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# A New Taxonomy for Technology-Enabled Diabetes Self-Management Interventions: Results of an Umbrella Review

**Deborah A. Greenwood, PhD, RN, BC-ADM, CDCES, FADCES[1], Michelle L. Litchman, PhD, FNP-BC, FAANP, FADCES[2], Diana Isaacs, PharmD, BCPS, BCACP, CDCES, BC-ADM, FCCP, FADCES[3], Julia E. Blanchette, PhD, RN, CDCES[2], Jane K. Dickinson, RN, PhD, CDCES[4], Allyson Hughes, PhD[5], Vanessa D. Colicchio, BSN, RN[2], Jiancheng Ye, MS[6], Kirsten Yehl, MS, MLIS[7], Andrew Todd, MLIS, BSN[8], and Malinda M. Peeples, MS, RN, CDCES, FADCES[9]**


## Abstract

**Background:** A 2017 umbrella review defined the technology-enabled self-management (TES) feedback loop associated with a significant reduction in A1C. The purpose of this 2021 review was to develop a taxonomy of intervention attributes in technology-enabled interventions; review recent, high-quality systematic reviews and meta-analyses to determine if the TES framework was described and if elements contribute to improved diabetes outcomes; and to identify gaps in the literature.

**Methods:** We identified key technology attributes needed to describe the active ingredients of TES interventions. We searched multiple databases for English language reviews published between April 2017 and April 2020, focused on PwD (population) receiving diabetes care and education (intervention) using technology-enabled self-management (comparator) in a randomized controlled trial, that impact glycemic, behavioral/psychosocial, and other diabetes self-management outcomes. AMSTAR-2 guidelines were used to assess 50 studies for methodological quality including risk of bias.

**Results:** The TES Taxonomy was developed to standardize the description of technology-enabled interventions; and ensure research uses the taxonomy for replication and evaluation. Of the 26 included reviews, most evaluated smartphones, mobile applications, texting, internet, and telehealth. Twenty-one meta-analyses with the TES feedback loop significantly lowered A1C.

**Conclusions:** Technology-enabled diabetes self-management interventions continue to be associated with improved clinical outcomes. The ongoing rapid adoption and engagement of technology makes it important to focus on uniform measures for behavioral/psychosocial outcomes to highlight healthy coping. Using the TES Taxonomy as a standard approach to describe technology-enabled interventions will support understanding of the impact technology has on diabetes outcomes.



### Keywords

A1C, diabetes care and education, diabetes self-management education and support, taxonomy, technology-enabled self-management, umbrella review


## Introduction

Multiple umbrella reviews identify significant improvement in clinical outcomes, including hemoglobin A1C (A1C) when technology is part of the model of care.[1-4] These technologies include diabetes devices (eg, connected pens, glucose monitors and continuous glucose monitors), mobile devices (eg, mobile applications, wearables, fitness trackers) and technology-enabled communications (eg, text messaging, 2-way chat). In a 2017 review of high-quality systematic reviews, a framework evolved identifying 4 key elements of technology-enabled interventions associated with significant change in A1C.[1] The technology-enabled self-management (TES) feedback loop includes communication between the

[1]School of Nursing, UT Health San Antonio, TX, USA
[2]University of Utah, College of Nursing, Salt Lake City, UT, USA
[3]Cleveland Clinic Diabetes Center, Cleveland, OH, USA
[4]Teachers College Columbia University, New York, NY, USA
[5]T1D Exchange, Boston, MA, USA
[6]Northwestern University Feinberg School of Medicine, Chicago, IL, USA
[7]Association of Diabetes Care & Education Specialists, Chicago, IL, USA
[8]University of Central Florida, College of Nursing, University Tower, Orlando, FL, USA
[9]Welldoc, Columbia, MD, USA

**Corresponding Author:**
Deborah A. Greenwood, PhD, RN, BC-ADM, CDCES, FADCES, School of Nursing, UT Health San Antonio, 7703 Floyd Curl Dr, San Antonio, TX 78229 USA.
Email: Deborah@deborahgreenwoodconsulting.com

care team and people with diabetes (PwD); transmission and analysis of patient generated health data (PGHD); general or tailored education based on ADCES7 Self-Care Behaviors™,[5] informed by PGHD; and individualized PGHD feedback delivered in real-time or asynchronously by technology or care team.[1]

As technology has evolved, digital/virtual programs focused on chronic condition management and supported by employers or health systems emerged (eg, Onduo, Livongo®, BlueStar®) that implement the TES feedback loop elements to provide care, education, and support. Additionally, the Association of Diabetes Care & Education Specialists (ADCES) has continued to define the role of the diabetes care and education specialist in the integration and implementation of technology-enabled self-management solutions.[6] While achieving target A1C is an essential piece of the puzzle, it is important to understand the type of technology, design of the interventions, user experience, and workflow, which influence glycemic, other physiological, and behavioral/psychosocial diabetes self-management outcomes.[7,8] Recent systematic reviews have evaluated the impact of technology in diabetes care and education. While numerous authors cite the 2017 review, most focus on the association of technology with lowering A1C. Since 2017, the National Standards for Diabetes Self-Management Education and Support[9] and the American Diabetes Association (ADA)[10] Standards of Care (SOC) have recognized the TES framework for effective technology-enabled interventions. However, it is unclear if the TES framework is being used as a guide to develop and evaluate technology-enabled interventions.

The purpose of this umbrella review was to (1) develop a taxonomy to describe intervention attributes in technology-enabled interventions; (2) review recent, high-quality systematic reviews and meta-analyses to determine if the elements of the TES framework were described and whether the elements continue to contribute to improved diabetes outcomes; and (3) to identify gaps in the literature regarding technology-enabled diabetes self-management.

## Methods

### Phase 1 Taxonomy Development

We reviewed the TES framework from the 2017 review[1] and identified additional key technology attributes needed to describe the active ingredients of technology-enabled interventions that lower A1C levels. As an exemplar, we applied the medication full prescribing information (FPI)[11] to define the detailed attributes of technology-enabled interventions, including indications, class, mechanism of action, active ingredients, dose, route, frequency, duration, and adverse effects.

The attribute definitions were evaluated for appropriateness and completeness in a 2-step process by applying the definitions to 3 representative technology studies.[12-14] First, 2 authors applied the definitions to each study, then a third author reviewed for discordance. The definitions were then revised and applied to the same studies in a second review. Figure 1 shows the application of the definitions to the studies.

