an effect size to evaluate the comparative effectiveness of their app because medication adherence data was solely accessible through their app and not available for the control condition.

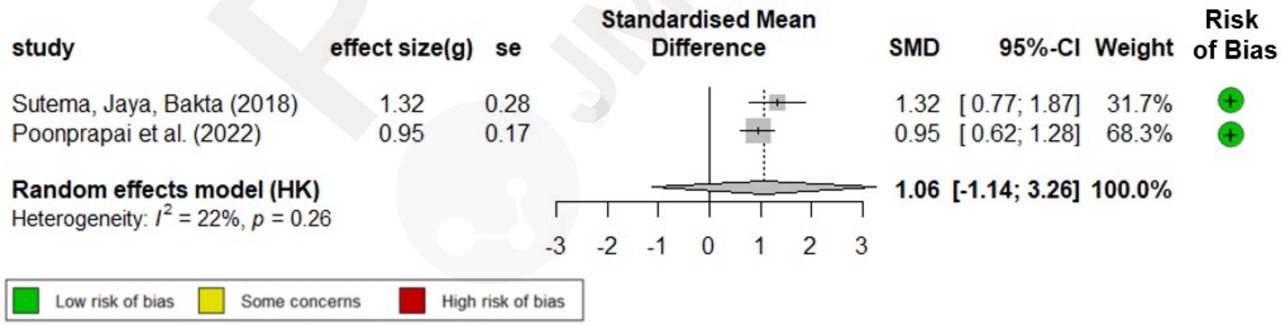

Figure 6. Forest plot of standardized mean differences of mHealth apps on improving medication adherence

Other diabetes-related outcome measures

Sun et al. [45] was the sole study identified that offered measurements for postprandial blood glucose (PBG) test, which is a measure of glucose in the blood after consuming a meal. They found that after 6 months of their app intervention, participants significantly reduced their PBG sugar levels (g: -0.67, 95% CI [-1.09 to -0.25]) compared to a usual care.

Two out of seven papers incorporated assessments of diabetes knowledge [44, 48]. [44] utilized a modified Michigan Diabetes Knowledge Scale [49], comprising 18 true/false statements, scored in terms of percentage correct, to evaluate participants' knowledge. After three months of app usage, no significant differences were observed between intervention and control groups, and knowledge scores increased for both groups (6.8 to 8.1%). The authors stated that participants in both groups had similar levels of health literacy at baseline. Although the study mentioned an educational component in their app, no data is presented specific to its usage. Alternatively, the control condition might have provided educational information, potentially explaining the absence of differential educational benefits. In contrast, [48] assessed participants' diabetes knowledge using the General Knowledge of Patients with Diabetes [50]. Once again, both intervention and control groups demonstrated increased knowledge over the trial duration, with notable between-group differences emerging after nine months (mean increase 2.22 pt. on a 21-item scale, $p<.001$) in favor of the mHealth app intervention, despite similar baseline performances. Though it is not advisable to make definitive conclusions from a single study, this outcome could offer an optimistic reference for designers and researchers that prolonged exposure to educational materials within a mHealth app (i.e., lasting 9 months) may lead to increased knowledge on diabetes for older adults beyond the knowledge gains of usual care conditions. For comparison, [28], based on three studies conducted with a wider age range, found that digital interventions for diabetes improved diabetes knowledge (g: 1.003, 95% CI [0.068 to 1.938].

Features of mHealth app interventions

We reviewed each intervention and the app components that may impact effectiveness. This analysis aimed to guide the development of future diabetes management RCTs and inform the design of other mHealth tools tailored for older adults. Out of the 7 papers, 3 (42.9%) explicitly mentioned the integration of their apps with a glucometer device to facilitate the monitoring of blood sugar levels for users. This integration between app and glucometer devices could potentially explain the observed positive effects in reducing sugar levels, as Millet et al., (2022) showed that the real-time continuous glucose monitoring is indeed effective in reducing sugar levels among older adults, which is an encouraging result given that Millet et al., (2022) found sustained benefits over a 12-months of monitoring use.

Only [43] mentioned the use of personalized goal settings as a behavioral strategy adopted and feature implemented in their app. Except for Esferjani et al., [47], where their app served solely as a platform for delivering educational information and videos, rather than for inputting data, all other interventions (85.71%) incorporated features enabling research participants to log and monitor their usage within the app. This prevalent inclusion is expected, as such basic functionality is commonplace across various apps. Four out of seven studies (57.14%) included data visualizations and monitoring components, enabling participants to receive feedback based on the input data. Also, 4 out of 7 studies (57.14%) explicitly referenced having a reminder feature (i.e., alarms and/or notifications), and the same proportion (57.14%) was found for the inclusion of educational materials. Table 2 presents a comprehensive comparison of all features as studied.

