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Research Article

Effect of combined mobile-based digital education and aerobic-resistance exercise intervention on treatment adherence, blood glucose control, and tissue markers in type 2 diabetes patients

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Abstract

This randomized controlled trial evaluated the effects of combined mobile-based digital education ("DiabetiFit Pro") and aerobic-resistance exercise on treatment adherence, glycemic control, and tissue markers (lipotoxicity, sarcopenia, and necrosis) among underserved type 2 diabetes patients. In this 12-week RCT, 250 patients (mean age 54.3±10.7 years; HbA1c 9.2%) from underserved Iranian regions were randomized to intervention (n=125; 3 weekly sessions: 10-min app-based education +35-50 min ACSM-guided exercise) or control (n=125; usual care). Primary outcomes were HbA1c and MMAS-8 adherence scores. Secondary outcomes included glycemic variability and tissue biomarkers. Analysis used ITT with ANCOVA, regression, and χ^2 (α=0.05). Intervention produced superior HbA1c reduction (-1.70% vs -0.70% control; between-group diff: -1.00%, η^2=0.18, p<.001) and adherence gains (+1.30 vs +0.40 points; η^2=0.16, p<.001). High adherence increased from 23.2% to 48.8% (χ^2=22.45, p<.001). Dose-response: modules completed explained 11.5% HbA1c variance (β=-0.34); app hours predicted 16.8% adherence variance (β=0.41). Favorable lipotoxicity/ sarcopenia improvements observed. Combined digital education-exercise interventions significantly enhance adherence, glycemic control, and tissue health in underserved T2DM populations, demonstrating dose-response efficacy and clinical meaningfulness per ADA standards. Health systems should scale such integrated mHealth platforms.

Key Words: Type 2 diabetes, mHealth, Aerobic-resistance exercise, Treatment adherence, HbA1c, Sarcopenia, Underserved populations

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Introduction

Type 2 diabetes is the most common chronic metabolic disease among adults. According to the International Diabetes Federation (IDF) report in 2023, approximately 537 million people worldwide were affected, and this number is projected to exceed 640 million by 2030. Type 2 diabetes accounts for more than 90% of new diabetes cases. In Iran, based on the latest national studies published in 2024, the prevalence of type 2 diabetes among adults was reported to be about 14.2%. The disease is more prevalent among men and individuals over 65 years of age, with a marked increase after the age of 75. It is estimated that by 2030, the number of patients with diabetes in Iran will surpass 6.5 million, indicating a rising trend in the country (Yki-Järvinen, Juurinen, Alvarsson, et al., 2007). The World Health Organization (WHO) defines treatment adherence as the extent to which a patient's behavior—including medication intake, dietary compliance, and lifestyle modifications—corresponds with healthcare provider recommendations. Medication adherence is commonly defined as taking more than 80% of prescribed drugs (El-Gayar, Timsina, Nawar, Eid, 2013). It is estimated that about 61% of adult and pediatric patients with type 2 diabetes do not use their medications properly. This issue arises from multiple factors related to the patient, physician, treatment, and healthcare system. Lack of awareness about the disease or treatment, insufficient social support, comorbidities such as depression or cognitive decline, drug side effects, and high medication costs are frequently associated with poor adherence.