### Phase 2 Umbrella Review

We identified parameters a priori and searched for English language reviews published between April 2017 and April 2020, focused on PwD (population) receiving diabetes care and education (intervention) and using technology enabled self-management in randomized controlled trials (comparator) that impact, glycemic, other physiological, and behavioral/psychosocial outcomes. A medical librarian searched multiple databases using subject headings and text words related to technology, diabetes mellitus, self-management, self-care or patient education, and systematic reviews or meta-analysis following Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) recommendations.[15] See Figure 2 for the PRISMA diagram.

*Sources, Searching, and Review.* Cumulative Index to Nursing and Allied Health Literature (CINAHL), Cochrane Database of Systematic Reviews, Cochrane Register of Controlled Trials, MEDLINE Complete, APA PsycInfo, and Web of Science were searched in April 2020 and repeated in June 2020 to retrieve current literature. (See Supplemental Appendix A). After identifying duplicates, reviewers screened abstracts from 723 articles specific to technology-enabled diabetes self-management or education interventions. Two independent reviewers screened each abstract (DI, ML, JB, JD, VC). A third reviewer (DG or MP) resolved disagreements. A total of 111 full text articles (US and international) met inclusion criteria. Reviews were included if 2 authors reviewed for inclusion criteria and identified 2 or more databases for their search strategy. Reviews were excluded if they did not measure outcomes, if studies were protocols of reviews or incomplete, if technology was not the focus of the study, or if studies were included in the 2017 review. Studies of school site/classroom interventions, diabetes devices only, or solely feasibility, costs, and mortality were excluded. Full text review was completed on 111 studies. Each study was reviewed by 2 independent reviewers (DG, DI, JB, JD, ML, MP, VC) and conflicts were discussed to consensus. Fifty studies were retained.

*Screening for Methodological Quality.* Four reviewers in teams of 2 (DG and DI; JB and JD) assessed the 50 studies for methodological quality, including risk of bias, following the AMSTAR-2 quality assessment guidelines.[16] This 16-question guideline was designed to identify critical flaws pertaining to study design and allow researchers to assign overall confidence. The research team identified 9

| | INDICATION | TECHNOLOGY CLASS | MECHANISM OF ACTION AND ACTIVE INGREDIENTS | DOSE | ROUTE | FREQUENCY | DURATION | ADVERSE EFFECTS |
|---|---|---|---|---|---|---|---|---|
| Example 1 MDIS [12] | Adults 18 years and older with T2D not using insulin pumps or with GDM and their PCP | Automated digital health via mobile app, tablet, and/or computer | Three group RCT to determine if a mobile intervention with automated, clinical and behavioral coaching for participants and data/reports for PCPs results in changes A1C (primary) and patient-related symptoms (secondary) including diabetes distress and other metabolic values (three groups- participant shared reports, raw data, or analyzed data with clinical decision support).<br><br>**Communication:** Both; one-way, within app automated real-time, data-driven messages for participants; two-way, participant transmitted analyzed app PGHD to provider for shared-decision making<br>**PGHD:** Both; participant tracked (glucose, food, activity, meds) and PGHD analyzed by mobile app following guidelines and sent to provider (initiated by participant)<br>**Education:** General education resources (videos, tips, articles) and tailored based on medication regimen (e.g. oral or insulin)<br>**Feedback:**<br>How: Data-driven real-time feedback messages based on BG readings, medication regimen and treatment plan; trending messages and in-app notification-based patterns of data, missing data or out of date exams, etc.<br>Who: In-app, automated, AI coaching for the participant and data visualization for the PCP | Personalized journey based on data entered; in app prompts for increasing engagement | Automated within app/ computer | Time: 24/7 availability; accessed as needed by participant<br><br>Data-driven: Real-time and trending messages based on data entered (value, time, etc) | 12-months; the intervention is ongoing and adapts to changes in medication and treatment plan | No negative technology related effects described |
| Example 2 REACH Trial [13] | Diverse adults with T2D, A1C > 6.8%, prescribed a daily diabetes medication, owning a cell phone with text capability; half were racial/ethnic minorities, uninsured, and low income | Text messaging via mobile phone | RCT with REACH compared to control to evaluate effect on A1C (primary outcome) and medication and self-care behaviors (secondary). The REACH group received three types of automated text messages; one-way self-care promotion (e.g. diet, exercise, BGM) and tailored texts based on their top 4 self-identified theory-based barriers (Information, motivation, behavioral skills model) to taking prescribed medication at baseline with tailoring updated at 3 and 6 months; interactive texts about medication taking behaviors for that day (Did you take all of your diabetes medications? Yes/no); weekly feedback texts with encouragement based on responses from interactive texts. Both groups had access to a helpline for questions about diabetes medications and quarterly newsletters on living with diabetes.<br><br>**Communication:** Both, one-way, study generated (messages promoting self-care) and two-way interactive (messages asking if they took all their diabetes medications)<br>**PGHD:** Both, tracked (yes/no to medication taking) and analyzed (tailored messages based on surveys)<br>**Education:** General and tailored based on self-identified barriers<br>**Feedback:**<br>How: Asynchronous; MEMOTEXT tailors, schedules, and sends text messages using participant data received through an API. Does not describe how the interactive responses are analyzed and follow-up messages generated<br>Who: Texts | First 6 months-daily scheduled texts; Second 6 months-participants could continue daily or choose a "low dose option" with 3-4 one-way texts and weekly interactive texts | Automated (MEMOTEXT digital health platform) | Time: Daily one-way texts<br><br>Data-driven: Weekly interactive texts | 12-months | Slow system response time; steps for carrying out the suggestions not provided; some messages implied a problem when none existed |
| Example 3 WISDM Trial [14] | Adults with T1D, ≥ 60 years use of insulin pump or MDI, A1C <10%, no use of RT-CGM in prior 3 months | RT-CGM | RCT to determine if CGM is effective in reducing hypoglycemia (< 70 mg/dL) compared to BGM.<br><br>**Communication:** Both; One-way-data from RT-CGM to participant; two-way between care team and participant<br>**PGHD:** Real-time glucose data tracked and analyzed with RT-CGM, real time safety alerts and alarms for hypo- (< 70 mg/dL and urgent low at 55 mg/dL) and hyperglycemia; retrospective data analyzed by clinicians<br>**Education:** General education by clinicians on diabetes management; tailored education based on retrospective PGHD to inform treatment recommendations. Additional instructions provided on using CGM trend arrows to adjust insulin dosing based on guidelines specific to an at-risk older adult population<br>**Feedback:**<br>How: Real-time and asynchronous<br>Who: RT-CGM and clinician | RT-CGM data accessible 24/7 | Both RT-CGM and clinician | Time: Study visits at 4, 8, 16, and 26 weeks<br><br>Data-driven: RT-CGM continuous data | 26 weeks | Alarm malfunction, stopped working, connectivity failure, sensor inaccuracy |

