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Post-Dinner Walking versus Active Stretching on Post-Meal Glucose in Type 2 Diabetes: A Randomized Trial

[1]Dr. Ramachandran S*, [2]Dr. Ajay Kumar, [3]Dr. Vijayakumar Palaniswamy, [4]Dr. Praveen B M, [5]Dr. S Jeyakumar, [6]Dr Senthil Nathan C V

[1]PDF scholar, Institute of Physiotherapy, Srinivas University, City Campus, Pandeshwar, Mangaluru 575001, Karnataka, India, Professor, Faculty of Physiotherapy, Dr. M.G.R. Educational and Research Institute, Velappanchavadi, Chennai 600077, Tamil Nadu , ramachandran.physio@drmgrdu.ac.in, Orcid ID: 0000-0001-7187-6083
[2]Institute of Physiotherapy, Srinivas University, City Campus, Pandeshwar, Mangalore 575001, Karnataka, India registrardevelopment@srinivasuniversity.edu.in, Orcid ID: 0000-0002-0633-1471
[3]Professor, Institute of Physiotherapy, Srinivas University, City Campus, Pandeshwar, Mangalore 575001, Karnataka, India Email: vijayakumarpalaniswamy.ipt@srinivasuniversity.edu.in, Orcid ID:0009-0002-0628-5505
[4]Professor, Srinivas University, City Campus, Pandeshwar, Mangalore 575001, Karnataka, India, researchdirector@srinivasuniversity.edu.in, Orcid ID: 0000-0003-2895-5952
[5]Professor, School of Health Sciences, Garden City University, Bangalore, Karnataka, Email jeysubikshaa@gmail.com
Orcid ID: 0009-0001-0866-8924
[6]Principal & Professor, Faculty of Physiotherapy, Dr. M.G.R. Educational and Research Institute, Velappanchavadi, Chennai 600077, Tamil Nadu, senthilnathan.physio@drmgrdu.ac.in, Orcid ID: 0000-0001-5152-4400

ABSTRACT: Post-dinner hyperglycemia contributes substantially to daily glycemic burden in type 2 diabetes mellitus (T2DM), yet many patients cannot walk after the evening meal. This randomized controlled trial compared post-prandial walking with post-prandial active stretching, a low-load indoor alternative, on post-dinner glucose excursions and glycemic variability. Sixty adults with T2DM (HbA1c 7.0–8.0%) were randomized, stratified by HbA1c, to walking (RPE 11–13) or active stretching (RPE 9–11) begun 15–30 min after dinner, five days per week for 12 weeks. Masked continuous glucose monitoring (CGM) was worn for 14 days at baseline and in weeks 11–12, each period including three standardized dinners. The primary outcome, the 0–3 h post-dinner incremental area under the glucose curve (iAUC), was analysed by intention-to-treat ANCOVA with multiple imputation. Fifty-four participants (90%) completed the trial. Post-dinner iAUC fell by 23.4% with walking and 12.1% with stretching; the adjusted between-group difference was -20.7 mg/dL·h (95% CI -35.9 to -5.6; p = 0.007; d = -0.72) and was robust across sensitivity analyses. Walking also lowered peak post-dinner glucose more (-16.7 mg/dL; Bonferroni-adjusted p = 0.027), whereas MAGE, CV, time in range and time above range did not differ, and the MAGE difference lay within the pre-specified 15 mg/dL margin. Adherence was 78% and 83%, respectively; no severe hypoglycemia occurred. Post-dinner walking blunts the evening glucose excursion more than active

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stretching, but stretching provides a meaningful partial benefit with comparable glycemic variability and is a practical indoor alternative when walking is not feasible.

1. INTRODUCTION

Type 2 diabetes mellitus (T2DM) impacts over 500 million adults globally and estimates suggest the weighted diabetes prevalence in India is 11.4% (Sun et al., 2022; Anjana et al., 2023). HbA1c is used to monitor glycemic status, however, this provides a measure of glucose exposure over a number of months and does not provide information on the magnitude or frequency of glucose excursions throughout the day. Post-prandial glucose increases are thought to contribute significantly to overall hyperglycemia in individuals with HbA1c near target (Monnier et al., 2003). Acute changes in glucose have also been shown to induce oxidative stress more potently than chronic hyperglycemia (Monnier et al., 2006). As a result, glycemic variability has emerged as a potential target for diabetes management (Ceriello et al., 2019). The importance of the dinner meal is highlighted due to its high carbohydrate content, typically being the largest meal of the day and often followed by a period of sedentary activity until bedtime.

Insulin independent translocation of GLUT4 transporters into the contractile skeletal muscle is thought to be present in insulin resistant skeletal muscle (Richter and Hargreaves, 2013; Sylow et al., 2017). This translocation can be exploited at the time of a post-prandial glucose increase. Acute studies suggest that moderate walking performed immediately following a meal helps reduce the post-prandial increase in glucose in T2DM patients (Larsen et al., 1997; Colberg et al., 2009). Short post-meal walking has also been shown to improve glycemic control over 24 hours in elderly patients (DiPietro et al., 2013). Additionally, walking following a meal has been shown to reduce post-prandial hyperglycemia more than walking without specified time after a meal (Reynolds et al., 2016). A study conducted in India demonstrated that short post-meal walking had a greater glucose lowering effect than a similar total duration of walking performed once per day (Pahra et al., 2017). Systematic reviews also demonstrate that post-meal walking results in a reduction of post-prandial excursions (Borror et al., 2018; Engeroff et al., 2023). Current guidelines also suggest walking after meals (Colberg et al., 2016; Kanaley et al., 2022).

Despite this, many individuals with T2DM are not able to walk after dinner due to joint pain, poor lighting on streets, safety concerns, bad weather or poor exercise tolerance. A home based exercise that can be done indoors, with minimal space or load would overcome these issues. One such activity is active stretching. This type of exercise can be done with little or no equipment, can be done by older or less mobile individuals and involves large muscle groups with low intensities. Acute studies have also suggested that static or passive stretching can result in a decrease in glucose levels (Nelson et al., 2011; Gurudut and Rajan, 2017). Additionally, low intensity muscle activity has also been shown to increase glucose uptake (Dempsey et al., 2016; Hamilton et al., 2022). However, these studies were acute and conducted with capillary glucose monitoring. None of these studies investigated the effectiveness of a stretching routine on post-dinner excursions as compared to walking over a number of weeks.