Table 2. mHealth app Features

Study		Logging and tracking	Monitoring and visualizations	Reminder	Education	Personalized goal setting	Reward system/ gamification	Social Support	Connection to health practitioners	Integration with glucometers
Takenga et al. (2014)		YES	YES	Unknown	Unknown	YES	Unknown	Unknown	YES	YES
Or & Tao (2016)		YES	YES	YES	YES	Unknown	Unknown	Unknown	Unknown	YES
Dugas et al. (2018)	Int. 1: (app only)	YES	YES	Unknown	YES	NO	YES	NO	NO	NO
	Int. 2: (app + provider)	YES	YES	Unknown	YES	NO	YES	NO	YES	NO
	Int. 3: (app + social team)	YES	YES	Unknown	YES	NO	YES	YES	NO	NO
	Int. 4: (app + provider + social team)	YES	YES	Unknown	YES	NO	YES	YES	YES	NO
Sutema, Jaya, Bakta (2018)	Medicine reminder application	YES	NO	YES	NO	NO	NO	NO	NO	Unknown
Sun et al. (2019)		YES	Unknown	YES	Unknown	Unknown	Unknown	NO	YES	YES
Esferjani et al. (2022)		NO	Unknown	NO	YES	Unknown	Unknown	YES	YES	Unknown
Poonprapai et al. (2022)		YES	YES	YES	YES	Unknown	YES	YES	YES	Unknown

Health professional involvement and social support

Among the 7 papers, 5 (71.43%) incorporated some form of connection between these apps and/or engagement with healthcare practitioners. For instance, in [45], participants in the intervention group utilized app-based diet management software to input their daily dietary intake. Subsequently, a dietitian received these daily records and provided monthly dietary recommendations back to the patients. In [43], therapy plans, instructions, and medical recommendations documented on patient portals were transmitted to users through the mobile application (Mobil Diab app). In [48] a research pharmacist provided 3 to 5 infographics on diabetes education daily over a three months period. For [47], the intervention included access to a WhatsApp group and training sessions conducted by health education and internal medicine experts. Lastly, [40] experimentally manipulated four different interventions, which included variations in the presence or absence of a provider during the app usage period.

Of the 7 studies, 3 of them (42.86%) incorporated built-in app features related to social support (i.e., peer communication as described in [40, 47] or family support as in [48]. Similar to the health provider involvement, out of these papers, only [40] specifically varied conditions by including or excluding social support alongside the app.

Attrition rates and app usage

Most studies do not report attrition rates. Out of the included studies, only [40, 44, 45] reported some information on app usage. Because attrition can pose questions to the long-term effects of these mHealth app interventions, we reported here the information available. In the study by Dugas et al. [40], older adults used the app for an average of 65.09 days over a 13-week period (SD = 25.38 days). Or and Tao [44] reported that during the first month, older adults used their app for an average of 23 days out of 30, which decreased to 17 days out of 30 by the third month. They found that older adults in both their app and control groups generally conducted self-measured blood pressure (SMBP) daily and self-measured blood glucose (SMBG) three to five times per week, with no significant differences between the two groups. Ninety-one percent of older adults in their intervention group consistently utilized the self-monitoring system over the 3-month study period. System usage was robust in the initial month but declined in the subsequent months for both patient groups. During the first month, twenty-eight out of thirty patients (93%) uploaded measurements at least three days per week. This percentage decreased over time to 67% in the second month and to 73% in the third month. Lastly, [45] reported that after their trial ended, over 89% of patients in the intervention group continued to measure their blood glucose level 2 to 3 days each week, which speaks to the level of engagement and usage of their app outside the scope of their RCT.

Discussion

Principal findings

This meta-analysis indicated that interventions utilizing mHealth apps through RCTs effectively enhanced diabetes-related outcomes among older adults, spanning various outcome measures. Moreover, the estimated effect sizes aligned with those observed in meta-analyses involving younger adults, a noteworthy finding in itself. There is often skepticism regarding the efficacy of mHealth interventions for older adults, presuming that these technologies might not be as beneficial for individuals less accustomed to them. However, our findings suggested that, at the very least, the examined apps demonstrated effectiveness comparable to those tested across a younger age range. If anything, we posit that by designing apps specifically tailored for older adults, we might anticipate even greater effect sizes and more successful technology implementations to support older individuals managing chronic conditions like diabetes. Such advantages might be enhanced if mHealth apps are specifically designed with and tailored for older adults, rather than adopting a one-size-fits-all approach. A personalized and adaptive learning strategy can be investigated, as its effectiveness have been evidenced in other domains and contexts (e.g., [51], reading literacy among young students).

In an era where technology integration in healthcare is increasingly prominent, particularly amidst the shift towards remote care and digital health solutions, our research holds significant implications that transcend the scope of this study. This meta-analysis carries relevance not only for healthcare providers but also for researchers, policymakers, and stakeholders on designing and developing mHealth apps for older adults.

For Healthcare Providers: Our findings underscore the potential of mHealth applications to enhance health outcomes among older adults across diverse healthcare settings. Providers seeking effective ways to leverage technology for improved patient care and health monitoring will find valuable insights within our study. We found that studies including some connection with healthcare providers [40, 45, 47, 48] reported a larger effectiveness in reducing HbA1c levels.