Abbreviations: A1C, glycosylated hemoglobin A1C; BGM; blood glucose monitoring; GDM, gestational diabetes; MDIS, mobile diabetes intervention study; PCP, primary care provider; PGHD, patient generated health data; REACH, Rapid Encouragement/Education And Communications for Health; RT-CGM, real-time continuous glucose monitor; T2D, type 2 diabetes; WISDM, Wireless Innovation for Seniors With Diabetes Mellitus

**Figure 1.** Taxonomy definitions applied to exemplar studies.

critical questions (# 1,2,3,4,5,6,8,9,16). Studies with one or more critical flaws were excluded. Studies with non-critical flaws but no critical flaws were included in the review and final analysis. Twenty-six reviews were retained. (See Supplemental Appendix A for critical questions and critical flaws)

*Data Extraction and Analysis.* Eight reviewers in teams of 2 (JB and JY; JD and AH; DG and DI; VC and ML) independently entered data into a data extraction table then met to confirm assessments. Tables included the following information: research question and components of PICO (population, intervention, comparator group, outcome); description of included studies (number, year, location, duration, participant characteristics, types of clinicians involved in interventions, technology and devices used); outcomes (technology usability, behavioral/psychosocial, ADCES7 Self-Care Behaviors™, physiological and glycemic including A1C); and TES features. Supplemental data were used where available to gather complete information.

## Results

### Phase 1

Building upon the 2017 TES feedback loop[1] and definitions applied in this review, we developed a preliminary taxonomy to be used when describing technology-enabled interventions. Similar to other taxonomies,[17] the Taxonomy of Technology-Enabled Self-Management Interventions (TES Taxonomy) was developed for 2 purposes: (1) to standardize the description of technology-enabled self-management interventions and (2) to ensure that future research uses the taxonomy to encourage replication, comparison, and evaluation.[18] Table 1 describes the attributes and the definitions of the TES Taxonomy.

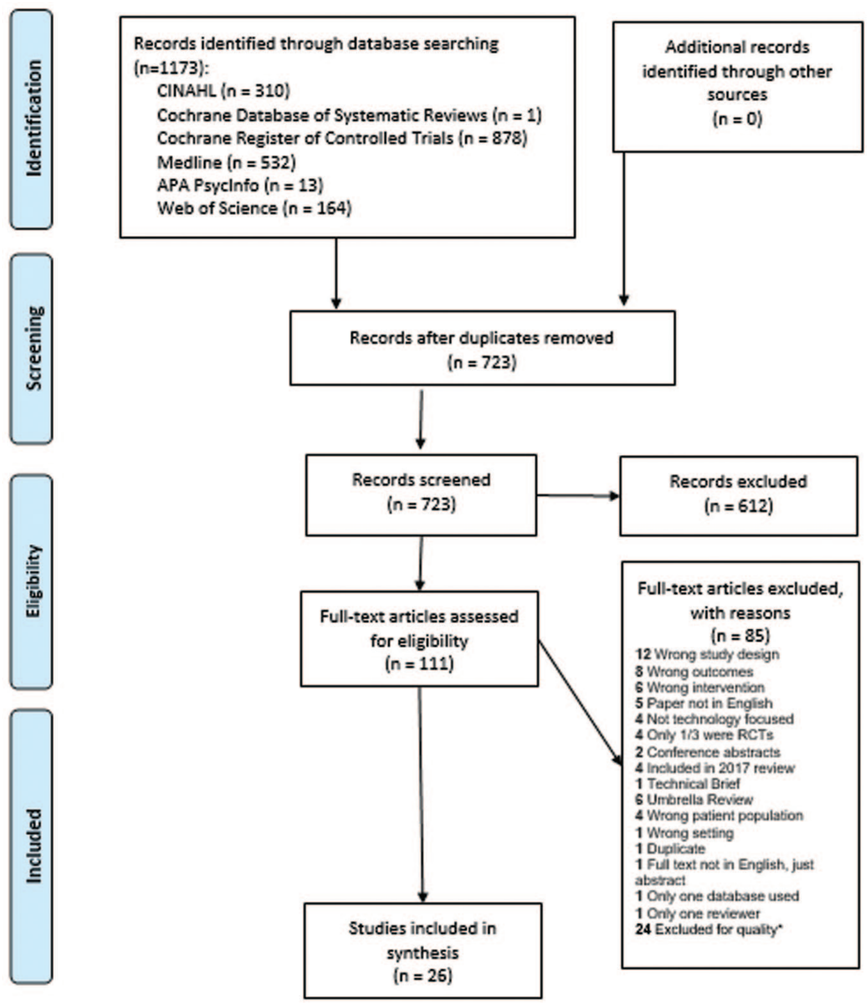


**Figure 2.** PRISMA flow diagram 2009.

## *Phase 2*

*Study Characteristics.* Twenty-six reviews, published between 2017 and 2020, conducted in multiple countries, were included in this umbrella review,[19-44] See Table 2. The number of studies in the selected reviews ranged from 7 to 111, and the number of participants ranged from 30 to 23,648. Participants included children through older adults with mean age range from 8-80 years. Three (11.5%) reviews did not report age ranges[26,34,42], 2 (9.5%) reported only "adults."[27,29] Four (15.4%) included studies with only T1D,[22,37,42,44] 14 (53.8%) included studies with only T2D,[19,20,23,24,27-29,31-33,38,39,42,44] and 12 (46.2%) reviews included both T1D and T2D.[21,24-26,29,34-36,39,41-43] Studies utilized a variety of clinicians; 3 (11.5%) studies did not report type of clinician[20,23,37], 5 (19.2%) studies stated only "healthcare professionals."[19,32,39,41,42]

*Technology and Outcomes.* Studies ($n$=26) reviewed multiple types of technology interventions and their impact on diabetes self-management outcomes (glycemic, other physiological and behavioral/psychosocial). Studies most frequently ($n$=18, 69.2%) evaluated smartphone and mobile applications (smartphone/apps)[19,20,22,25-27,29-31,33-37,39-42] followed by text messaging and secure messaging (texting/secure messaging [$n$=14, 53.8%]),[19,23-35] internet or website interventions (web/internet/websites/portals [$n$=13, 50.0%]),[22,24-33,35,43] and telehealth related patient-provider interactions (telehealth/video conferencing/telemedicine/provider chat [$n$=12, 46.2%]).[21,22,24,29-36,43] Technology interventions are displayed in Table 3.