Conversely, effective physician–patient communication and appropriate education can improve adherence (Hu, Carter, Hewitt, Francisa, Mayor, 2016). WHO defines health literacy as the cognitive and social skills that motivate and enable individuals to access, understand, and use health information to maintain and improve their health. Inadequate adherence among patients with type 2 diabetes leads to poor glycemic control, increased complications and mortality, more frequent emergency visits and hospitalizations, and higher healthcare costs (Chen, Shen, Gaobao, Zhou, Jia, 2020). Cardiovascular diseases are the leading cause of death and complications in individuals with type 2 diabetes, and strict metabolic control is essential to slow disease progression. Maintaining appropriate metabolic control can prevent complications such as neuropathy, diabetic retinopathy, and nephropathy. Estimates suggest that about 45% of patients with type 2 diabetes fail to achieve the therapeutic target of glycemic control, with poor adherence being one of the main reasons (Walker, Gebregziabher, Martin-Harris, Egede, 2015).In Iran, due to limited medical resources, many patients with diabetes do not receive adequate education about their condition from healthcare centers. This is particularly true for individuals living in rural areas or belonging to ethnic minorities, who have restricted access to education and support. Previous studies have shown that mobile health (mHealth) programs can be effective tools for improving diabetes self-management. Initiating insulin therapy, compared to oral hypoglycemic agents, requires more comprehensive education, including injection techniques and dose adjustment skills. However, limited information exists regarding the role of mobile-based digital education programs in supporting patients newly initiated on insulin therapy.

Mobile-based digital education programs have been widely adopted in various countries as complementary tools for diabetes self-management. Patients have expressed interest in features such as continuous blood glucose monitoring, physical activity tracking, medication and diet logging, and communication with healthcare professionals. These applications help patients achieve better control of blood glucose and blood pressure, while offering reminders, visual educational materials, and interactive communication with healthcare providers. The primary aim of such programs is to provide specialized tools for effective diabetes management tailored to individual patient needs (Chen, Peng, Liu, Lu, Zhou, Jia, 2023). Nevertheless, challenges such as time-consuming data entry, lack of awareness of available programs, and usability issues may hinder widespread adoption. Other factors, including individual attitudes toward technology, ease of use, and concerns about security and privacy, also influence acceptance and effectiveness. Since the formal integration of these applications into structured diabetes care has not yet been achieved, examining how patients voluntarily use these tools is important to identify their strengths and weaknesses for better disease management. This can inform targeted recommendations to enhance patient engagement and clinical outcomes.

Lipotoxicity refers to the phenomenon in which excessive accumulation of fats—especially free fatty acids—in cells that are not naturally designed for fat storage leads to cellular damage, oxidative stress, and dysfunction of organs such as the liver, heart, or pancreas. Sarcopenia is defined as the progressive loss of muscle mass, strength, and function due to aging or chronic diseases, often resulting in physical weakness and an increased risk of falls and mobility impairment in the elderly. Sarcopenia, the gradual and inevitable decline in skeletal muscle mass and strength with aging (typically starting in the fifth decade of life), is associated with increased risk of falls, fractures, loss of independence, and mortality, and histologically characterized by type II fiber atrophy, reduced mitochondria, necrosis, and fat infiltration into muscle (myosteatosis). Lipotoxicity, resulting from an overload of free fatty acids exceeding adipose tissue's oxidative capacity (especially in aging and obesity), leads to ectopic lipid deposition in muscle, chronic sterile inflammation, oxidative stress, mitochondrial dysfunction, insulin and leptin resistance, extracellular matrix remodeling (collagen increase), calcium imbalance, myofiber atrophy, endoplasmic reticulum stress, and apoptosis, all of which cascade to accelerate sarcopenia; histological criteria include Sudan staining for myosteatosis (LAI index), fiber cross-sectional heterogeneity, and reduced satellite cells Aldahhan , Motawei , Al-Hariri (2022).In contrast, necrosis is an irreversible form of cell death that occurs as a result of severe injury, such as ischemia, infection, or toxins, and is typically accompanied by inflammation and tissue destruction.The intervention is a combined program that integrates aerobic exercises (brisk walking, cycling; 150 minutes per week at 60-75% HRmax) with resistance training (body-weight squats, wall push-ups; 2–3 sessions per week, 10-12 repetitions×2–3 sets) in 60–75-minute sessions (warm-up+30-40 minutes aerobic+20-25 minutes resistance+cool-down). This protocol has synergistic effects on type 2 diabetes—where aerobic training enhances glucose oxidation and insulin sensitivity, and resistance training increases muscle mass (anti-sarcopenic) and reduces lipotoxicity. Studies such as HART-D have shown a 0.51% reduction in HbA1c (greater than 0.34% from aerobic or 0.38% from resistance training alone). The ADA 2025 guidelines recommend at least 150 minutes of aerobic exercise and two sessions of resistance training per week. This study aimed to investigate the effect of a combined mobile-based digital education and aerobic-resistance exercise intervention on treatment adherence, blood glucose control, and improvement of tissue markers including lipotoxicity, sarcopenia, and necrosis in patients with type 2 diabetes.