For Policymakers: We emphasize the need to consider mHealth app interventions as a viable strategy to address healthcare challenges among older populations, particularly in regions with varying healthcare resources. By examining the varying outcomes among mHealth interventions across economically diverse regions and healthcare settings, this study underscores the importance of understanding the contexts in which these interventions are implemented. Although these findings are influenced by the quality of available evidence, and the scarce number of RCTs in the area, they suggest practical implications for effective mHealth design to support health management across different healthcare environments. For example, future interventions should consider the usability and appropriateness of technology for older adults, ensuring compatibility with existing healthcare infrastructures.

For Researchers: Beyond the specific applications in healthcare for older adults, our work extends to the broader context of mHealth's effectiveness and adaptability in various health environments. It serves as a foundational contribution, inviting further exploration of personalized technology's impact on health management and beyond. For example, [30]'s meta-analysis on the effectiveness of eHealth nutritional interventions found an overall positive improvement on fasting blood glucose, body fat, triglyceride levels and calorie intake for middle-aged and older adults. Our meta-analysis contributes to this literature by expanding the founded benefits to investigate apps designed for blood glucose management. Because our meta-analysis includes only RCTs, we believe that our estimated effect-size should reflect the diverse components of mHealth apps beyond their educational content. Since many of these educational components are also present in RCT control groups, the differential impact of these apps likely resides in other components absent from such controls. Researchers could further continue to explore and attempt to disentangle the educational benefits of these interventions from features related to self-management. We provided a summary of the components present in each of these app interventions to guide that exploration.

Moreover, dynamic and personalized educational materials should be explored as a way to continuously engage users, mitigating app abandonment, and augment the benefits observed by [30] and the studies in our meta-analysis. The support components of a technology that can best support health goals is dependent on the patient’s journey [52], but the stage of diagnoses was not reported.

Some interventions did not demonstrate benefits, particularly the more dated RCTs in our sample, but the findings indicate that the use of mHealth may yield significant improvements compared to traditional healthcare methods, especially in blended care approaches. We position our study as foundational research that illuminates effective mHealth app intervention design for older adults and serves as a catalyst for broader investigations into personalized technology’s impact on healthcare in our increasingly digital age.

Strengths and limitations

Our review has several strengths. It provides evidence regarding the effects of mobile app- interventions developed for diabetes on patient outcomes tested with older adults. To our knowledge, this is the first to estimate the effectiveness of RCT interventions answering if mHealth apps improve older adults' diabetes management. Our review provides an evidence-based review of the features of such interventions and their associations with improvements in glycemic control and medication adherence.

Our study has limitations. This analysis drew upon RCT interventions conducted exclusively with older adults that adopted a mHealth app to improve outcome measures related to diabetes, investigating various populations across different diabetes types (I and II), education levels, and socioeconomic statuses in diverse settings. The RCTs included in this study exhibited moderate to high methodological quality, despite potential limitations stemming from their small sample sizes, which might have influenced the overall representation of mHealth intervention progress. We attempted to circumvent this limitation by ordering our identified studies based on their publication chronology to provide readers a way to identify potential progresses as technology advances and sample sizes increased. As depicted in Figure 2, it is compelling that RCT interventions advanced over time, as shown by improvement in the assessment of biases across various dimensions. This suggests a promising trend towards the adoption of more rigorous RCT methodologies within the field.

Specifically, this review highlighted the characteristics and outcomes of mHealth interventions for patients with diabetes. We did not explore interventions for other chronic illnesses such as hypertension, cholesterol, COPD, arthritis, or liver diseases. In future studies we will expand our approach to different chronic conditions and explore similarities and condition-specific features. Furthermore, terms such as tele-monitoring and telemedicine, sometimes falling under the broader umbrella of mHealth, were not employed in the literature search.

Studies were heterogeneous in intervention duration, technology exposure, and outcome variable measures, making it difficult or sometimes infeasible to compare quantitatively across studies and generalize based on length of the interventions. We circumvented this limitation by providing information on intervention duration length so a qualitative comparison could be inferred by readers. Our analyses were limited to the final effect based on these reported durations, and thus future studies should take in account what is the minimum technology exposure time needed to observe some significant improvement, as more studies and evidences accumulate in the literature.

Our search was not updated to include reviews published after December 2022, and we did not contacted the authors of the identified papers to confirmed if the published information was correct, nor to obtain more details about the interventions published. Although that would allow us to better identify characteristics, such as the unknown information reported in Table 2, we defended our choice in this case based on the idea that the information should be publicly available on published RCT papers, which are at the core of the replication principle in science.

Conclusion

In conclusion, this meta-analysis provided compelling evidence that mHealth interventions utilizing mobile apps significantly enhanced diabetes-related outcomes among older adults. Our findings not only underscored the effectiveness of these interventions across various outcome measures but also challenged the skepticism surrounding their applicability to older populations. The observed effect sizes were comparable to those found in studies involving younger adults, suggesting promising potential for mHealth technologies in managing chronic conditions among older demographics.

As healthcare increasingly integrates technology, particularly amidst the current trend towards remote care and digital health solutions, our research carries significant implications. It informs healthcare providers of the valuable role mHealth apps can play in enhancing patient care and health monitoring, especially when integrated into clinical practice. For researchers, our study extends beyond diabetes management, highlighting broader implications for the effectiveness and adaptability of mHealth in diverse health environments. It calls for further exploration into personalized technology's impact on health management, encouraging future studies to refine and optimize interventions tailored specifically for older adults.