Continuous glucose monitoring (CGM) facilitates the observation of postprandial fluctuations and glycemic variability in real-world environments using established metrics (Danne et al., 2017; Battelino et al., 2019). To the best of our knowledge, no research has juxtaposed post-dinner walking with post-dinner active stretching with continuous glucose monitoring. The objective of this research was to examine the impact of 12 weeks of walking and physical stretching after meals on post-dinner glucose fluctuations and glycemic variability, as measured by continuous glucose monitoring (CGM) in patients with type 2 diabetes mellitus (T2DM). We hypothesized that ambulation would lead to a more significant decrease in postprandial iAUC compared to active stretching. We further posited that active stretching would lead to a decrease in MAGE comparable to a drop of 15 mg/dL seen with walking.

2. MATERIALS AND METHODS

2.1. Study design, setting and ethics

A two arm, parallel, assessor blind, trial with a 1:1 allocation ratio was conducted in accordance with the CONSORT 2010 statement (Schulz et al., 2010). The study was conducted at the outpatient diabetes clinic of ACS Medical College & Hospital. The protocol was approved by the Institutional Review Board and was performed in accordance with the Declaration of Helsinki. Every participant furnished signed informed consent.

2.2. Participants

Adults (both male and female) aged 40-65 years with T2DM for at least one year, HbA1c 7.0-8.0%, on a stable oral antidiabetic therapy for at least three months, able to ambulate independently and have a smartphone to upload continuous glucose monitor (CGM) data were eligible. Exclusion criteria included use of insulin or a change in sulfonylurea dose within the previous three months, unstable angina or uncontrolled cardiovascular disease, foot ulcer, severe peripheral neuropathy or proliferative retinopathy, severe neurological or musculoskeletal impairment, allergy to sensor adhesive of the CGM device, and habitual walking after dinner three or more days per week. Height, weight, waist circumference and blood pressure were measured using standard procedures. Body mass index (BMI) was assessed based on Asian standards (WHO Expert Consultation, 2004). The International Physical Activity Questionnaire (IPAQ) was used to assess habitual physical activity levels (Craig et al., 2003).

2.3. Sample size

Based on acute post-meal walking studies a within within group difference in post-dinner iAUC of 0.8 standard deviations (d = 0.8) was assumed. With two-tailed $\alpha = 0.05$ and 80% power 26 participants were required per group using G*Power. Allowing for 15% dropout 30 participants were recruited per group (60 total).

2.4. Randomization, allocation concealment and blinding

Block randomization, created by computer, was stratified according to baseline HbA1c levels (stratum 1: HbA1c 7.0-7.5%; stratum 2: HbA1c 7.6-8.0%) and conducted by an investigator who was not engaged in participant recruiting. The allocation was hidden inside consecutively numbered, opaque, and sealed envelopes, which were revealed after the baseline continuous glucose monitoring. The continuous glucose monitor (CGM) was used in a concealed manner, preventing individuals from accessing their glucose readings. Continuous glucose monitoring data were retrieved and evaluated by an assessor unaware of treatment assignment. Owing to the characteristics of the therapies, neither the participants nor their therapists were subjected to blinding.

2.5. Interventions

Both groups participated in five days of exercise per week for 12 weeks beginning 15-30 minutes after the conclusion of the dinner meal. Exercise duration for weeks 1-2 was 20 minutes and for weeks 3-12 was 30 minutes. The walking group (Group A) exercised at moderate intensities corresponding to a rating of perceived exertion (RPE) of 11-13 on the Borg 6-20 scale (Borg, 1982). Indoor walking or walking along a fixed route was permitted if outdoor walking was not safe. The active stretching group (Group B) performed a 5-minute warm up involving arm circles, in place marching and trunk rotation before active and static stretching of the calf, hamstring, quadriceps, hip flexors, gluteals, trunk and upper limbs (3 × 30 seconds each) at an RPE of 9-11. The exercise was conducted using a video and illustrated booklet. Exercise sessions were recorded in a diary and verified by weekly video or phone call. Participants were educated about symptomatic hypoglycemia and the use of a glucometer to measure symptomatic hypoglycemia. Antidiabetic medications were unchanged throughout the study.

2.6. Continuous glucose monitoring and test dinners

A masked flash CGM (FreeStyle Libre Pro, Abbott Diabetes Care) was worn for 14 days at baseline (prior to randomization) and again during weeks 11-12. During three test days in each phase participants were provided with a standardized dinner with a fixed carbohydrate content which was served as a menu. Participants were also asked to record the start and end times of dinner and in weeks 11-12 the start and end time of exercise. CGM data were considered valid only if the sensor was worn for at least 70% of the time (Battelino et al., 2019). Data were exported from the sensor and analyzed using iglu package in R (Broll et al., 2021) and EasyGV.

2.7. Outcome measures

The primary outcome metric was the increase in glucose area under the curve from 0-3 hours post-initiation of the test supper (iAUC, mg/dL·h) averaged over the three testing days. Secondary outcome measures included mean amplitude of glucose excursions (MAGE) (Service et al., 1970), coefficient of variation (CV), time in range (TIR, 70-180 mg/dL), time above range (TAR, >180 and >250 mg/dL) and time below range (TBR, <70 mg/dL) over the 14 day period (Battelino et al., 2019), time to peak and peak glucose after dinner. Descriptive measures included mean glucose levels, glucose management indicator (GMI) (Bergenstal et al., 2018) and time below range of <54 mg/dL. Other outcome measures include adherence (percentage of 60 prescribed sessions completed; adherent if ≥80%), mean RPE during exercise session, relative timing of exercise to dinner,

symptomatic and glucometer-confirmed hypoglycemia (<70 mg/dL), severe hypoglycemia requiring assistance (American Diabetes Association Professional Practice Committee, 2025) and any other adverse events.

2.8. Statistical analysis

The evaluation was conducted in accordance with the intention to treat (ITT) approach, including all 60 randomized participants. Data deficiencies at week 12 were rectified by multiple imputation. For each outcome 50 data sets were generated by Bayesian linear regression imputation using baseline value, treatment, HbA1c stratum, age, sex, BMI and adherence as predictors. Estimates were pooled using Rubin's rules (Rubin, 1987; Sterne et al., 2009). Between group differences were estimated using analysis of covariance (ANCOVA) of the value at week 12 adjusted for the baseline value and HbA1c strata (Vickers and Altman, 2001). Differences were expressed as the adjusted mean difference (walking − stretching) with 95% confidence intervals (CI) and Cohen's d with 95% CI. Secondary CGM measures were analyzed using the same methods. A Bonferroni correction was applied across the eight pre-specified secondary outcomes (MAGE, CV, TIR, TAR >180, TAR >250, TBR <70, time to peak and peak glucose). The exploratory hypothesis for MAGE was evaluated to determine whether the 95% confidence interval for the between group difference was within 15 mg/dL of the difference achieved by walking.