The studies explored diabetes self-management (glycemic, other physiological and behavioral/psychological) related outcomes (Table 3). For glycemic outcomes, most ($n$=24, 92.3%)[19-27,29-43] studies included A1C as an outcome. The most common technology interventions and glycemic

**Table 1.** Taxonomy of Technology-Enabled Self-Management Interventions (TES Taxonomy).

| Taxonomy attributes | Definition |
|---|---|
| Indication | Identifies who the intervention is for and who it is not for |
| Technology class | Describes the main technology device class (eg, BGM, CGM, mobile apps, text messaging, insulin pump, pen devices, online peer support) |
| Mechanism of action and active ingredients | Provides a description of the intervention including individual components and desired outcomes, and defines the features of the TES Feedback loop: |
| | Communication: One-way, 2-way, both |
| | PGHD: Data tracked, analyzed or both |
| | Education: General or tailored based on PGHD |
| | Feedback: |
| | How: Real-time, asynchronous, or both |
| | Who: Human (care team, interventionist) or technology (AI) |
| Dose | Describes how much of the intervention is delivered (eg, just in time, accessible 24/7, anytime anywhere, front loaded with taper) |
| Route | How the intervention is delivered (eg, automated, human-augmented, or both) and who or what delivers it |
| Frequency | Describes how often and when the intervention is delivered |
| | Time-based: Daily, weekly, as needed, etc. |
| | Data-driven |
| Duration | Describes how long the intervention is delivered. (eg, 12-weeks, 6-months, maintenance, intermittent) |
| Adverse effects | Describes any untoward effects identified from the study (eg, device malfunction vs user device issues, technical connectivity issue or Internet access) |

Abbreviations: AI, artificial intelligence; BGM, blood glucose monitoring; CGM, continuous glucose monitoring; PGHD, patient generated health data; TES, technology-enabled self-management.

outcomes were smartphone, mobile applications, and A1C ($n$=18, 69.2%),[19,20,22,25-27,29-31,33-37,39-42] with most ($n$=13/18, 72.2%) having statistically significant findings.[19,22,25,29-31,33-37,39,40,42] Over half of the studies assessed non-glycemic physiological outcomes (other physiological outcomes) ($n$=14, 53.8%).[19,21,25,27-32,35,38,40,43,44] The most common other physiological outcome measured was BMI ($n$=8, 33.3%),[19-21,25,27,29,30,43] which was assessed in relation to smartphone and mobile application interventions ($n$=6/8, 75.0%).[19,20,25,27,29,30] No studies assessing BMI reported statistical significance. Thirteen studies (50.0%) assessed behavioral/psychosocial outcomes.[19,21,23,26,29-32,34,35,38,40,41] The most common behavioral/psychosocial outcome measure, quality of life ($n$=8, 30.8%)[19,21,23,29-32,40] was linked to texting/SMS interventions (n=6/8, 75.0%).[19,29-32,40] However, only one study found a significant outcome between quality of life and texting/SMS interventions.[29] Another common outcome measured was general self-management behaviors ($n$=7, 26.9%)[23,26,31,34,35,38,41] using smartphone and mobile applications ($n$=5/7, 71.4%).[26,31,34,35,41] However, none of these outcomes were significant.

Interventions incorporating multiple modalities (eg, texting or telehealth in combination with web-based tools) more frequently had significant outcomes compared to single interventions. There is also strong evidence supporting A1C reduction with a variety of technologies (Table 3). Three studies identified that technology-enabled interventions were more effective in people with T2D,[36,39,40] one study determined interventions were more effective in T1D;[26] however, no pattern emerged to identify technologies with the greatest reduction in A1C for specific populations. Two studies reported greater short-term A1C reductions at the first follow-up timepoint.[21,24]

Table 4 identifies the ADCES7 self-care behaviors™[5] addressed by the studies included in the reviews. Healthy eating was the most common self-care behavior addressed in the studies and being active ranked second highest. Only eight (38%) studies included problem–solving,[19,22,24,26,27,30,42,43] which ranked second lowest, and 5 (23.8%) studies focused on healthy coping.[19,24,29,30,34]

*Intervention Features.* In this review we evaluated the 4 essential intervention features of the TES feedback loop: communication, patient generated health data (PGHD) analysis, education, and feedback. We used the TES feature definitions from Greenwood et al,[1] and expanded the definition of feedback into 2 sub-categories. To compare the results of this study with the 2017 research, the 21 studies that included a meta-analysis with significant mean difference in A1C between the intervention and control groups are displayed in Table 5. In the table, the authors are ordered by the mean difference in A1C from greatest to least.

Communication was defined as a one-way or 2-way exchange of information between the participant and care team. Twenty reviews described studies with 2-way communication, with one study including only one-directional texts.[23] while 18 (85.7%)[19,20,22,24-37,39-44] of the studies included both one-way and 2-way communication. PGHD