Policymakers are urged to consider mHealth app interventions as a viable strategy for addressing healthcare challenges among older populations, particularly in regions with varying healthcare resources. By examining outcomes across countries and economic contexts, our study highlighted the importance of tailoring interventions to be user-friendly and compatible with existing healthcare infrastructures.

Our review was strengthened by its focus on RCTs and methodological rigor, including assessments of bias and study quality. Nevertheless, we acknowledged limitations such as heterogeneous study designs and varying intervention durations. Future research should explore interventions for other chronic conditions and further refine the design and implementation of mHealth technologies to maximize their effectiveness in older adult populations. In summary, this meta-analysis serves as foundational research that not only validated the efficacy of mHealth apps in diabetes management for older adults but stimulated ongoing dialogue and innovation in the field of digital health. As technology continues to evolve, so too will the opportunities to optimize healthcare delivery and improve outcomes for older adults through tailored and evidence-based interventions.

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Conflicts of Interest

None declared.

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Abbreviations

ADA: American Diabetes Association
APP: application
BG: Blood glucose
CDC: Centers for Disease Control and Prevention
COPD: Chronic obstructive pulmonary disease
CREATE: Center for Research and Education on Aging and Technology Enhancement
FBS: Fasting blood sugar
HbA1c: Glycated hemoglobin
mHealth: mobile Health
mHealth app: mobile Health application
NCOA: National Council on Aging
NIA: National Institutes of Health
PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analysis
PBG: Postprandial Blood Glucose
RCT: Randomized Controlled Trial
RoB2: Cochrane Risk of Bias 2.0 tool for randomized trials
SMBG: Self-measured blood glucose
SMBP: Self-measured blood pressure
WHO: World Health Organization (WHO)

Appendix A. Query strings and general search strategy

1. Mobile health applications (combine using OR)
    - App
    - Cell Phone
    - Digital technolog*
    - Mobile
    - mHealth app
    - Mobile Application
    - Smartphone
    - Phone

AND

2. Age-related terms (combine using OR)
    - Age
    - Aged
    - Aging
    - Elderly
    - Geriatric*
    - Older adult*
    - Seniors

AND

3. Health condition-related (Diabetes) terms (combine using OR)
    - Diabet*
    - Gluco*
    - Glycemi*
    - Insulin
    - Mellitus
    - Sugar
    - A1C
    - Hemoglobin

For a complete list of query strings for each data, see: https://doi.org/10.17605/OSF.IO/AWVCX

Appendix B. Publication bias and sensitivity analysis

The funnel plot (Figure 7) provides a visual representation of the relationship between the effect sizes of individual studies and their precision as measured by standard error. We present this analysis exclusively for the HbA1c measure, as it is the outcome reported by the majority of the studies (6 papers with 9 RCT interventions).

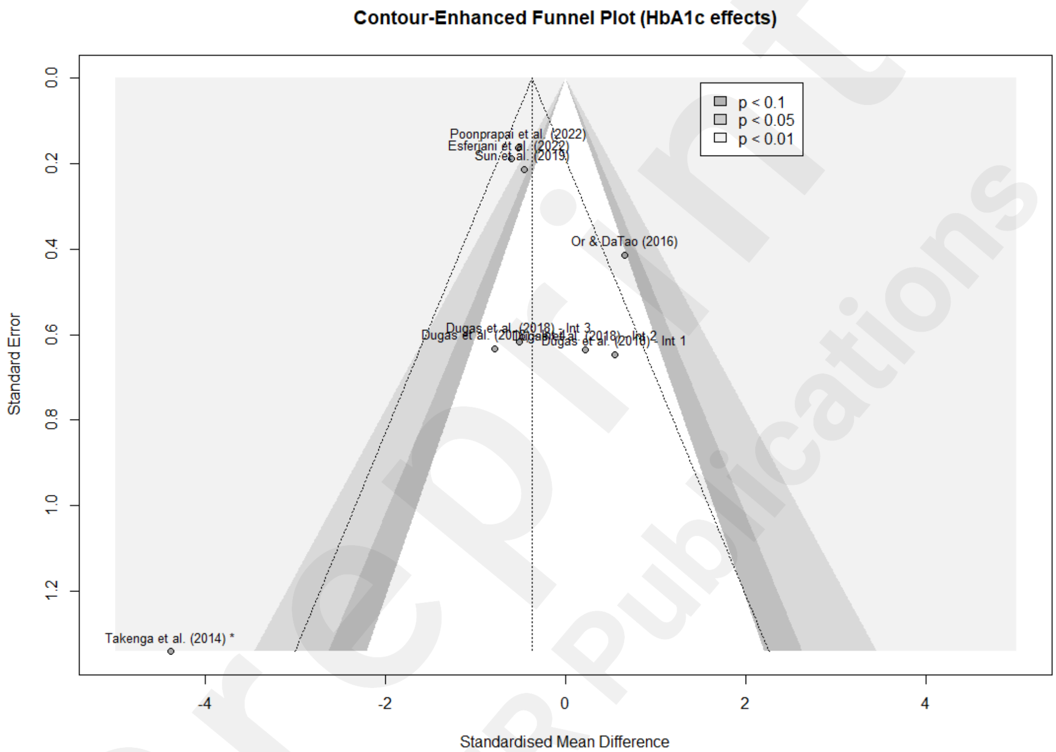


Figure 7. Funnel plot of standard error by standardized mean differences on the effects on HbA1c. HbA1c measures provided for 9 studies