Pre-specified sensitivity analyses for the primary outcome included a complete case ANCOVA, baseline observation carried forward, a per-protocol analysis which excluded individuals with ≥80% adherence, additional adjustments for age, sex, BMI and sulfonylurea use, heteroscedasticity robust (HC3) standard errors, and non-parametric analysis (rank-based ANCOVA and Mann-Whitney U test on change scores). Assumptions for ANCOVA including normality of residuals, homogeneity of regression slopes and homogeneity of variances were tested for all models. Within group changes were evaluated with paired t tests or Wilcoxon signed-rank tests for non-normally distributed data. Responder rates (≥10%, ≥20% and ≥30% reduction in iAUC) were evaluated using Fisher's exact test. Exploratory analyses included subgroup effects with interaction terms between group and subgroups and the relationship between adherence and change in iAUC (Spearman's ϱ). Descriptive measures of baseline characteristics were reported without significance testing in accordance with CONSORT recommendations. Significance was set at two-sided $p < 0.05$. Analyses were conducted using Python 3 (pandas, SciPy, statsmodels and scikit-learn).

3. RESULTS AND DISCUSSION

3.1. Participant flow and baseline characteristics

60 participants were randomised. Three walkers and two stretchers withdrew, and one stretcher completed the intervention but had 65% CGM data at week 12; therefore 54 participants (90%) had complete data for the primary outcome (27 per group) (**Figure 1**). Reasons for withdrawal were relocation, knee pain when walking, and loss to follow-up in the walking group, and perceived lack of benefit and a family illness in the stretching group. Data quality was good; the median sensor wear was 93.2% at baseline and 91.6% at week 12. Participants in the two groups were comparable at baseline (Table 1). The mean age of the participants was between 49 and 52 years and the mean HbA1c was 7.4-7.5%. Approximately 60% of the participants were classified as obese by the Asian standards and 23% in each group were using sulfonylureas. There were comparable baseline CGM profiles including post-dinner iAUC. There were only small differences in age and sex, which were assessed using a sensitivity analysis that adjusted for these factors.

3.2. Primary outcome: post-dinner glucose excursion

Both interventions showed a reduction in post-dinner glucose excursion but the reduction seen with walking was approximately twice that seen with stretching (Table 2; **Figure 2**). The ITT analysis found that iAUC at week 12 for the walking group was 20.7 mg/dL·h lower than for the stretching group (95% CI −35.9 to −5.6, $p = 0.007$). This is a moderate to large effect ($d = -0.72$, 95% CI −1.24 to −0.19). This result was found in all sensitivity analyses including complete case analysis, carry forward from baseline, additional covariate adjustment, robust standard errors and non parametric tests (all $p \leq 0.025$). The per-protocol analysis showed a similar effect size to the ITT analysis but was not statistically significant ($p = 0.092$). This is likely due to loss of power as a result of excluding 20 participants, rather than a smaller true effect. The cumulative responder analysis shows that walking caused the entire responder distribution to shift in the direction of the greater reduction in iAUC (**Figure 3**). 59.3% of walkers and 33.3% of stretchers had an iAUC reduction of at least 20% (number needed to treat = 3.9). None of the individual responder comparisons were significant. Therefore the null hypothesis can be rejected in favour of H_1.

The finding that walking is beneficial is consistent with acute studies which have found that postprandial walking reduces postprandial glucose in both individuals with and without T2DM (Colberg et al., 2009; Nygaard et al., 2009; Reynolds et al., 2016; Bellini et al., 2022) and consistent with a meta-analysis showing that exercise performed after a meal produces the greater reduction in glycemic excursion compared to exercise performed before a meal (Engeroff et al., 2023). This study extends these findings in two ways. Firstly it shows that a benefit was present with 12 weeks of practice of the exercises at home in free-living conditions with masked CGM rather than during a single session. Secondly the exercise compared to sitting was active and time matched, so the difference between the groups can be attributed to the benefit of walking over low intensity activity. It is also plausible that walking has this effect due to the large contraction of large lower limb muscles for 30 minutes at moderate intensity resulting in a proportionate increase in muscle glucose uptake related to the muscle mass and intensity of muscle contraction. Also exercise performed 15-30 minutes after dinner occurs at the peak of the glucose excursion following a meal (Richter and Hargreaves, 2013; Haxhi et al., 2013; Erickson et al., 2017).

Stretching is also not inert. The 12.1% reduction in iAUC within the stretching group is consistent with acutely reported reductions in blood glucose resulting from a single 20 minute stretching session (Nelson et al., 2011; Gurudut and Rajan, 2017) and with reports that low intensity muscle activity interrupting sedentary behaviour after a meal can result in reductions in postprandial glucose in individuals with T2DM (Dempsey et al., 2016; Buffey et al., 2022). The magnitude of the effect observed between groups (d = 0.72) is also similar to the assumed effect size used in sample size calculations (0.8) and therefore the primary outcome for this study was well powered.

3.3. Secondary outcomes: peak response, glycemic variability and time in ranges

Only peak post-dinner glucose was different between the groups. There was a 16.7 mg/dL lower peak glucose for walkers compared to stretchers (95% CI −27.9 to −5.5; d = −0.79). This difference was also found to be significant following adjustment for multiple comparisons (adjusted p = 0.027) (Table 3; **Figure 4**). The peak post-dinner glucose was also reduced with walking but with a minimal change in the time of the peak glucose. Stretching also reduced peak glucose but to a lesser extent (**Figure 5**). There was no difference in time-to-peak between the groups. However, few participants in either group achieved the postprandial target of <180 mg/dL at week 12 (one stretcher and two walkers). This suggests that exercise alone is not sufficient to result in normalization of the post-prandial peak glucose in this population (American Diabetes Association Professional Practice Committee, 2025).

There were no differences in MAGE, CV, mean glucose, GMI, TIR or TAR between the groups at week 12 (Table 3). The adjusted difference in MAGE was −2.7 mg/dL (95% CI −8.1 to 2.7). The maximum possible difference in MAGE for walkers (8.1 mg/dL) is well within the pre-specified 15 mg/dL difference. Therefore the exploratory hypothesis H_2 can be supported. Within the walking group there were small improvements in mean glucose, GMI and TAR >250 mg/dL and within the stretching group there were improvements in peak glucose and TAR >250 mg/dL but there were no differences between groups for any of these secondary outcomes. The percentage of participants with TIR >70% and TAR <25% increased from 18.5% to 25.9% with walking and from 7.4% to 22.2% with stretching.