**Table 2.** Study Characteristics ($n=26$).

| Authors | Articles (n) | Subjects (n) | Mean age or range (years) | Country/continent, language | Clinician |
|---|---|---|---|---|---|
| Aminuddin et al[19] | 26 | 2645 | 47.5-65.8 | Bangladesh, China, Democratic Republic of Congo, Finland, India, Iran, Japan, Mexico, Norway, Philippines, South Korea, Thailand, US<br>English | HCPs |
| Cai et al[20] | 14 | 2129 | 51.1-66.1 | Canada, China, Finland, India, Japan, Korea, Mexico, Norway, Spain, US<br>English | Not reported |
| Faruque et al[21] | 111 | 23648 | 24-75 | Australia, Canada, Korea, US<br>English | CDE/BCADM/Educator, MD/DO, Peer/CHW, Pharmacist, Psychologist/behaviorist, RDN/Dietitian/Nutritionist, RN<br>Others: Allied health, Care manager, Diabetes team, Exercise Physiologist, Exercise trainer, Non-specialized support, Researcher |
| Feigerlová et al[22] | 8 | 757 | 15-38.4 | Australia, Italy, Spain, US<br>No language restrictions | CDE/BCADM/Educator, MD/DO<br>Other: Nurse care manager |
| Haider et al[23] | 11 | 1710 | 47-59 | China, Hungary, India, US, New Zealand, Iran, Bangladesh, UAE, Philippines<br>English | Not reported |
| Heitkemper et al[24] | 13 | 3257 | 50.5-70.9 | US or not reported Cantonese, English, Spanish | CDE/BCADM/Educator, Peer/CHW, RDN/Dietitian/Nutritionist, RN<br>Others: Clinician, Research coordinator |
| Hu et al[25] | 14 | 1324 | 25-68 | Canada, China, Greece, India, Israel, Italy, Korea, Poland Saudi Arabia, Spain, US<br>English | CDE/BCADM/Educator, MD/DO, RN<br>Others: CDS systems, Diabetes teams, Research teams (Caregivers, Nursing specialists, Researchers) |
| Huang et al[26] | 13 | 1164 | Not reported | Asia, Australia<br>English | RN |
| Kirk et al[27] | 35 | 4528 | Adults | Australia, Belgium, Brazil, Canada,<br>Denmark, Finland, France, Germany, India<br>Netherlands, South Korea, UK, US<br>English | MD/DO, RN<br>Others: Healthcare team, Researcher |
| Kongstad et al[28] | 27 | 4215 | 51.7-62 | Country/continent not reported<br>Danish, English, Norwegian, Swedish | Coach, Peer/CHW, RDN/Dietitian/Nutritionist, RN |
| Kuo et al[29] | 16 | 30-786 | Adults | Australia, Canada, England, Germany, Netherlands, South Korea, Thailand, US<br>Chinese, English | Coach, Peer/CHW, RN<br>Not reported |
| Lee et al[30] | 41 | 2582 | Children and teens (mean 14, range: 10-17). Adults (mean 24, range: 24-43). | Asia, Europe, North America<br>No language restrictions | Case Manager, CDE/BCADM/Educator, Peer/CHW, MD/DO, Pharmacist, Psychologist/Behaviorist, RDN/Dietitian/Nutritionist, RN |
| Liu et al[31] | 24 | 2285 | 48.4-69.5 | Africa, Asia, Europe, North America<br>English | CDE/BCADM/Educator, Coach, MD/DO, Peer/CHW, RN |
| Michaud et al[32] | 17 | 2453 | 46.7-66.2 | Countries/continents not reported<br>English | HCPs<br>Other: specialized team |
| Shen et al[33] | 35 | 6475 | 42.3-79.9 | Canada, China, Congo, England, Finland, Italy, Japan, Korea, Norway, Poland, Spain, Turkey, US<br>*Language not reported | CDE/BCADM/Educator, MD/DO, RN |
| So and Chung[34] | 7 | 853 | Not reported | Iran, South Korea, US<br>English | MD/DO, RN<br>Other: Student |
| Tao et al[35] | 80 | 11820 | 8.5-70.8 | Asia, Europe, North America, Oceania<br>English | Coach, NP, Peer/CHW |
| Tchero et al[36] | 42 | 6170 | 13.3-71 | Australia, Canada, China, Georgia, Finland, France, Greece, Israel, Italy, Japan, Korea, Poland, South Korea, Spain, UK, US<br>English | CDE/BCADM/Educator Coach, NP, Pharmacist, RN |
| Wang et al[37] | 8 | 602 | 12.9-38.4 | Australia, France, Germany, Italy, Scotland, US<br>English | Not reported |
| Wei et al[38] | 18 | 3954 | 52-68 | Australia, Belgium, China, Germany, Iran, Jordan, Korea, UK, US<br>English | Pharmacist, Psychologist/Behaviorist, RDN/Dietitian/Nutritionist, RN<br>Others: Clinicians, Paraprofessionals |
| Wu et al[39] | 13 | 974 | Not reported | Australia, Italy, Japan, Korea, Netherlands, Norway, UK, US<br>Chinese, English | HCPs |
| Wu et al[40] | 17 | 2225 | 42.3-65.8 | Canada, Democratic Republic of the Congo, Finland, Japan, Korea, Mexico, Norway, UK, US<br>No language restrictions | HCPs |
| Wu et al[41] | 19 | 6294 | 45.5-68.4 | US, Europe<br>English | HCPs, MD/DO, RN<br>Others: Clinical health psychologists, Exercise experts |
| Wu et al[42] | 26 | 2526 | T1D: 34.9-39.7 T2D: 44.7-66.3 | Type 1: Australia, Europe<br>Type 2: Asia, Australia, Europe, North America<br>Pre-diabetes: US<br>GDM: US<br>No language restrictions | HCPs |
| Yang et al[43] | 17 | 20-237 | 26.35-63.8 | Australia, Belgium, China, Denmark, Egypt, Greece, Iran, Thailand, Turkey, UK, US<br>English | RN |
| Yoshida et al[44] | 32 | 3290 | 45-67 | China, Iran, India, Japan, South Korea, US<br>Europe<br>English | MD/DO, RN<br>Others: Medical care providers; some non-medical |

Abbreviations: BC-ADM, board certified, advanced diabetes management; CDE, certified diabetes educator (now known as certified diabetes care and education specialists); CHW, community health worker; HCP, healthcare professional/provider; MD/DO, physician; NP, nurse practitioner; RDN, registered dietitian nutritionist; RN, registered nurse; T1D, type 1 diabetes; T2D, type 2 diabetes.

**Table 3.** Types of Technology Included in the Interventions and Outcomes Measured (*n* = 26).

| Authors | Type of technology | | | | | | | | | | | Diabetes outcomes | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | Glycemic[a] | Other physiological[b] | Behavorial and psychosocial[c] |
| Aminuddin et al[19] | X | X | | | | | | | | | | A1C[d] | BMI, BP | QoL, SE[d] |
| Cai et al[20] | X | | | | | | | | | | | A1C | BMI, WC | |
| Faruque et al[21] | | | | X | X | | X | | | | | A1C[i], Hypo | BMI | D, DD, QoL |
| Feigerlová et al[22] | X | | X | X | | | | | | | | A1C[d] | | |
| Haider et al[23] | | X | | | X | | | | | | | A1C[d] | | PS, QoL, SE, SM |
| Heitkemper et al[24] | | X | X | X | X | X | | | X | | | A1C[i] | | |
| Hu et al[25] | X | X | X | | X | X | X | | | | | A1C[d], Hypo | BMI | |
| Huang et al[26] | X | X | X | | X | | | | | | | A1C[f,j], Gluc[f], Hypo | | PS, SM |
| Kirk et al[27] | X | X | X | | X | | X | | X | | | A1C, Gluc | BMI, BP, PA[d], Weight | |
| Kongstad et al[28] | | X | X | | X | | X | | | | | | PA[d] | |
| Kuo et al[29] | X | X | X | X | X | X | X | X | | | | A1C[d] | BMI, PA[d], Weight[d] | E[d], QoL[d], SE[d] |
| Lee et al[30] | X | X | X | X | | X | | | | | | A1C[d], Gluc, Hypo | BMI, BP, HLD, Weight | QoL |
| Liu et al[31] | X | X | X | X | | X | | | X | X | | A1C[d] | BP[d] | QoL, SM |
| Michaud et al[32] | | X | X | X | X | X | | | X | | | A1C[d] | Weight | QoL |
| Shen et al[33] | X | X | X | X | | | | X | | | | A1C[d] | | |
| So and Chung[34] | X | X | | X | X | | | | | | | A1C[d], Gluc | | SM |
| Tao et al[35] | X | X | X | X | | X | | X | | X | | A1C[d] | | DD, PS, SM |
| Tchero et al[36] | X | | | X | | | | X | | | | A1C[d,g] | | |
| Wang et al[37] | X | | | | | | | | | | | A1C[e] | | |
| Wei et al[38] | | | | | X | | | | | | | A1C[d] | BP, HLD, Weight | SM |
| Wu et al[39] | X | | | | X | | | | | | | A1C[d] | BP, HLD, Weight | QoL |
| Wu et al[40] | X | | | | | | | | | | | A1C[d], Gluc | | |
| Wu et al[41] | X | | | | | | | | | | | A1C[h] | | SM |
| Wu et al[42] | X | | | | | | | | | | | A1C[g] | | |
| Yang et al[43] | | | X | X | X | | X | | | | | A1C[d], Gluc[d] | BMI, HLD | |
| Yoshida et al[44] | | | | | | | | | | | X | | BP[d], HLD, Weight | |

