A randomized controlled trial: Effects of outdoor exercise on blood glucose and sleep in T2DM with wearable devices in a mHealth model

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Table of Contents

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Yue-Xia Han[1]; Xi-Shuang Chen[1]; Jingxian Fang[1]; Sui-Jun Wang[1]; Fang Huang[1]; Jian Meng[1]; Hui-Zhen Liu[1]; Yu Han[1]; Hui-Ming Zou[1]; Xue Hu[1]; Qing Gu[1]; Qian-Wen Ma[1]

[1] Yangpu District Shidong Hospital of Shanghai, Endocrinology and Metabolism Shanghai CN

Corresponding Author:
Sui-Jun Wang

Yangpu District Shidong Hospital of Shanghai, Endocrinology and Metabolism
No.999, Shiguang Road, Yangpu District, Shanghai, China
Shanghai
CN

Abstract

Background: Exercise is considered an important component of lifestyle management for T2DM. Outdoor exercise has been shown to enhance individuals' perception of their overall health status.

Objective: This study aimed to explore the role of outdoor exercise on blood glucose management and sleep quality in patients with T2DM.

Methods: The study was a randomized controlled trial in which participants were randomized (1:1) to indoor or outdoor training group for 12 weeks. The outdoor Tai Chi group classes are conducted in an open and flat park surrounded mostly by trees. As for the indoor environment, it is a dance studio with a constant temperature maintained at 22.2°C. Visual contact with the outdoors is possible through windows facing the road. The enrolled population performed aerobic 24-style Tai Chi exercise three times a week, lasting 60–90 minutes with 15 minutes of warm-up and cool-down included. During the 12-week long program study, all participants had sensors from the Guardian Sensors 3 continuous glucose monitoring (CGM) system implanted subcutaneously in their upper arms and paired with the Medtronic Guardian Connect CGM device. The sleep quality and quantity were assessed before and after the training program using the Pittsburgh Sleep Quality Index (PSQI) scale and sleep monitoring bracelet.Each patient also simultaneously wore a sunshine duration monitoring bracelet, through which daily sunshine duration was counted. The primary outcome was the absolute change in HbA1c levels within and between the two groups at 12 weeks. The secondary outcomes were changes in BMI, waist circumference, the time in range?TIR? measured by CGM? plasma glucose levels, daily sunshine duration? total sleep time (minutes slept between bedtime and wake time), sleep efficiency (percentage of time asleep while in bed), and wake after sleep onset (minutes awake between sleep onset and wake time).

Results: When comparing the primary outcomes at 12 weeks, we found a significant difference in the outdoor and indoor Tai Chi groups in HbA1c. The interaction effect was significant ($p = 0.012$). The outdoor Tai Chi group showed significant improvement in PSQI, Total sleep time, and Sleep efficiency, and the indoor Tai Chi group showed insignificant changes. Still, the time effect and group effect were significant.

Conclusions: In summary, this study demonstrated that outdoor Tai Chi significantly improves waist circumference, BMI, blood glucose levels, sleep quality and sun exposure. In contrast, indoor Tai Chi was relatively weak but also provided some health benefits.

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Yue-Xia Han †[1], Xi-Shuang Chen †[1], Fang Huang [1], Jian Meng [1], Hui-Zhen Liu [1], Yu Han [1], Hui-Ming Zou [1], Qing Gu [1], Xue Hu [1], Qian-Wen Ma [1], Jing-Xian Fang *[1], Sui-Jun Wang *[1]

1 Yangpu District Shidong Hospital of Shanghai, Endocrinology and Metabolism

address: No.999, Shiguang Road, Yangpu District, Shanghai, China

ZIP code: 200438

*CORRESPONDENCE

Jing-Xian Fang; Yangpu District Shidong Hospital of Shanghai, Endocrinology and Metabolism

e-mail address：fjx2012bbt@163.com

Sui-Jun Wang; Yangpu District Shidong Hospital of Shanghai, Endocrinology and Metabolism

e-mail address：drwangsuijun@163.com

Contributing authors

Jian Meng; Yangpu District Shidong Hospital of Shanghai, Endocrinology and Metabolism

e-mail address：drmengjian@163.com

Xi-Shuang Chen; Yangpu District Shidong Hospital of Shanghai, Endocrinology and Metabolism

e-mail address：drchenxishuang@126.com

Yue-Xia Han; Yangpu District Shidong Hospital of Shanghai, Endocrinology and Metabolism

e-mail address：drhanyuexia@sina.com

Yu Han; Yangpu District Shidong Hospital of Shanghai, Endocrinology and Metabolism

e-mail address：drhanyusd@sina.com

Hui-Ming Zou; Yangpu District Shidong Hospital of Shanghai, Endocrinology and Metabolism

e-mail address：drzouhuiming@163.com

Qing Gu; Yangpu District Shidong Hospital of Shanghai, Endocrinology and Metabolism

e-mail address：drguqingsd@163.com

Xue Hu; Yangpu District Shidong Hospital of Shanghai, Endocrinology and Metabolism