The finding of a significant effect on post-dinner glucose excursion and no significant effect on other glycemic metrics is interesting. The change in iAUC is correlated with the change in peak glucose (ϱ = 0.53) and only weakly correlated with changes in mean glucose (ϱ = 0.23) and TIR (ϱ = −0.18). Mean glucose, TIR and TAR can be almost interchangeably with each other ($|\varrho|$ 0.84-0.98). A 30-minute exercise performed after one meal will affect only a small proportion of the 24-hour glucose profile and will be diluted over 14 day averages. Therefore, longer follow-up or exercise performed after every meal may be required to significantly alter TIR or HbA1c (DiPietro et al., 2013; Pahra et al., 2017). The baseline MAGE (≈100 mg/dL) and CV (≈25%) are also within the agreed upon range for a stable profile (CV ≤36%) defined by the international consensus (Battelino et al., 2019) which leaves little change in the variability measures. Therefore, the postprandial measures of iAUC and peak are the most sensitive measures to use in evaluating postprandial exercise interventions.

3.4. Adherence, exercise intensity and fidelity

The median adherence to walking was 78% and the median adherence to stretching was 83%. 46.7% of walkers and 70.0% of stretchers achieved at least 80% adherence to their exercise regimen (Table 4). Adherence to walking declined over time after week 6 but adherence to stretching remained constant (**Figure 6**). Exercise intensity was as expected (mean RPE 12.4 for walking vs. 10.1 for stretching). Exercise on the test days started a median of 20 minutes after dinner. 86-91% of the sessions

started between 15-30 minutes after dinner. Standardised dinners were consumed as prescribed on ≥93% of the days. Dinner times did not vary between time points so differences in amount of food consumed are unlikely to account for the results. There was no relationship between adherence and reduction in iAUC in either the walking or stretching groups ($\varrho = 0.06$, $p = 0.78$ for walkers and $\varrho = 0.15$, $p = 0.47$ for stretchers). The advantage of walking was present for all levels of adherence. The greater adherence to stretching despite the smaller reduction in iAUC suggests that it is an acceptable indoor activity. In both the walking and stretching groups diary entries attributed missed exercises to visitors at home, fatigue or rain which may be more relevant to outdoor walking exercise.

3.5. Safety

There was no severe hypoglycaemia and no participants dropped out for reasons of hypoglycaemia (Table 4). Glucometer confirmed hypoglycaemia (<70 mg/dL) was reported by 8 walkers and 5 stretchers ($p = 0.53$). However, 42 of the 43 confirmed hypoglycaemia events occurred in the 14 participants who were on sulfonylureas (**Figure 7**). This is consistent with the known risk of hypoglycaemia with sulfonylureas (Schopman et al., 2014) and suggests that the difference in hypoglycaemia events was due to sulfonylurea use rather than type of exercise. There was a slight increase in time below 70 mg/dL with walking compared to stretching but this was not statistically significant. No participants exceeded the consensus level of 4%. For patients on sulfonylureas it is important to monitor glucose and reassess medication when prescribing postprandial exercise. Other adverse events were mild with 5 walkers reporting knee aches or calf soreness which did not prevent continued participation in the study. One walker withdrew due to knee pain and one stretcher reported one episode of lightheadedness with normal capillary glucose.

3.6. Exploratory subgroup analysis

The benefit of walking was present in all subgroups (**Figure 8**). Interaction analysis showed a greater benefit of walking in patients with higher HbA1c (7.6-8.0%; −47.0 vs −8.0 mg/dL·h; p for interaction = 0.015), in patients under 51 years of age ($p = 0.047$) and in patients with diabetes for 7 years or more ($p = 0.040$). This finding for higher HbA1c is plausible due to greater postprandial glucose excursions available for glucose uptake via muscle contraction. However these subgroups were small and seven interactions were tested. Therefore these results should be considered hypothesis generating.

3.7. Strengths and limitations

This study had a number of strengths. Stratification was done according to HbA1c and allocation was concealed. CGM was masked and outcome assessment was blinded. Standardised test dinners were used and timing of the dinner was recorded. The exercise was active and time matched. CGM data quality was high. Attrition was low and balanced between the groups. ITT analysis was used with multiple imputation. All pre-specified sensitivity analyses showed consistent results. Limitations of the study include the single centre nature of the study and the limited sample size which may limit power for the secondary outcomes and subgroup analyses. The participants were not blinded to the type of exercise. Adherence was self reported. Follow-up was only 12 weeks which is too short to measure changes in HbA1c or long-term maintenance. Diet outside of the test dinners was not controlled. The results of this study pertain to adults with moderately controlled T2DM (HbA1c 7.0-8.0%) who are not on insulin therapy.

4. CONCLUSIONS

In adults with moderately controlled T2DM, 12 weeks of post-dinner walking resulted in a greater reduction of post-dinner glucose excursion and peak glucose compared to post-dinner active stretching. Both interventions showed comparable effects on time in ranges and glycemic variability and both were safe. Walking should continue as the preferred post-dinner activity but active stretching resulted in approximately half the reduction in iAUC. However stretching was slightly more adhered to and can be a practical indoor alternative for individuals who are unable to walk after dinner. Future studies should look at alternating or combined walking and stretching exercise, exercise after every meal, longer follow-up with HbA1c as an outcome measure and targeted exercise in individuals with higher HbA1c levels. Attention should be paid to monitoring for hypoglycaemia in individuals on sulfonylureas.

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Author contributions:

Dr. S Ramachandran: conceptualization, methodology, investigation, data curation, writing – original draft.

Dr Ajay Kumar: supervision, data collection, writing – review and editing

Dr. Vijayakumar Palaniswamy: supervision, methodology, writing – review and editing.

Dr Praveen B M: Statistical analysis and visualization, review and editing.

Dr. S Jeyakumar: Statistical analysis, data curation and visualization

Dr C V Senthil Nathan: Statistical analysis, data curation and visualization

Dr. Mohan Kumar G: data curation, Statistical analysis and visualization

Dr. Rajalaxmi V: writing – review and editing and visualization

All authors read and approved the final manuscript.

Conflict of interest

The authors declare that they have no potential conflict of interest.

Ethics statement

The study was approved by the Institutional Review Board of Faculty of Physiotherapy (2402/CVP/PHYSIO/IRB/2026) conducted in accordance with the ICMR

National Ethical Guidelines (2017) and the Declaration of Helsinki. Written informed consent was obtained from all participants.

Data availability statement

The dataset supporting the findings of this study is available from the corresponding author on reasonable request.