**Type of Technology (listed in order of most common)**

1. Smartphones/Apps (applications)
2. Texting and SMS (short message service)
3. Web/Internet/Websites/Portals
4. Telehealth/Video Conferencing/Telemedicine/Provider Chat
5. Telephone
6. Remote Monitoring
7. Email Messaging
8. Personal Computer
9. Wearables
10. Digital Therapeutics
11. Health Information Technologies[12]

[a]A1C, hemoglobin A1C; Gluc, fasting blood glucose; Hypo, hypoglycemia.
[b]BMI, body mass index; BP, blood pressure; HLD, hyperlipidemia; PA, physical activity; WC, waist circumference; Weight.
[c]D, depression/depressive symptoms; DD, diabetes distress; E, empowerment; PS, patient satisfaction; QoL, quality of life; SE, self-efficacy; SM, self-management.
[d]Statically significant outcome.
[e]Significant with Apps only (not SMS).
[f]Significant with SMS only (not Apps).
[g]Significant mean difference larger in T2D.
[h]Significant in just T2D.
[i]Greatest reduction at first follow-up timepoint.
[j]Greater significance in T1D.

was defined as either tracked or tracked and analyzed (both). Fifteen (71.4%) of the reviews[19,21,23,25,30-33,35,36,39-43] described PGHD as both and 5 (23.8%) reviews[24,26,27,29,38] described as tracked only. One did not clarify how PGHD were used, but detailed that interventions included either texts or a diabetes management app.[37] Education content was defined as either general self-management education or tailored based on self-care behaviors and PGHD, with 19 of the reviews identifying both types of education (90.4%).[19,21,23-27,29-33,35,36,39-43] General education was described in one[38] (4.7%) and not described in one[37] (4.7%). In this review, we expanded feedback into 2 sub-categories: how the feedback was provided, either real time or asynchronously, and who provided the feedback, an individual/diabetes team member or via an automated response. In this review, feedback to participants was reported as asynchronous by 5 (23.8%) reviews,[21,23,26,31,39] both asynchronous and real-time by 14[19,24,25,27,29,30,32,33,36,37,40-43] (66.6%) and only real-time by 2[35,38] (9.5%) reviews. The

**Table 4.** ADCES7 Self-Care Behaviors™ Addressed by Technology (*n* = 26).

| Authors | Healthy eating | Being active | Monitoring | Taking medications | Reducing risk | Problem solving | Healthy coping |
|---|---|---|---|---|---|---|---|
| Aminuddin et al[19] | X | X | X | X | X | X | X |
| Cai et al[20] | X | X | X | | X | | |
| Faruque et al[21] | X | X | | X | | | |
| Feigerlová et al[22] | | | | X | | X | |
| Haider et al[23] | X | X | X | | | | |
| Heitkemper et al[24] | X | X | X | X | X | X | X |
| Hu et al[25] | X | X | X | X | | | |
| Huang et al[26] | X | X | X | X | | X | |
| Kirk et al[27] | X | X | | | | X | |
| Kongstad et al[28] | | X | | | | | |
| Kuo et al[29] | X | X | | | | | X |
| Lee et al[30] | X | | X | X | X | X | X |
| Liu et al[31] | | | | X | | | |
| Michaud et al[32] | X | X | X | X | | | |
| Shen et al[33] | X | X | X | X | X | | |
| So and Chung[34] | X | X | X | | | | X |
| Tao et al[35] | X | | X | X | | | |
| Tchero et al[36] | | | X | | X | | |
| Wang et al[37] | | | | | X | | |
| Wei et al[38] | X | X | X | X | | | |
| Wu et al[39] | X | X | | X | | | |
| Wu et al[40] | X | X | X | X | | | |
| Wu et al[41] | X | X | | | X | | |
| Wu et al[42] | | | | | X | X | |
| Yang et al[43] | X | X | X | X | | X | |
| Yoshida et al[44] | | | X | X | | | |
| Total | 19 | 18 | 16 | 16 | 9 | 8 | 5 |

feedback was reported as delivered by an individual/diabetes care team in 7 (33%) reviews.[19,21,24,26,29,38,41] One (4.7%) described only automated feedback[37] and 13 (61.9%) reviews[23,25,27,30-33,35,36,39,40,42,43] described both individual/team and automated feedback.

*Gaps for Technology-Enabled Self-Management.* A key finding is that the systematic reviews and meta-analyses lacked overall intervention descriptions making it difficult to identify the mechanism of action of the intervention and which features impacted health outcomes. Supplemental Appendix B applies the TES Taxonomy to the 21 meta-analyses in Table 5. Five additional gaps were identified (Table 6). There was lack of evaluation of the impact of continuous glucose monitoring (CGM) or mobile health interventions, and minimal focus on healthy coping or evaluation of pyschosocial impact. In addition there was limited description of theoretical frameworks used to develop interventions. Finally, studies need to report on ethnicity/race and health disparities.[45-50]

## Discussion

The intent of this umbrella review was to develop a taxonomy to describe intervention attributes in technology-enabled interventions and review high-quality systematic reviews and meta-analyses, published since the original 2017 review, to determine if the elements of the TES framework are being described in the interventions, and if the elements continue to result in achieving diabetes outcomes. Additionally, this umbrella review identified significant gaps in the literature regarding technology-enabled diabetes self-management. Our findings confirm technology-enabled self-management interventions with a TES feedback loop continue to be associated with a reduction in A1C.