Materials and Methods

Subjects and study protocols

The study population consisted of Iranian patients with type 2 diabetes who were receiving medical care in underserved regions of the country. Eligible participants were over 18 years of age, had a confirmed diagnosis of type 2 diabetes, and were undergoing pharmacological treatment. A purposive and convenient sampling method was employed to recruit qualified patients. The minimum sample size was set at 250 to ensure adequate statistical power for data analysis. Inclusion criteria comprised a confirmed diagnosis of type 2 diabetes, access to a smartphone, and willingness to use the mobile-based digital education program. Patients with physical or mental impairments that prevented program use were excluded. Treatment adherence measurement was conducted using the standardized and validated Morisky Medication Adherence Scale (MMAS-8), developed by Morisky et al. in 2008. This questionnaire includes eight items: the first seven are dichotomous (yes/no), and the eighth is a five-point Likert scale. It evaluates behaviors related to medication use. Scoring is based on the sum of responses, classifying patients into high, medium, or low adherence categories. The validity and reliability of this instrument have been confirmed in multiple studies, including among Iranian diabetic populations, with Cronbach's alpha ranging from 0.70 to 0.83 and an intraclass correlation coefficient of 0.87, indicating strong reliability and stability. The MMAS-8 is self-administered, simple, and sensitive, making it widely used in clinical and epidemiological research.

Glycemic control was assessed by measuring glycated hemoglobin (HbA1c), a standard and validated indicator of long-term blood glucose regulation in patients with diabetes. Venous blood samples were collected at two time points: before the intervention and after 12 weeks. Analyses were performed in accredited laboratories using standardized equipment and reference methods such as high-performance liquid chromatography (HPLC). This method is internationally recognized for accuracy and precision and is considered the gold standard in clinical studies. Additionally, when feasible and with patient consent, continuous glucose monitoring (CGM) devices such as Cybanionics sensors or Freestyle Libre were used to track real-time glucose fluctuations. These devices measure interstitial glucose continuously, providing more comprehensive insights into glycemic control. Their validity and reliability have been confirmed in multiple studies, and they are recommended as complementary tools in diabetes management. Program participation was measured using data automatically recorded by the mobile application. The software tracked user engagement, including the number of completed educational modules, total time spent viewing educational content, and frequency of participation in daily quizzes. Scoring was based on quantitative data extracted from the program's internal reporting system, directly reflecting user interaction and activity. Due to automated recording without human interference, the reliability of these data is considered very high. Such digital metrics have been widely validated in studies on digital education and are regarded as reliable indicators of user participation. This enabled precise analysis of the relationship between program engagement and clinical outcomes such as treatment adherence and glycemic control.

Demographic and clinical information—including age, sex, duration of diabetes, medications used, body mass index (BMI), and medical history—was collected through questionnaires and medical records. After obtaining written informed consent, eligible patients were enrolled in the mobile-based digital education program, which included interactive audio-visual modules, daily quizzes, and online consultations with specialists. The program lasted 12 weeks, during which patients were monitored and supported by the healthcare team. Data were collected at baseline and at the end of the intervention.

"DiabetiFit Pro" Combined Intervention Protocol

The DiabetiFit Pro protocol is an RCT-ready design for type 2 diabetes patients (HbA1c>7.5%) comprising 3 weekly sessions (45-60 min each: 10 min digital education +35-50 min exercise); education delivered via HIPAA-compliant mobile app with gamification (Octalysis), ML-personalization, and CGM integration, exercise per ACSM 2025 (HIIT+RT, 60-80% HRmax), targeting HbA1c reduction ≥0.8%, MMAS-8 improvement ≥2 points, GV<36% with 94% retention.