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Table 1. Baseline characteristics of randomized participants by group

Characteristic	Walking (n = 30)	Stretching (n = 30)
Demographic and clinical		
Age (years)	49.3 ± 7.7	52.0 ± 6.4
Female sex, n (%)	10 (33.3)	14 (46.7)
Diabetes duration (years)	7.2 ± 3.5	6.4 ± 2.7
BMI (kg/m²)	26.3 ± 3.6	26.1 ± 2.4
Obese (BMI ≥25 kg/m²), n (%)	19 (63.3)	18 (60.0)
Waist circumference (cm)	91.7 ± 9.4	88.4 ± 9.1
HbA1c (%)	7.4 ± 0.2	7.5 ± 0.2
HbA1c stratum 7.6–8.0%, n (%)	8 (26.7)	9 (30.0)
Systolic / diastolic BP (mmHg)	131.7 ± 11.6 / 80.9 ± 7.7	129.0 ± 13.2 / 80.3 ± 9.4
Metformin plus other oral agent, n (%)	13 (43.3)	11 (36.7)
Sulfonylurea use, n (%)	7 (23.3)	7 (23.3)
IPAQ total (MET-min/week), median (IQR)	394 (175–1110)	488 (240–826)
Low physical activity (IPAQ), n (%)	15 (50.0)	14 (48.3)
Baseline CGM		
Post-dinner iAUC 0–3 h (mg/dL·h)	187.1 ± 57.4	184.6 ± 55.4
Peak post-dinner glucose (mg/dL)	250.3 ± 33.4	245.8 ± 30.3
MAGE (mg/dL)	102.3 ± 13.0	101.4 ± 14.1
CV (%)	25.1 ± 3.9	24.7 ± 2.9
Mean glucose (mg/dL)	167.4 ± 10.5	168.4 ± 13.4
Time in range 70–180 mg/dL (%)	67.4 ± 9.4	65.8 ± 10.4
Time above 180 mg/dL (%)	32.2 ± 9.6	33.8 ± 10.8

Values are mean ± SD unless otherwise stated. BMI categories follow WHO Asian cut-offs. Waist circumference missing for one walker and IPAQ for one stretcher. Statistical tests of baseline differences are not reported, in line with CONSORT recommendations. BP, blood pressure; CGM, continuous glucose monitoring; CV, coefficient of variation; iAUC, incremental area under the curve; IPAQ, International Physical Activity Questionnaire; MAGE, mean amplitude of glycemic excursions.

Table 2. Post-dinner iAUC (0–3 h, mg/dL·h) at baseline and week 12, and between-group effects

Group / analysis	**Baseline**	**Week 12**	**Change (95% CI)**	**% change**	**p value**
Walking (n = 27)	186.2 ± 59.4	142.9 ± 53.2	-43.3 (-56.2 to -30.4)	-23.4	<0.001
Stretching (n = 27)	185.8 ± 57.0	162.7 ± 51.1	-23.1 (-34.7 to -11.5)	-12.1	<0.001
Between-group comparison (walking − stretching)	**n**	**Adjusted difference (95% CI)**	**Cohen's d (95% CI)**		**p value**
ITT, multiple imputation (primary)	**60**	**-20.7 (-35.9 to -5.6)**	**-0.72 (-1.24 to -0.19)**		**0.007**
Complete-case analysis	54	-20.4 (-35.7 to -5.2)			0.010
Baseline observation carried forward	60	-18.0 (-32.7 to -3.4)			0.017
Complete case, adjusted for age, sex, BMI and sulfonylurea	54	-21.7 (-37.6 to -5.8)			0.008
Complete case, robust (HC3) standard errors	54	-20.4 (-35.8 to -5.0)			0.009
Per-protocol (adherence ≥80%)	34	-16.6 (-36.2 to 2.9)			0.092
Rank-based ANCOVA (non-parametric)	54	—			0.017

Upper panel: completers, mean ± SD; within-group p from paired t-test. Lower panel: ANCOVA of week-12 iAUC adjusted for baseline iAUC and HbA1c stratum; multiple imputation with m = 50 data sets pooled by Rubin's rules. Per-protocol analysis included 14 walkers and 20 stretchers. ITT, intention-to-treat; SE, standard error.

Table 3. Secondary CGM outcomes at baseline and week 12 and adjusted between-group differences

Outcome	Walking baseline	Walking week 12	Stretching baseline	Stretching week 12	Adjusted difference (95% CI)	p value	Bonferroni p	d
Peak post-dinner glucose (mg/dL)	**249.3 ± 33.6**	**221.3 ± 29.7**	**249.4 ± 29.8**	**236.6 ± 29.6**	**-16.7 (-27.9 to -5.5)**	**0.003**	**0.027**	**-0.79**
Time-to-peak (min)	65.6 ± 13.3	68.7 ± 13.2	69.3 ± 16.2	71.9 ± 16.3	-0.1 (-5.8 to 5.5)	0.959	1.000	-0.01
MAGE (mg/dL)	102.2 ± 13.7	98.5 ± 14.1	102.4 ± 14.4	100.9 ± 12.9	-2.7 (-8.1 to 2.7)	0.327	1.000	-0.26
CV (%)	25.43 ± 3.92	25.38 ± 4.14	24.79 ± 3.07	24.50 ± 3.05	0.25 (-0.92 to 1.42)	0.675	1.000	0.12
Time in range 70–180 mg/dL (%)	68.1 ± 8.6	69.8 ± 7.7	64.1 ± 9.3	65.5 ± 10.4	0.8 (-2.1 to 3.7)	0.585	1.000	0.15
Time above 180 mg/dL (%)	31.5 ± 8.8	29.6 ± 8.1	35.5 ± 9.8	34.2 ± 10.6	-1.1 (-4.0 to 1.8)	0.449	1.000	-0.21
Time above 250 mg/dL (%)	4.73 ± 1.86	3.67 ± 1.82	5.41 ± 2.85	4.67 ± 2.62	-0.47 (-1.20 to 0.25)	0.198	1.000	-0.35
Time below 70 mg/dL (%)	0.40 ± 0.67	0.57 ± 0.86	0.36 ± 0.94	0.31 ± 0.52	0.23 (-0.12 to 0.57)	0.193	1.000	0.34
Mean glucose (mg/dL) ‡	166.6 ± 10.0	163.2 ± 10.3	170.3 ± 12.5	168.3 ± 13.4	-1.5 (-5.1 to 2.2)	0.433	—	-0.21
GMI (%) ‡	7.29 ± 0.24	7.21 ± 0.25	7.38 ± 0.30	7.33 ± 0.32	-0.04 (-0.12 to 0.05)	0.426	—	-0.22
Time below 54 mg/dL (%) ‡	0.06 ± 0.15	0.11 ± 0.25	0.06 ± 0.16	0.04 ± 0.08	0.07 (-0.02 to 0.17)	0.133	—	0.39

Baseline and week-12 values are mean ± SD in completers (n = 27 per group). Adjusted differences (walking − stretching) are from intention-to-treat ANCOVA with multiple imputation (n = 60) adjusted for baseline value and HbA1c stratum; for time in range a positive difference favours walking, for all other outcomes a negative difference favours walking. Bonferroni correction was applied across the eight protocol-specified secondary outcomes; ‡ additional descriptive outcome, not corrected. d, Cohen's d; CV, coefficient of variation; GMI, glucose management indicator; MAGE, mean amplitude of glycemic excursions.