### *The Taxonomy of Technology-Enabled Self-Management Interventions (TES Taxonomy)*

Given the evolving models of care and the rapid influx of technology-enabled interventions, more emphasis needs to be placed on clear description of the design and process of implementing interventions. The lack of description of intervention components and how the TES features are operationalized makes it difficult to pinpoint types or features of technology-enabled interventions that impact glycemic, other physiological and behavioral/psychosocial diabetes self-management outcomes. Research, including systematic reviews, should fully describe intervention details, including participant characteristics; who the interventionist(s) were; what type of technology was used, including details

**Table 5.** Technology-Enabled Self-Management (TES) Feedback Loop Intervention Features of Studies With Meta-Analysis and Significant A1C Mean Difference Between Intervention and Control Group ($n=21$).

| Authors[a] | Communication one-way, 2-way, or both | Patient generated health data tracked, analyzed or both | Education content general, tailored or both | Feedback How: Realtime, asynchronous or both | Feedback-Who: Individual/team, automated or both | A1C significant mean difference (%) |
|---|---|---|---|---|---|---|
| Yang et al[43] | Both | Both | Both | Both | Both | −0.68 |
| Wu et al[39] | Both | Both | Both | AS | Both | −0.67 (T2D)<br>−0.37 (T1D) |
| Huang et al[26] | Both | Tracked | Both | AS | I/T | −0.62 (SMS)<br>−0.99 (T1D)<br>−0.65 (T2D) |
| Faruque et al[21] | Two | Both | Both | AS | I/T | −0.57 (3 m)<br>−0.28 (4-12 m)<br>−0.26 (>12 m) |
| Aminuddin et al[19] | Both | Both | Both | Both | I/T | −0.55 |
| Wu et al[40] | Both | Both | Both | Both | Both | −0.51 |
| Heitkemper et al[24] | Both | Tracked | Both | Both | I/T | −0.36 (6 m)<br>−0.27 (12 m) |
| Shen et al[33] | Both | Both | Both | Both | Both | −0.48 |
| Tchero et al[36] | Both | Both | Both | Both | Both | −0.48 (T2D)<br>−0.26 (T1D) |
| Kuo et al[29] | Both | Tracked | Both | Both | I/T | −0.43 |
| Liu et al[31] | Both | Both | Both | AS | Both | −0.42 |
| Tao et al[35] | Both | Both | Both | RT | Both | −0.31 |
| Michaud et al[32] | Both | Both | Both | Both | Both | −0.30 |
| Haider et al[23] | One-way | Both | Both | AS | Both | −0.38 |
| Kirk et al[27] | Both | Tracked | Both | Both | Both | −0.38 |
| Hu et al[25] | Both | Both | Both | Both | Both | −0.28 |
| Wang et al[37] | Both | None | None | Both | Automated[b] | −0.25 (apps) |
| Wu et al[42] | Both | Both | Both | Both | Both | −0.25 (T2D) |
| Wu et al[41] | Both | Both | Both | Both | I/T | −0.22 |
| Lee et al[30] | Both | Both | Both | Both | Both | −0.18 |
| Wei et al[38] | Two | Tracked | General | RT | I/T | −0.12 |

Abbreviations: Apps, applications; AS, asynchronous; I/T, individual/team; m, months; RT, real-time; SMS, short message service; T1D, type 1 diabetes; T2D, type 2 diabetes.
[a]Authors ordered from greatest A1C decrease.
[b]Some not defined.

on automation or tailored delivery; how often participants interacted with technology and/or the interventionist, including the duration of the intervention; while following a systematic process. A 2019 paper referenced key characteristics of digital interventions that need to be identified prior to recommending the intervention, specifically the "mechanism of action" that will impact outcomes.[51] Incorporating the TES Taxonomy can support recommendations of technology-enabled interventions by clinicians. Recent research describes similar challenges with digital health interventions, indicating a lack of consistency in reporting original research, which makes conducting systematic reviews more challenging.[8,52] This lack of overall description could happen for several reasons, including publication word limitations or proprietary concerns. Scientists should be clear when reporting methodology so appropriate conclusions can be drawn.

## *Update to the 2017 Review*

In this update, mobile and smartphone interventions were successful in lowering A1C with 2 studies reporting greater change in A1C in T2D compared to T1D.[36,42] Similar to our original review, there was heterogeneity in the interventions, technologies, and methodologies. In addition to A1C being the most common clinical outcome reported, there is a lack of assessment and evaluation of psychosocial and self-management outcomes. When assessed, self-report and inadequately validated instruments were used, limiting the ability to draw comparisons and statistical conclusions.

Most reviews were meta-analyses focusing on A1C outcomes, not narratively summarizing interventions in detail. Compared to 2017, this update found that more reviews described "both" basic and advanced TES framework features, possibly reflecting the evolving technology available for interventions. Several studies in our update identified that interventions combining multiple technologies lowered A1C significantly which corresponds to the ADA 2021 SOC recommendation: "systems that combine technology and online coaching can be beneficial in treating prediabetes and diabetes for some individuals."[10]

Different from the 2017 review, we extracted the clinician's specialty (eg, RN, MD, coach) to understand their role in implementing the technology intervention. However, clinicians were not always reported, and it was not clear which

**Table 6.** Research Gaps Identified and Future Opportunities.

| Gaps | Our findings | Opportunities for future research |
|---|---|---|
| 1. Lack of CGM/mobile health research integrated into self-management interventions | While CGM and mobile health research exists, studies specific to CGM/mobile health and its integration with behavior change are lacking | Future research is needed to understand how patient- generated BGM/CGM and mobile health data are being used to impact self-management, tailor education, and engage in real-time 2-way communication with the care team. |
| 2. Lack of interventions focused on healthy coping | Healthy coping is central to all other diabetes self-care behaviors.[5] Yet, there was an overall lack of interventions that described healthy coping and therefore it is unknown if healthy coping was delivered, and if so to what extent. | There is a myriad of opportunities to support healthy coping using technology approaches. Online peer support has been found to support healthy coping[45] and can be delivered by community health workers.[46] Exploration of technology-delivered healthy coping is needed. |
| 3. Minimal data on psychosocial impact | While psychosocial outcomes were examined (ie, quality of life, diabetes distress, depressive symptoms), validated tools were not always used in the systematic reviews studied. | Using validated tools while not overwhelming participants with survey questions can be challenging. We recommend researchers follow guidelines recommended by the ADA position statement on psychosocial care.[47] |
| 4. Lack of theoretical frameworks | Systematic reviews are not describing guiding theoretical frameworks when designing interventions to impact behavior change. | Future research needs to report on all theoretical frameworks and identify when they are lacking. |
| 5. Health inequity and health disparities | The primary systematic reviews did not report ethnicity/race/disability data, and therefore we are unable to report on those data. However, we know diabetes disparities exist. Often individuals with disabilities are excluded from research.[48] Further, technology disparities exist.[49,50] | Future research should seek to identify how diabetes technologies work in a variety of populations, including those from different race and ethnic categories, but also those who may have disabilities that may or may not be related to diabetes (ie, blind or low vision, deaf or hard of hearing). |