e-mail address：drhuxue@163.com

Qian-Wen Ma; Yangpu District Shidong Hospital of Shanghai, Endocrinology and Metabolism

e-mail address：drmaqianwen@163.com

Hui-Zhen Liu; Yangpu District Shidong Hospital of Shanghai, Endocrinology and Metabolism

e-mail address：drliuhuizhen@163.com

Fang Huang; Yangpu District Shidong Hospital of Shanghai, Endocrinology and Metabolism

e-mail address：drhuangfangsd@sina.com

†These authors share first authorship

Abstract

Background: Exercise is considered an important component of lifestyle management for T2DM. Outdoor exercise has been shown to enhance individuals' perception of their overall health status. This study aimed to explore the role of outdoor exercise on blood glucose management and sleep quality in patients with T2DM.

Material & methods: The study was a randomized controlled trial in which participants were randomized (1:1) to indoor or outdoor training group for 12 weeks. The outdoor Tai Chi group classes are conducted in an open and flat park surrounded mostly by trees. As for the indoor environment, it is a dance studio with a constant temperature maintained at 22.2°C. Visual contact with the outdoors is possible through windows facing the road. The enrolled population performed aerobic 24-style Tai Chi exercise three times a week, lasting 60–90 minutes with 15 minutes of warm-up and cool-down included. During the 12-week long program study, all participants had sensors from the Guardian Sensors 3 continuous glucose monitoring (CGM) system implanted subcutaneously in their upper arms and paired with the Medtronic Guardian Connect CGM device. The sleep quality and quantity were assessed before and after the training program using the Pittsburgh Sleep Quality Index (PSQI) scale and sleep monitoring bracelet.Each patient also simultaneously wore a sunshine duration monitoring bracelet, through which daily sunshine duration was counted. The primary outcome was the absolute change in HbA1c levels within and between the two groups at 12 weeks. The secondary outcomes were changes in BMI, waist circumference, the time in range（TIR） measured by CGM， plasma glucose levels, daily sunshine duration， total sleep time (minutes slept between bedtime and wake time), sleep efficiency (percentage of time asleep while in bed), and wake after sleep onset (minutes awake between sleep onset and wake time).

Results: When comparing the primary outcomes at 12 weeks, we found a significant difference in the outdoor and indoor Tai Chi groups in HbA1c. The interaction effect was significant ($p = 0.012$). The outdoor Tai Chi group showed significant improvement in PSQI, Total sleep time, and Sleep efficiency, and the indoor Tai Chi group showed insignificant changes. Still, the time effect and group effect were significant.

Conclusion: In summary, this study demonstrated that outdoor Tai Chi significantly improves waist circumference, BMI, blood glucose levels, sleep quality and sun exposure. In contrast, indoor Tai Chi was relatively weak but also provided some health benefits.

KEYWORDS: Type 2 diabetes mellitus, outdoor exercise, 24-style Tai Chi, sleep quality, sleep quantity

Introduction

In recent years, exercise has received widespread attention as one of the most important means of improving the health status of patients with type 2 diabetes mellitus (T2DM)[1]. Exercise is considered an important component of lifestyle management for T2DM, as it can help improve blood glucose control, reduce body weight, increase insulin sensitivity, and improve cardiovascular health[2]. People who are physically active regularly tend to sleep better and for longer periods than those with sedentary lifestyles[3]. Long-term physical activity has a positive effect on sleep quality[4].

24-Style Tai Chi is a long-standing fitness activity. Its movements are gentle and harmonized with breathing, aiming to enhance physical fitness. This exercise effectively activates multiple organs throughout the body and promotes blood circulation, thus regulating and optimizing metabolism and sleep[5].

Wearable digital devices are often placed on the wrist to continuously and instantly monitor an individual's health. They provide comprehensive feedback on health status in real time by tracking data such as steps, calories burned, heart rate, and sleep patterns. These devices give users a clear picture of their activity, motivating them to adjust their habits and adopt a healthier lifestyle[6].

The CGM system is a portable and efficient glucose monitoring tool that provides users with an accurate and real-time glucose monitoring solution by continuously monitoring glucose concentration in the ISF. The advantages of the CGM system are especially evident in situations where glucose levels fluctuate rapidly, such as during exercise. It helps users better understand their blood glucose status to adjust and manage their blood glucose accordingly[7].

Outdoor exercise has been shown to enhance individuals' perception of their overall health status. Exposure to natural environments, such as parks or forests, promotes well-being and can positively impact self-esteem and body image. Outdoor exercises are often more enjoyable and stimulating, increasing participation and motivation[8].

Based on this rationale, we aim to explore the potential benefits of outdoor Tai Chi exercise for T2DM through an M-Health model. The study will utilize wearable devices to monitor exercise data, blood glucose levels, and other physiological indicators in patients with T2DM. By analyzing this data, the role of wearable devices in tracking patient health, providing personalized exercise recommendations and improving the effectiveness of exercise interventions will be evaluated.

Methods

Study design

The study was a randomized controlled trial in which participants were equally assigned to indoor or outdoor training group for 12 weeks using a permutation block randomization method (block randomization). Figure 1 provides a flowchart of the recruitment and allocation of study participants.