Table 4. Adherence, exercise intensity, protocol fidelity and safety outcomes by group

Measure	Walking (n = 30)	Stretching (n = 30)	p value
Adherence and intensity			
Sessions completed (of 60), median (IQR)	47 (43–51)	50 (47–54)	0.074
Adherence (%), median (IQR)	78 (72–85)	83 (78–89)	0.074
Adherent (≥80%), n (%)	14 (46.7)	21 (70.0)	0.115
RPE within target band, n (%)	22 (73.3)	23 (76.7)	1.000
Mean RPE (Borg 6–20), mean ± SD	12.4 ± 1.0	10.1 ± 0.9	<0.001
Protocol fidelity (week-12 test days)			
Dinner-end to exercise start (min), median (IQR)	20 (20–25)	20 (15–25)	0.117
Started within 15–30 min window, n/N (%)	60/70 (85.7)	70/77 (90.9)	0.440
Exercise duration on test days (min), mean ± SD	29.6 ± 3.6	27.9 ± 3.1	0.002
Standardized dinner eaten as given, baseline, n/N (%)	84/90 (93.3)	84/90 (93.3)	1.000
Standardized dinner eaten as given, week 12, n/N (%)	80/81 (98.8)	81/84 (96.4)	0.621
Safety (12 weeks)			
Symptomatic hypoglycemia, participants n (%) [episodes]	9 (30.0) [38]	7 (23.3) [28]	0.771
Confirmed hypoglycemia <70 mg/dL, participants n (%) [episodes]	8 (26.7) [25]	5 (16.7) [18]	0.532
Severe hypoglycemia (assistance required), n (%)	0 (0.0)	0 (0.0)	—
Other adverse events, participants n (%)	5 (16.7)	1 (3.3)	0.195
CGM TBR <70 mg/dL ≥4% at week 12, n/N	0/27	0/27	—
CGM TBR <54 mg/dL ≥1% at week 12, n/N	1/27	0/27	—

p values from Mann–Whitney U test, independent t-test or Fisher's exact test, as appropriate. Timing and duration refer to week-12 test-day sessions in which exercise was performed. Of the 43 confirmed hypoglycemic episodes, 42 occurred in the 14 sulfonylurea users. RPE, rating of perceived exertion (Borg 6–20); TBR, time below range.

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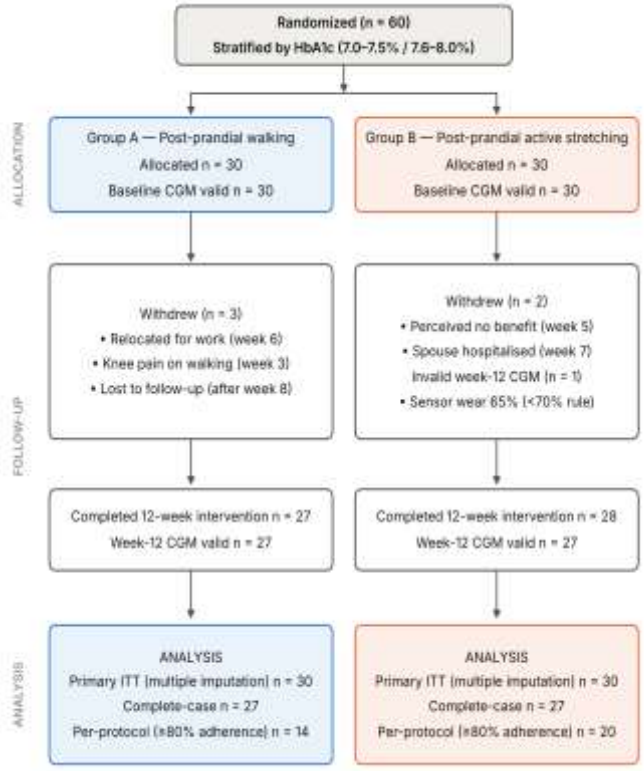


Figure 1. CONSORT flow chart of participants through the study. Withdrawals and CGM invalidity within each treatment group are displayed along with the size of each population in each analysis. ITT, intention-to-treat.

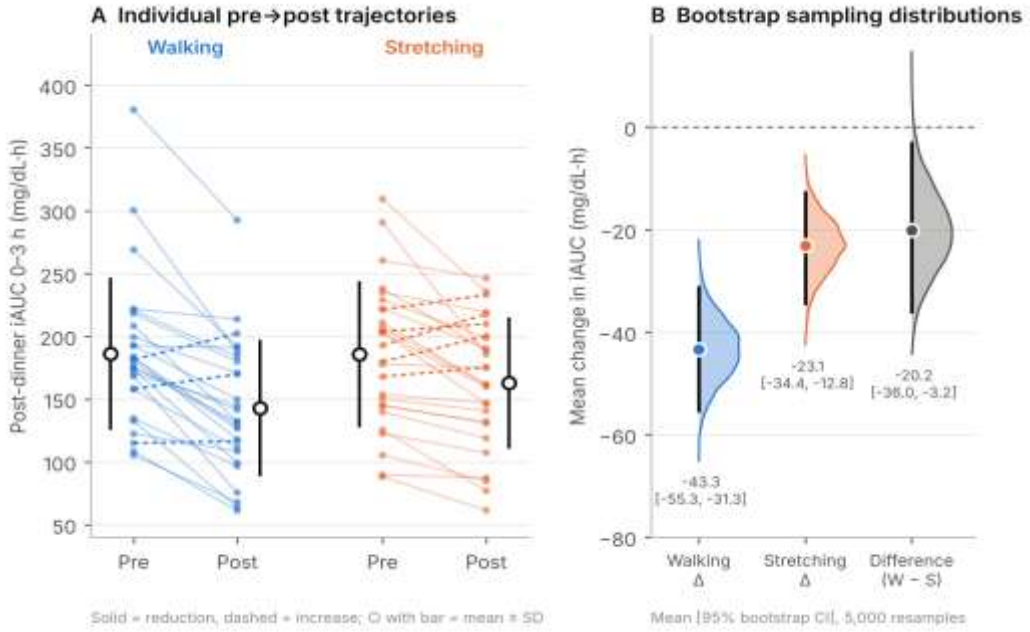


Figure 2. Change in post-dinner incremental area under the glucose curve (iAUC, 0-3 h) from the stretching and walking groups. (A) Individual pre- to post-test change trajectories for all participants with complete data (n = 27 per group). Solid lines represent decreases and dashed lines increases. Open circles with error bars represent means ± SD. (B) Bootstrap distributions of mean change within each group (5,000 samples) and the difference between groups. Means and 95% confidence intervals are shown.