Abbreviations: BGM, blood glucose monitoring; CGM, continuous glucose monitoring.

clinicians were conducting the intervention tasks. Overall, intervention details were minimal, making it challenging to understand the active ingredient of the technology. When we applied the TES Taxonomy to the 21 meta-analyses (Supplemental Appendix B), we were able to define a more complete picture of the interventions that significantly lowered A1C; however, there were missing data for several attributes. If original studies and reviews incorporated a taxonomy to describe interventions, data synthesis would be streamlined, and more clarity would exist.

## *Research Gaps Identified and Future Opportunities*

Based on gaps identified, opportunities for future research are suggested (Table 6). Despite the rise in adoption of CGM and integrated apps, and a focus on time-in-range as a metric of diabetes management, current reviews do not include these elements. Mobile health and digital health interventions may be evaluated more often as real-world evidence and not in randomized controlled trials, thus not included in systematic review data.

Coping is the cornerstone for diabetes self-management;[5] however, healthy coping was not evaluated in these studies. In this update, 15% ($n=4$) included healthy coping, compared to 24% ($n=6$) in the previous review. Although healthy coping was not evaluated, behavioral/psychosocial outcomes were measured and found to often influence healthy coping outcomes. Technology has primarily focused on tracking metabolic measures and not on psychosocial needs. However, technology interventions can leverage the real-time capability of smartphones to capture mood assessment, social determinants of health data, and other information to provide inputs for automated or human coaching.

Technology intervention development and research should be guided by theoretical frameworks, yet they were rarely described. Frameworks typically address behavioral or therapeutic approaches, and they can also guide technology implementation. While the TES framework describes the necessary intervention features to achieve diabetes outcomes, it does not describe the process of implementing technology into a clinic, health system, or community setting. The ADA SOC 2021 indicate that "diabetes technology, when coupled with education and follow-up, can improve the lives and health of PwD; however, the complexity and rapid change of the diabetes technology landscape can also be a barrier to patient and provider implementation."[10] People with diabetes need HCPs who are knowledgeable about diabetes technologies, especially as diabetes technology use is shifting from specialty to primary care.

Two recent publications provide guidance regarding technology optimization and integration.[53,54] The Identify, Configure, Collaborate (ICC) Framework describes a 3-step, simplified, systematic approach to optimize technology-enabled diabetes care and education. This framework can streamline the process of technology implementation and use of PGHD. Additionally, the DATAA Model, presents a simple approach for HCPs and PwD to collaborate and evaluate ambulatory glucose profile data.[54] These publications can support researchers and clinicians in systematically describing their processes to facilitate evaluation and understanding of what works.

Health disparities exist with diabetes technology. Recent data from the T1D Exchange demonstrated that while use of technology has increased over the past 10 years, individuals with low socio-economic status (SES) and non-white racial/ethnic groups have lower technology use and higher A1C levels.[50] Smartphones can increase access to diabetes technologies, and yet diverse populations continue to be underrepresented.[49,50] Research has shown that implicit provider bias limits the prescription of technology in lower SES and non-white populations.[49] Lack of trust in research teams, difficulty recruiting, and overt exclusion from studies is problematic. Future studies, when possible, could consider subgroup analysis of underrepresented groups.

Designing technology interventions to address disparities, disabilities, and non-English speaking individuals (inclusive design) could increase inclusion and equity. Developing options for one population (eg, flashing light alerts for Deaf populations) may provide derivative benefits for other populations.[48-50] Diabetes technologies should be accessible, affordable, and available to all populations.

## Conclusion

Technology-enabled diabetes self-management interventions continue to be associated with improved clinical outcomes. The rapid adoption and engagement with technology requires a focus on uniform measures for psychosocial outcomes, including healthy coping. Using the TES Taxonomy as a standard approach to describe technology-enabled interventions will support further understanding of the impact that technology has on diabetes outcomes and provide a systematic framework for ADCES to frame strategic conversations for technology and practice.

### Abbreviations

A1c, hemoglobin A1c; AI, artificial intelligence; API, application programing interface; AS, asynchronous; BGM, blood glucose monitoring; BMI, body mass index; BP, blood pressure; CGM, continuous glucose monitoring; GCM, gestational diabetes; D, depression/depressive symptoms; DD, diabetes distress; E, empowerment; Gluc, fasting blood glucose; HCP, healthcare professional; HLD, hyperlipidemia; Hypo, hypoglycemia; I/T, individual/team; M, months; MDI, multiple daily injections; MDIS, mobile diabetes intervention study; PA, physical activity; PGHD, patient generated health data; PS, patient satisfaction; QoL, quality of life; REACH, rapid education/encouragement and communications for health; RCT, randomized clinical trial; RT, real time; SE, self-efficacy; SM, self-management; TES, technology-enabled self-management; T1D, type 1 diabetes; T2D, type 2 diabetes; WC, waist circumference

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### ORCID iDs

Deborah A. Greenwood https://orcid.org/0000-0002-7603-4624
Michelle L. Litchman https://orcid.org/0000-0002-8928-5748
Julia E. Blanchette https://orcid.org/0000-0002-6714-4792
Jane K. Dickinson https://orcid.org/0000-0003-0732-8116
Allyson Hughes https://orcid.org/0000-0003-1054-7096
Vanessa D. Colicchio https://orcid.org/0000-0002-4656-2047
Jiancheng Ye https://orcid.org/0000-0003-4143-8423
Kirsten Yehl https://orcid.org/0000-0002-5763-4464
Andrew Todd https://orcid.org/0000-0002-4989-7280
Malinda M. Peeples https://orcid.org/0000-0003-4097-1584

## Supplemental Material

Supplemental material for this article is available online.

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