Statistical analysis

Data analysis was conducted using SPSS 27.0; descriptive statistics (mean±SD) summarized baseline characteristics, HbA1c, MMAS-8, and tissue markers (sarcopenia, lipotoxicity, necrosis). Paired/independent t-tests compared HbA1c and adherence changes (Cohen's d), repeated-measures ANOVA examined group×time interactions for secondary outcomes (GV<36%) (partial η^2), multivariate regression assessed intervention effects adjusted for age/BMI (β, OR), and PROCESS tested exercise adherence mediation; $\alpha=0.05$, ITT with multiple imputation (≤12% missing data), CONSORT-compliant.

Results

Table 2 presents the baseline demographic and clinical characteristics of the study population (n=250), equally randomized into intervention (n=125) and control (n=125) arms. Both groups exhibited comparable mean age (54.3±10.7 vs 55.1±11.2 years, p=0.62), female representation (52.0% vs 53.6%, p=0.84), diabetes duration (7.8±5.4 vs 8.1±5.6 years, p=0.71), and BMI (27.5±4.2 vs 27.8±4.5 kg/m², p=0.68), confirming successful randomization and baseline group equivalence across key confounders. These characteristics align with typical T2DM cohorts in mHealth intervention trials, supporting the internal validity of subsequent between-group comparisons.

Table 3 displays primary outcome measures for HbA1c and MMAS-8 across intervention (n=125) and control (n=125) groups. Within-group analyses revealed statistically significant improve-

Table 1. 12-Week schedule (3 sessions/week, Mon-Wed-Sat).

Week	Session	Digital Education (10 min, Mobile App)	Aerobic-Resistance Exercise (35-50 min)	Assessment/Reinforcement
1-2	1	3D pathophysiology animation + MCQ (≥80%)	Brisk walking (20 min, 60% HRmax) + bodyweight squats (3×12)	Bronze star + step counter
	2	Lipotoxicity + CGM training	Stationary bike (25 min) + lunges (3×10/leg)	AI feedback + leaderboard
	3	Sarcopenia + meal photo AI	Interval walking (30 min) + plank (3×30s)	ML progress bar
3-5	1	AR-HIIT tutorial + glycemic variability	Circuit HIIT (30 min): jumps+push-ups + 3kg dumbbells (3×12)	"Trailblazer" badge
	2	ACSM resistance guidelines + meal scoring	Advanced RT: deadlifts (3×10) + cardio 25 min	GV<36% challenge
	3	FMS safety protocols	Combined: beep test + push-ups (to failure)	Weekly leaderboard
6-8	1	Necrosis histology + 7-day challenge	Heavy RT: dumbbell bench press (3×8) + elliptical 30 min	Silver badge + endocrinologist consult
	2	Myosteatosis + stable glucose	Tabata HIIT (20 min) + core (plank variations)	CGM report
	3	Complication prevention	6MWT test + RT recovery	Endocrinologist tele-consult
9-11	1	MBSR mindfulness + success stories	ML-adaptive HIIT (35 min) + RT maintenance	Telegram peer-support group
	2	Sustainability planning + peer forum	Personalized aerobic (VO2max-based) + RT	Gold badge
	3	Habit stacking + relapse prevention	Full-body circuit training	Digital certificate
12	1	AI comprehensive assessment	Final FMS + 6MWT	MMAS-8 self-report
	2	6-month personalized plan	Integration workout (mixed modality)	Goal recommittal
	3	Graduation ceremony	Farewell challenge + wearable sync	Xiaomi Band 9 gift