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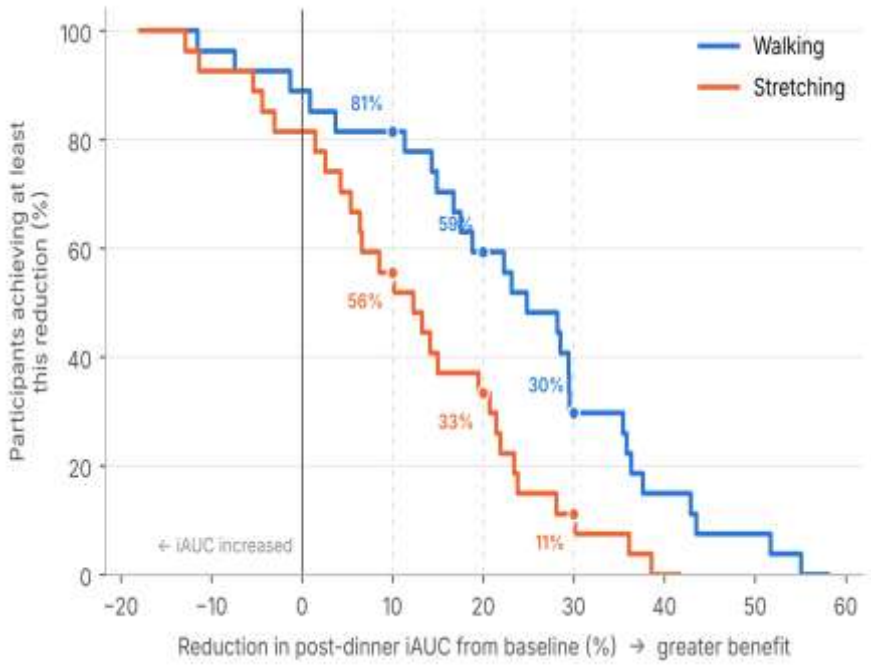


Figure 3. Cumulative responder curve for the percentage change in post-dinner iAUC. For each level along the x-axis, the curve represents the percentage of participants who had a reduction in iAUC of at least the level shown (n = 27 per group). The points represent the percentages who had a reduction of ≥10%, ≥20% and ≥30%.

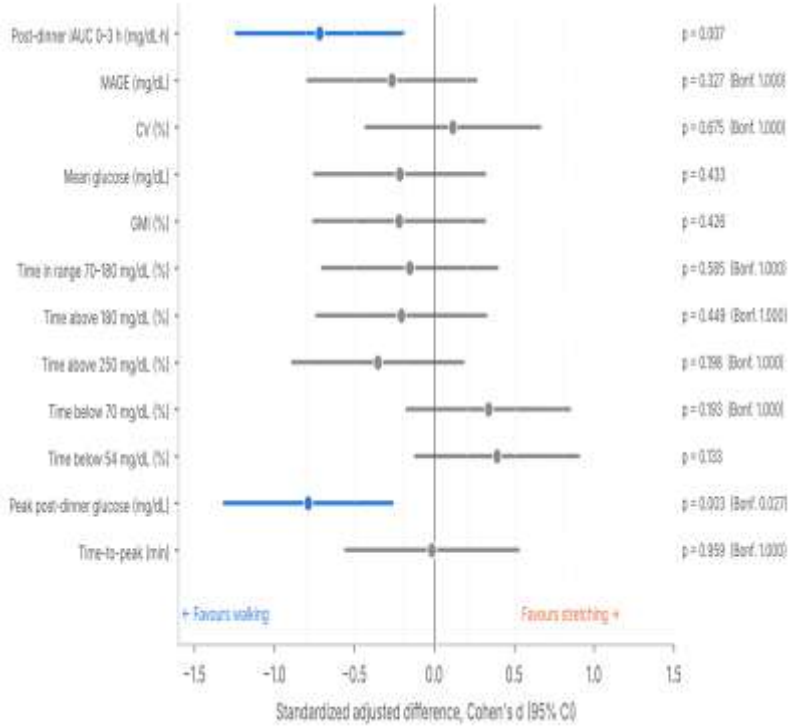


Figure 4. Standardized differences between groups for all CGM measures at week 12. Cohen's d with 95% confidence intervals from intention-to-treat ANCOVA analyses adjusted for baseline value and HbA1c strata (multiple imputation, m = 50), with the direction such that differences to the left of zero are in favour of walking. For time in range the sign is reversed. Blue points represent $p < 0.05$. Bonferroni-adjusted p values are shown for the eight secondary outcomes defined by the protocol.

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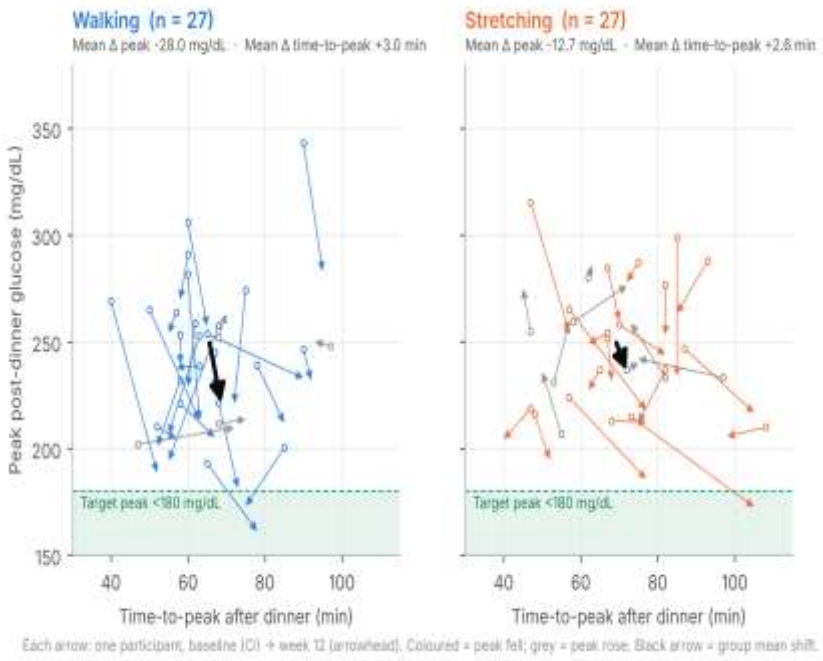


Figure 5. Change from baseline to week 12 in time to peak post-dinner glucose and peak post-dinner glucose. Arrows connect a participant's baseline point (open circle) to their point at week 12 (arrowhead). Coloured arrows represent a decrease in peak post-dinner glucose and grey arrows a rise. The bold black arrow represents change in group means. The shaded area represents the post-prandial target of <180 mg/dL.