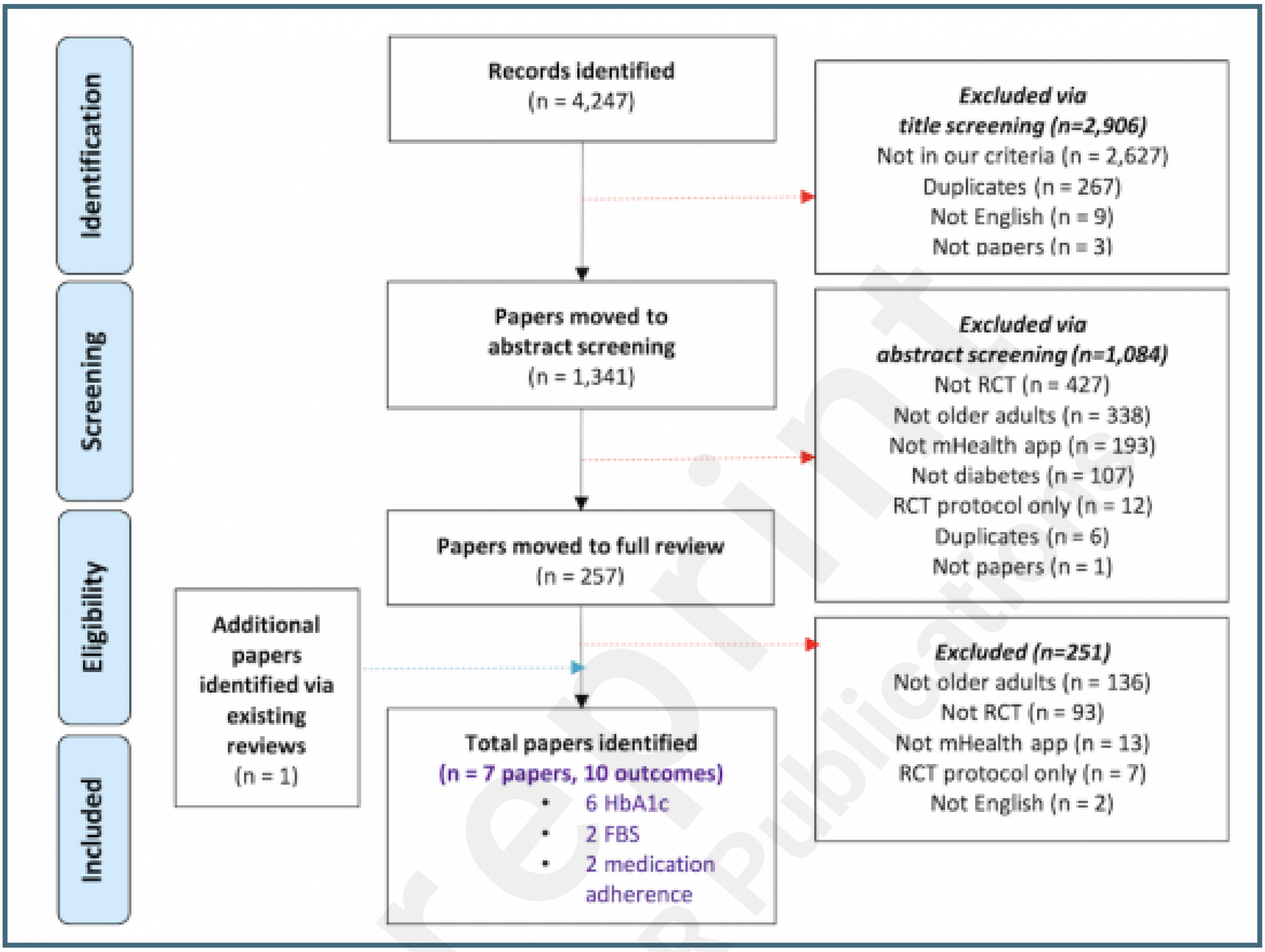
While our plot reveals a relatively asymmetrical distribution of studies around the average: 3 to the right of the line, 6 to the left of the line, the Begg and Mazumdar correlation test [53] (p = .677) and the Egger's test of the intercept [54] were not significant (t = 0.140, df = 7, p-value = .891). Hence, the visual asymmetry conveyed is probably not caused by file-drawing (unpublished RCT studies not showing benefits of mHealth applications), but more likely due to the small number of study effects. For the sake of completeness, we also conducted a Duval and Tweedie's trim and fill test [55] to account for the potential impact of publication bias on meta-analytic results by estimating and adjusting for missing studies. We estimate the effect size that would have been observed if all studies, regardless of their results, had been published. The Duval and Tweedie's test [55] under the random effects model, yields a point estimate for the combined studies of -0.376 (95% confidence interval: -0.711 to
-0.04), using the trim and fill function [56], trimfill(), *metafor* package), these values remain unchanged. Hence, we found no evidence that publication biases could impact the