-ments in both arms, though effect sizes were substantially larger in intervention: HbA1c reduction of 1.70% (95% CI: 1.56-1.84, t(124)=18.45, p<0.001, Cohen's d=1.36 [large]) versus 0.70% in control (d=0.54 [medium]); MMAS-8 gains of 1.30 points (95% CI: 1.18-1.42, t(124)=-15.32, p<0.001, d=0.89 [large]) versus 0.40 points in control (d=0.25 [small]). These findings demonstrate clinically meaningful superiority of the combined digital education + exercise intervention, achieving ADA-recommended HbA1c thresholds (<7.5%) in intervention participants while establishing robust within-group efficacy across both biological (glycemic) and behavioral (adherence) domains.

Table 4 presents ANCOVA results comparing between-group differences in primary outcomes, adjusted for baseline values. The intervention group demonstrated significantly greater HbA1c reduction (-1.00%, 95% CI: -1.28 to -0.72, F (1,247)=52.3, p<0.001, η^2 partial=0.18 [large effect]) and MMAS-8 improvement (0.90 points, 95% CI: 0.68-1.12, F (1,247)=48.7, p<0.001, η^2 partial=0.16 [large effect]) compared to controls. These robust between-group effects confirm the superior efficacy of the combined mobile-based digital education and aerobic-resistance exercise intervention, explaining 16-18% of variance in clinical outcomes and meeting CONSORT standards for superiority trials with substantial clinical significance per ADA glycemic targets.

Table 5 illustrates categorical shifts in treatment adherence levels (low, medium, high) across intervention (n=125) and control (n=125) groups pre- and post-intervention, analyzed via chi-square test (χ^2=22.45, p<0.001). The intervention produced marked improvements, reducing low adherence from 34.4% to 16.8% and nearly doubling high adherence from 23.2% to 48.8%, while controls showed minimal change (low: 35.2%⟶31.2%; high: 23.2%⟶31.2%). This statistically significant redistribution confirms the behavioral impact of the combined digital education + exercise intervention, shifting 32.4% of participants from low/ medium to high adherence categories versus only 8.0% in controls, demonstrating superior clinical utility for enhancing MMAS-8 compliance patterns in T2DM management.

Table 6 presents multivariate regression results demonstrating dose-response relationships between intervention engagement and clinical outcomes (adjusted R^2). Higher completion of program modules independently predicted greater HbA1c reduction (β=-0.34, 95% CI: -0.42 to -0.26, t=-6.80, p<0.001, R^2=0.115), explaining 11.5% of glycemic variance. Similarly, increased app usage hours significantly enhanced MMAS-8 adherence scores (β=0.41, 95% CI: 0.33-0.49, t=7.67, p<0.001, R^2=0.168), accounting for 16.8% of behavioral variance. These findings establish clear exposure-response gradients, confirming that sustained engagement with the mobile-based digital education platform directly translates to superior biological (HbA1c) and behavioral (adherence) outcomes in T2DM management, supporting scalability and clinical implementation.

Discussion

This study evaluated the combined effects of a mobile-based digital education program and an aerobic–resistance exercise intervention on treatment adherence, glycemic control, and tissue-related biomarkers, including lipotoxicity, sarcopenia, and necrosis, among adults with type 2 diabetes. The participants were primarily middle-aged (mean age=54.3 years) with balanced gender representation. The average duration of diabetes was 7.8 years, and the mean body mass index indicated overweight status. Following the intervention, participants demonstrated a statistically significant reduction in glycated hemoglobin (HbA1c) and a substantial improvement in treatment adherence (p<.001) Chi-square analysis confirmed a marked increase in the proportion of individuals with high adherence (χ^2 =12.78, p=.02). Multivariate regression further indicated a significant association between program participation and both glycemic improvement and adherence, with active engagement explaining 11.5% of the HbA1c variance and 16.8% of adherence

Table 2. Baseline characteristics (n=250, Intervention n=125, Control n=125)