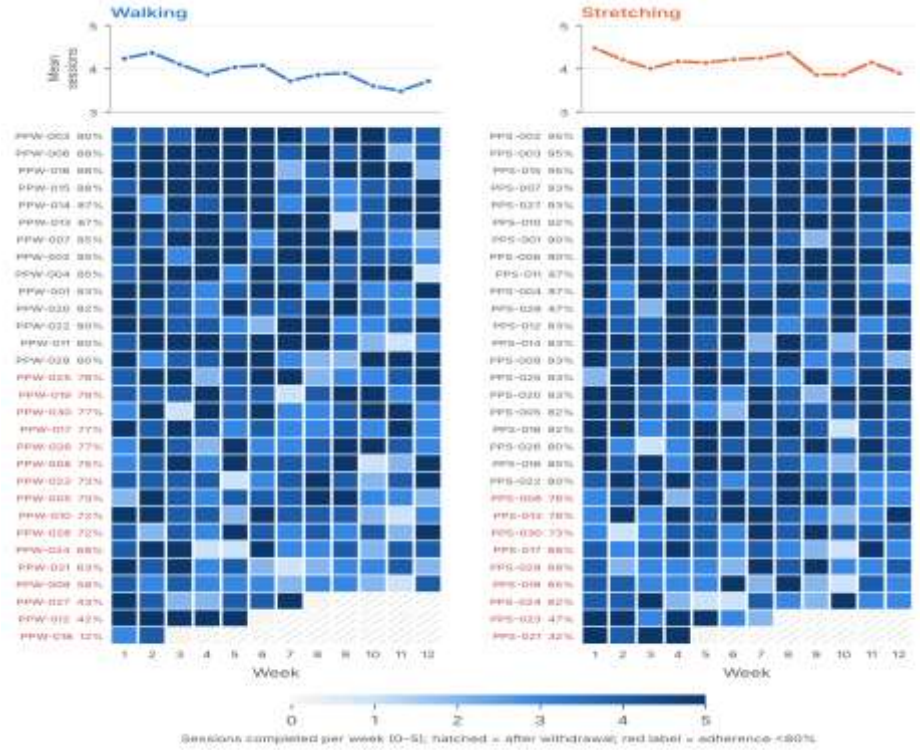


Figure 6. Weekly compliance with the post-dinner exercise intervention. Each row represents a participant and participants are ordered by overall compliance (shown adjacent to their identification number; red = <80%). Each box represents the number of exercises completed during that week (max of 5). Hatched boxes represent exercises completed after a participant has withdrawn from the study. The line above each panel represents the mean number of exercises per week for the group.

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Figure 7. Hypoglycaemia (<70 mg/dL) confirmed by glucometer by group and sulfonylurea use. Each symbol represents the number of hypoglycaemic events confirmed by glucometer in a participant over the 12 week period. Circles represent participants not taking a sulfonylurea (SU) and triangles represent participants taking a sulfonylurea. Σ represents the total number of hypoglycaemic events.

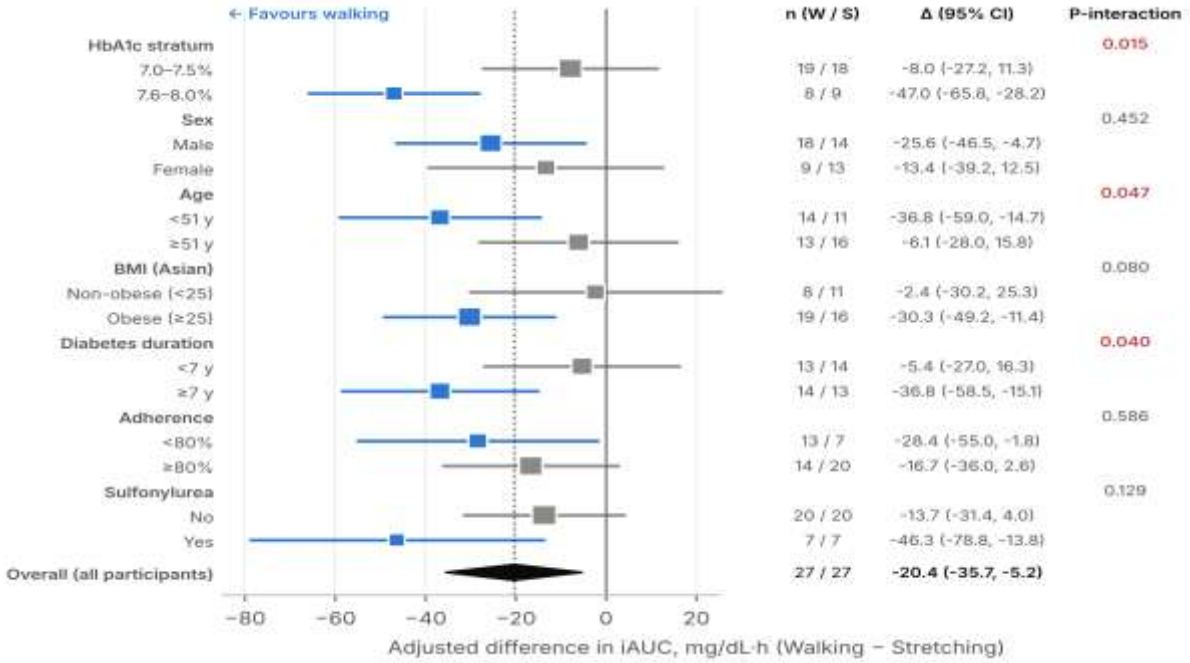


Figure 8. Exploratory subgroup analysis of the primary outcome. Adjusted difference in change from baseline to week 12 in post-dinner iAUC (walking − stretching) with 95% confidence intervals for each subgroup (complete cases). The size of each square is representative of the size of the subgroup. Blue intervals do not contain zero. The diamond and dotted line represent the overall effect. Interaction p values <0.05 are in red.