interpretation of the observed intervention effect sizes estimated. The spread of points in the funnel plot also help to indicate the heterogeneity among the included studies. In particularly, [43] shows an effect size beyond 4 units of the standardized mean difference, a variability of effect size that is perhaps beyond what would be expected by chance alone. Hence, we suggest caution on the interpretation of findings for this study in particularly. While cultural differences, small sample of participants in this study, and different technologies might help to explain differences in effect sizes between mHealth interventions and usual care control conditions, our study helps to estimate the most probable likelihood that mHealth applications have an effectiveness beyond the usual care.

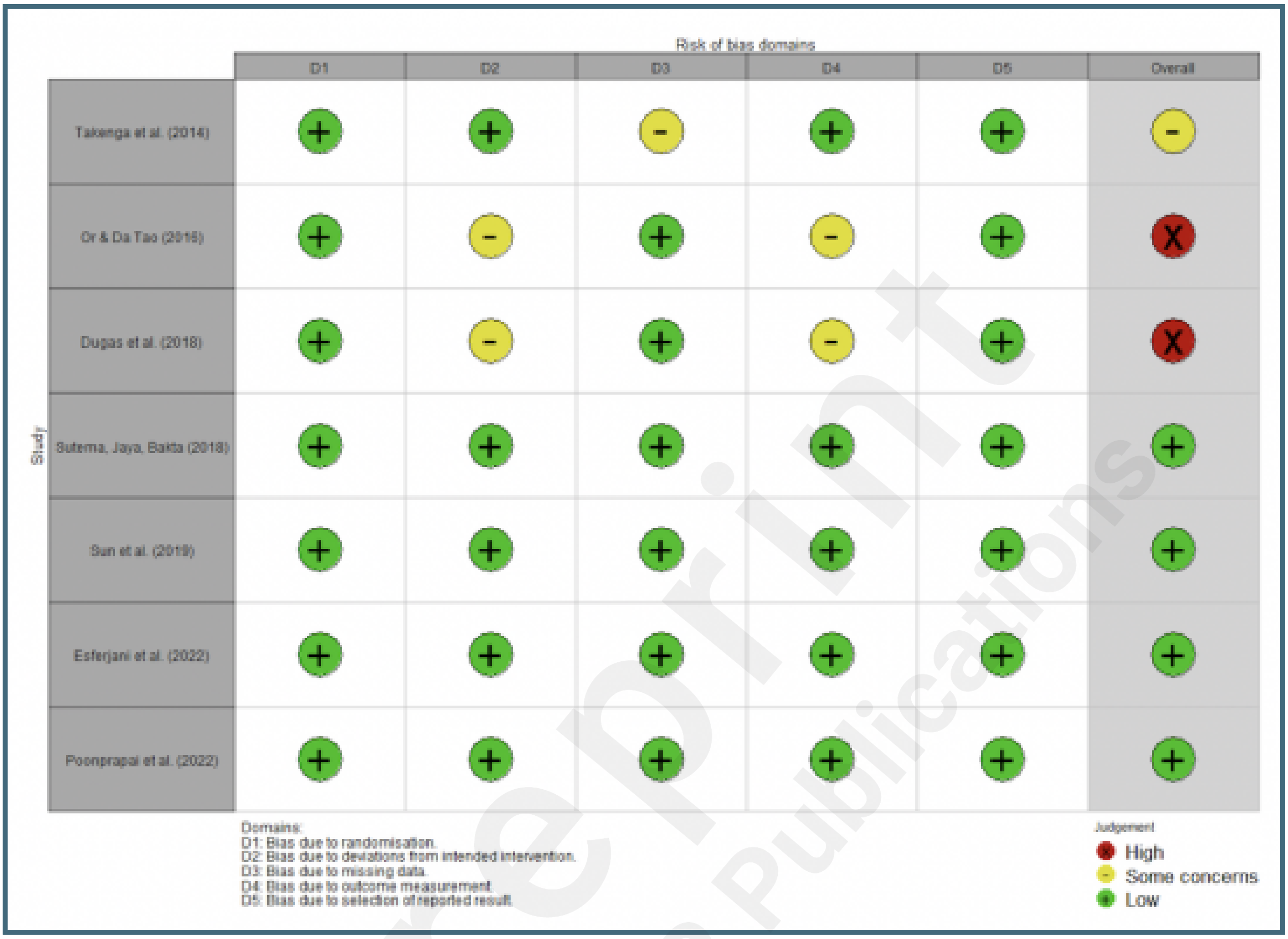
Supplementary Files

Figures

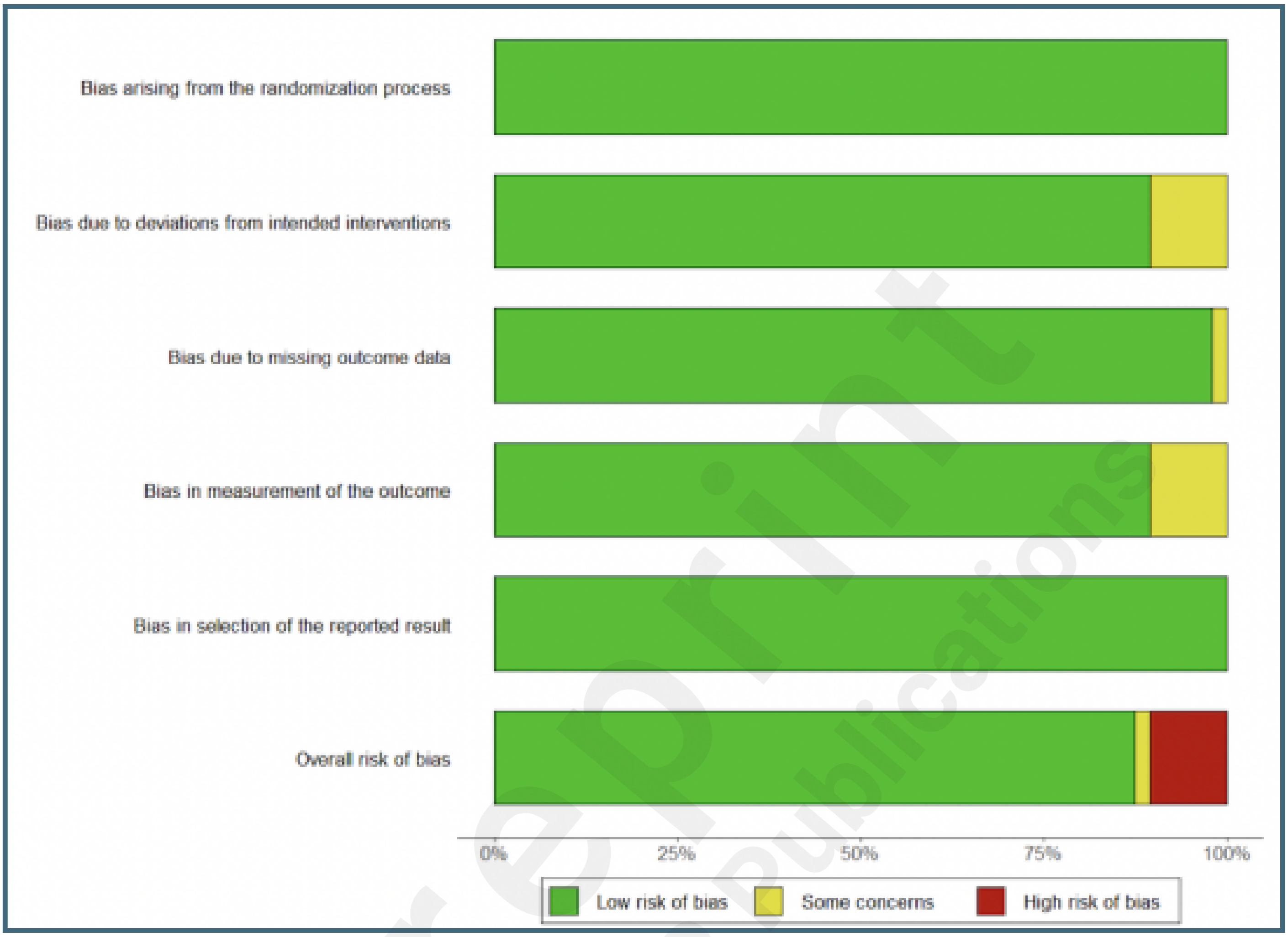
PRISMA flowchart of studies included in the review.



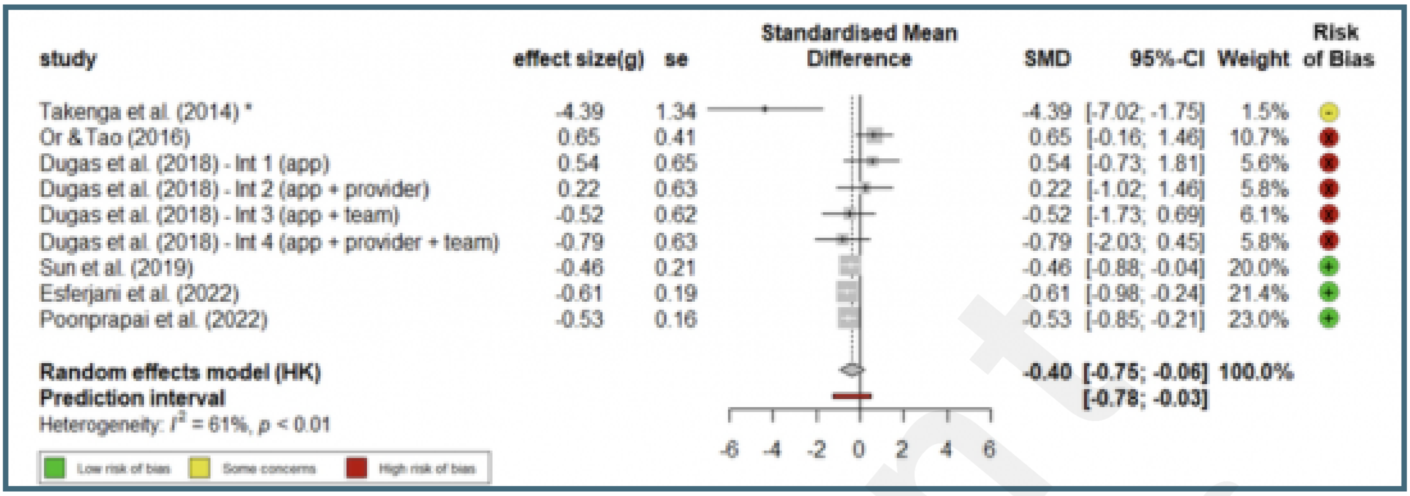
Risk of bias assessment summary (RoB 2.0).