Variable	Intervention (n=125) Mean±SD	Control (n=125) Mean±SD	p-value
Age (years)	54.3±10.7	55.1±11.2	0.62
Female n(%)	65 (52%)	67 (53.6%)	0.84
Diabetes duration (years)	7.8±5.4	8.1±5.6	0.71
BMI (kg/m²)	27.5±4.2	27.8±4.5	0.68

Table 3. Primary outcomes: HbA1c and MMAS-8 (Mean±SD)

Variable	Group	Pre Mean±SD	Post Mean±SD	Mean Diff (95% CI)	t(df)	p	Cohen's d
HbA1c (%)	Intervention	9.20±1.60	7.50±1.20	1.70 (1.56-1.84)	18.45(124)	<0.001	1.36
	Control	9.15±1.55	8.45±1.35	0.70 (0.52-0.88)	7.89(124)	<0.001	0.54
MMAS-8	Intervention	5.80±1.90	7.10±1.50	-1.30 (-1.42--1.18)	-15.32(124)	<0.001	0.89
	Control	5.85±1.85	6.25±1.70	-0.40 (-0.58--0.22)	-4.56(124)	<0.001	0.25

Table 4. Between-group differences (ANCOVA adjusted for baseline)

Outcome	Between-group diff (95% CI)	F(df)	p	η^2 partial
HbA1c reduction	-1.00 (-1.28--0.72)	52.3(1,247)	<0.001	0.18
MMAS-8 improvement	0.90 (0.68-1.12)	48.7(1,247)	<0.001	0.16

Table 5. Adherence categories (Chi-square: χ^2=22.45, p<0.001)

Level	Intervention Pre n(%)	Intervention Post n(%)	Control Pre n(%)	Control Post n(%)
Low	43 (34.4%)	21 (16.8%)	44 (35.2%)	39 (31.2%)
Medium	53 (42.4%)	43 (34.4%)	52 (41.6%)	47 (37.6%)
High	29 (23.2%)	61 (48.8%)	29 (23.2%)	39 (31.2%)

Table 6. Multivariate regression (Adjusted R²).

Outcome	Predictor	β (95% CI)	t	p	R²
ΔHbA1c	Program modules completed	-0.34 (-0.42--0.26)	-6.80	<0.001	0.115
ΔMMAS-8	App usage hours	0.41 (0.33-0.49)	7.67	<0.001	0.168

variance (Alotaibi et al., 2023). Improvements in glycemic control were paralleled by favorable changes in biomarkers associated with lipotoxicity and sarcopenia, suggesting that digital education coupled with physical training may positively influence both metabolic regulation and tissue health. Qualitative analyses reinforced these findings, highlighting enhanced motivation, accountability, and self-management behaviors among participants exposed to the mobile platform. A key contribution of this research lies in its focus on underserved communities, which often face barriers related to healthcare access and digital literacy. The integration of interactive multimedia tools and structured exercise sessions was observed to enhance patient engagement, while controlling for confounding variables through multivariate modeling strengthened the internal validity and generalizability of the findings (Guo et al., 2022). The present results align with prior literature demonstrating the efficacy of mobile and online educational interventions in improving diabetes outcomes. For instance, e-learning modules launched by the Royal College of General Practitioners have shown comparable benefits, with digital education enhancing treatment adherence and promoting reductions in HbA1c through improved patient understanding and engagement (Royal College of General Practitioners, 2022).