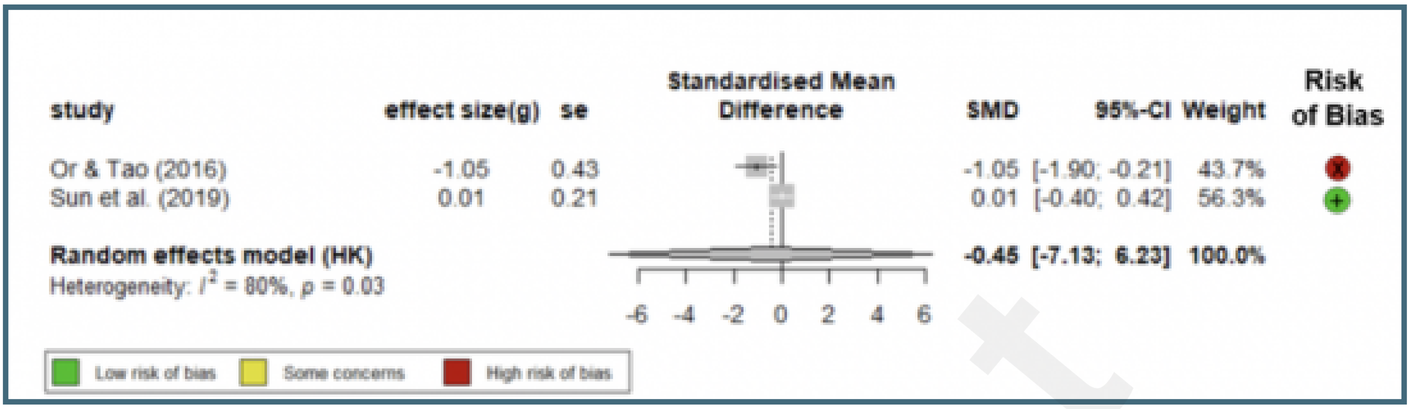
Bias appraisal across domains.



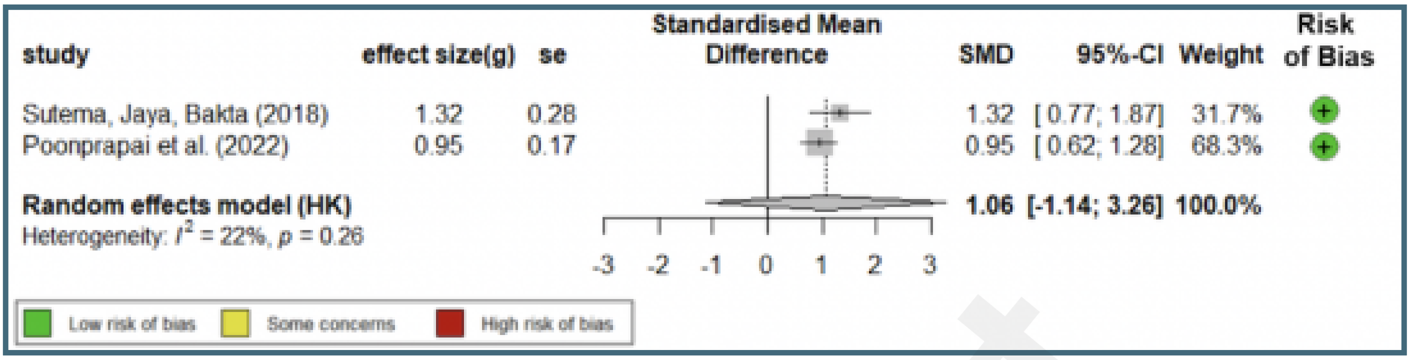
Forest plot of standardized mean differences of mHealth apps on HbA1c reduction.



Forest plot of standardized mean differences of mHealth apps on FBS reduction.



Forest plot of standardized mean differences of mHealth apps on improving medication adherence.



Funnel plot of standard error by standardized mean differences on the effects on HbA1c. HbA1c measures provided for 9 studies.