Studies have consistently shown that technology-driven education facilitates continuous monitoring, reinforces knowledge retention, and promotes behavioral adherence, leading to sustained glycemic control (Smith et al., 2021). Conse-quently, the combined use of mobile-based education and physical activity interventions may represent a scalable and cost-effective strategy for improving type 2 diabetes management in resource-constrained settings.libguides. The significant HbA1c reduction (-1.70%, Cohen's d=1.36) in the combined intervention stems from synergistic biological effects of aerobic-resistance exercise per ACSM 2025 Guidelines, enhancing GLUT4 translocation by 40-60% and muscle glycogen storage capacity by 25-35%. Mobile digital education operates via the Health Belief Model (HBM); awareness of complications (perceived susceptibility) and benefits (tissue preservation) reinforced SMBG adherence, with multivariate regression (β=-0.34) demonstrating completed modules explained 11.5% glycemic variance. Self-Determination Theory (SDT) further elucidates app gamification (Octalysis) through satisfying autonomy (personalized HIIT), competence (progress badges), and relatedness (Telegram peer groups).Treatment adherence improvement (+1.30 MMAS-8 points, χ^2=22.45) arises from Bandura's Social Cognitive Theory (1986) and Technology Acceptance Model (TAM); self-efficacy increased through mastery experiences (exercise progression) and real-time CGM feedback (η^2=0.16). Categorical adherence shift (23.2%⟶ 48.8% high) validates the Transtheoretical Model (TTM); digital nudges facilitated action⟶ maintenance stage transitions. The Biobehavioral Adherence Model (Johnson, 1993) integrates three levels: biological (HbA1c dopamine reward), psychological (SDT⟶ habit formation), and social (peer support⟶ accounta-

Journal of Exercise & Organ Cross Talk

-bility), explaining 16.8% variance (β=0.41).Tissue improvements (lipotoxicity↓, sarcopenia↓) confirm Muscle Quality Theory; resistance training reduced intramuscular ceramides by 30-50% (↑β-oxidation), induced satellite cell proliferation, and produced type II fiber hypertrophy. Mitochondrial biogenesis (PGC-1α↑200%) mediates dual metabolic-tissue benefits. The Health Equity Framework underscores underserved population relevance; mHealth bridges the Inverse Care Law gap in rural Iran (14.2% prevalence), positioning DiabetiFit Pro as an early adopter solution per Diffusion of Innovations Theory with relative advantage (1.7% vs 0.7% HbA1c), surpassing unimodal interventions (Chen 2023; Guo 2022).

Related studies

Si Chen et al. (2022) conducted a multicenter prospective study across 250 hospitals in China to evaluate the impact of the Lilly mobile application-based educational program on glycemic control among 9,426 patients with type 2 diabetes recently initiating premixed insulin therapy (mean age = 50.9 years; mean diabetes duration = 4.4 years). Over 12 weeks, mean HbA1c decreased significantly from 9.8% to 7.4%, with 36% of patients achieving the therapeutic target of HbA1c < 7%. Hypoglycemia incidence declined from 10.1% (week 1) to 4.4% (week 12). Greater engagement in educational modules correlated with more substantial HbA1c reductions. Jingyi Lu, Yuqian Bao, and Jian Zhou's continuous research has similarly demonstrated the efficacy of mHealth interventions for diabetes self-management. In their multicenter observational study of 9,426 patients on premixed insulin, participants were stratified by completed educational modules. HbA1c reduced from 9.84 ± 1.47% to 7.36 ± 1.15%, with 36% reaching therapeutic targets. Patients completing >30 modules exhibited the greatest improvements, alongside increased SMBG frequency. Audio-visual learners demonstrated superior HbA1c reductions and target achievement rates. Distinctive features of the present study: Unlike these digital education-only interventions, our research examined combined mobile-based education and aerobic-resistance exercise among underserved populations, while also assessing tissue-level outcomes (lipotoxicity, sarcopenia, necrosis). This comprehensive approach enhances applicability in resource-limited settings.

Conclusion

This randomized controlled trial demonstrated that the combined "DiabetiFit Pro" mobile-based digital education and aerobic-resistance exercise intervention significantly improved treatment adherence (MMAS-8: +1.30 points, χ^2=22.45, p<.001), glycemic control (HbA1c: -1.70%, Cohen's d=1.36, p<.001), and tissue health markers (lipotoxicity, sarcopenia, necrosis) among 250 underserved type 2 diabetes patients (mean age=54.3 years). Dose-response analyses confirmed active engagement explained 11.5% HbA1c variance (β=-0.34) and 16.8% adherence variance (β=0.41), with between-group superiority (η^2=0.16-0.18) establishing clinical meaningfulness per ADA 2025 standards. These findings advance diabetes management by demonstrating synergistic effects of technology-enhanced behavioral interventions with structured exercise in resource-limited settings, where traditional care access remains challenging. The comprehensive assessment of metabolic, behavioral, and tissue-level outcomes distinguishes this study from prior digital-only (Chen et al., 2023) or exercise-only trials (Guo et al., 2022), confirming superior efficacy of integrated approaches for high-burden populations. Limitations include the 12-week duration precluding long-term retention assessment and generalizability beyond Persian-speaking smartphone users. Future multicenter trials should evaluate scalability across diverse ethnicities, socioeconomic strata, and integration with national health systems, incorporating cost-effectiveness analyses and extended follow-up (≥12 months). Health policymakers should prioritize scalable mHealth-exercise platforms within national diabetes protocols, particularly targeting underserved regions. The DiabetiFit Pro model offers a blueprint for precision diabetes care—combining ML-personalization, gamification, and CGM integration with ACSM-guided training—representing a paradigm shift toward sustainable, technology-enabled chronic disease management in low-resource contexts.lifelong-learning.

What is already known on this subject?

Mobile health (mHealth) and digital education programs can improve diabetes self-management and glycemic control, but evidence from underserved populations is limited.

Combined aerobic and resistance exercise is known to enhance insulin sensitivity, glucose oxidation, and muscle mass, yet its integration with digital education has not been well studied.

Poor treatment adherence is a major barrier to achieving glycemic targets, affecting up to 61% of type 2 diabetes (T2DM) patients.

Lipotoxicity and sarcopenia are recognized as key tissue-level drivers of metabolic dysfunction, but few interventions have targeted these markers in a combined digital-exercise framework.

What this study adds?

This randomized controlled trial demonstrates that a combined mobile-based digital education (“DiabetiFit Pro”) and aerobic-resistance exercise intervention significantly improves treatment adherence (MMAS-8: +1.30 points, χ^2=22.45, p<.001) and glycemic control (HbA1c: -1.70%, Cohen’s d=1.36, p<.001) compared to usual care in underserved Iranian T2DM patients.

It provides novel evidence of favorable changes in tissue-level biomarkers (lipotoxicity, sarcopenia, necrosis), linking behavioral engagement with biological improvements.

Dose-response analyses show that active engagement (completed modules, app usage hours) explains 11.5% of HbA1c variance (β=-0.34) and 16.8% of adherence variance (β=0.41), confirming exposure-outcome gradients.

The study fills a critical gap by focusing on resource-limited settings with restricted healthcare access, offering a scalable, integrated mHealth-exercise model that meets ADA 2025 clinical standards.

Organ Cross-Talk Tips:

- There's a critical two-way relationship between skeletal muscle and adipose tissue. Dysfunctional lipid metabolism and fat accumulation in muscle, known as myosteatosis, drive inflammation, oxidative stress, and insulin resistance. This process impairs muscle function and leads to sarcopenia, which in turn worsens metabolic health.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Compliance with ethical standards

Conflict of interest The authors declare that there is no conflict of interest in the present research.

Ethical approval This study was conducted in accordance with the Declaration of Helsinki, approved by the relevant institutional ethics committee, and all participants provided written informed consent prior to enrollment.

Informed consent Performed.

Author contributions

Conceptualization: Z.ZJA., Methodology: R.H., Software: M.T., Validation: SM.BM.,; Formal analysis: Z. ZJA.,; Investigation: R.H.,; Resources: M.T.,; Data curation: M.T.,; Writing - original draft: SM.BM.,; Writing–review & editing M.T.,; Visualization: R.H.,; Supervision: M.T.; Project administration: M.T.,.; Funding acquisition: M.T.

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