All participants signed an informed consent form, and the Institutional Review Boards of all participating institutions approved the study (2024-013-01). The study was registered on the Chinese Clinical Trial Register, ChiCTR2200057863(19/03/2022).

Study participants

Participants were recruited from diabetic patients admitted to our hospital between January 2024 and March 2024.

The inclusion criteria were as follows: (1) aged between 55 and 75 years, (2) presence of T2DM lasting between 1 and 5 years, (3) Glycosylated hemoglobin (HbA1c) ≥6.5%，(4) BMI between 23 and 33 kg/m2

Exclusion criteria included (1) body mass index (BMI) greater than 40 kg/m^2; (2) unstable hypertension (upper limit of acceptable blood pressure (BP) of 140/90 mmHg); (3) Being pregnant at baseline; (4) Severe retinopathy; (5) Cognitive impairment.

The criteria for withdrawal are as follows: (1) loss of visits; (2) occurrence of a serious adverse event; (3) inability to adhere to the intervention medication as required by the trial.

Calculation of Sample Size

The sample size was determined based on findings from a previous meta-analysis[9]. The hypothesis was that outdoor Tai Chi exercises would prove more effective than indoors. A two-sided hypothesis test was conducted at a significance level of 0.05, with a 1:1 allocation ratio between groups. Aiming for 90% statistical power to detect a significant effect of the outdoor group compared to indoor, and accounting for an estimated 20% attrition rate, a sample size of 100 participants was ultimately selected, with 50 assigned to each group.

Intervention

The intervention method was conducted as follows.

The outdoor Tai Chi group classes are conducted in an open and flat park surrounded mostly by trees. The temperature ranges between 20 and 25 degrees Celsius. The humidity is between 46-90%, averaging at 76%. The weather is predominantly cloudy and moderate, with several sunny days interspersed. As for the indoor environment, it is a dance studio with a constant temperature maintained at 22.2°C. Visual contact with the outdoors is possible through windows facing the road.

The enrolled population performed aerobic 24-style Tai Chi exercise three times a week, lasting 60–90 minutes with 15 minutes of warm-up and cool-down included. Training is at 8 a.m.

All exercise sessions were supervised by exercise physiologists at our facility. No adverse events were observed in the experimental period.

During the 12-week long program study, all participants had sensors from the Guardian Sensors 3 continuous glucose monitoring (CGM) system implanted subcutaneously in their upper arms and paired with the Medtronic Guardian Connect CGM device. This device transmits blood glucose readings and trending information in real time to a receiver or the patient's smartphone. To ensure continuous monitoring of data, participants were provided with transmitters and an ample supply of sensors, which were replaced at a frequency of every two weeks. In addition, participants and their guardians received personalized instructions covering the operation of the CGM system and the sensor replacement process. In the study, the hypoglycemia alert threshold was set at 4.0 mmol/l and the hyperglycemia alert threshold was set at 20.0 mmol/l. Once the alerts were triggered, study participants were actively encouraged to contact the study team for further guidance and support.

The sleep quality and quantity were assessed before and after the training program (week 12) using the Pittsburgh Sleep Quality Index (PSQI) scale and sleep monitoring bracelet.

Sleep quality is assessed through the Pittsburgh Sleep Quality Index (PSQI). This clinical sleep behavioral questionnaire has been validated in patients with different chronic diseases and the general population[10].

The PSQI questionnaire is divided into 10 questions, of which 1-4 are open-ended, and 5-10 are semi-open-ended. The PSQI rating ranges from 0 to 21. Each domain has a set weighting of 0 to 3 points, and the total score is the sum of the seven domain scores. A total PSQI score above 5 indicates poor sleep quality[11].

Objective characteristics of sleep-wake cycles were monitored with a sleep-monitoring bracelet. A professional checks this bracelet daily to ensure the patient wears it correctly and the battery is fully charged. This checking ensures the accuracy and reliability of the bracelet and avoids inaccurate monitoring data due to insufficient power or improper wearing. The bracelet automatically records the following data: total sleep time (minutes slept between bedtime and wake time), sleep efficiency (percentage of time asleep while in bed), and wake after sleep onset (minutes awake between sleep onset and wake time).

Each patient also simultaneously wore a sunshine duration monitoring bracelet, through which daily sunshine duration was counted.

Outcomes

The primary outcome was the absolute change in HbA1c levels within and between the two groups at 12 weeks. The secondary outcomes were changes in BMI, waist circumference, the time in range（TIR） measured by CGM， plasma glucose levels, daily sunshine duration， total sleep time (minutes slept between bedtime and wake time), sleep efficiency (percentage of time asleep while in bed), and wake after sleep onset (minutes awake between sleep onset and wake time).

Time in range (TIR) is the percentage of time that the target blood glucose range is between 3.3mmol/l and 7.8mmol/l.

Statistical analysis

Prism 7.01 software was applied for data processing. Measurement data were described as the mean ± standard deviation. Counting data was represented by frequency and percentage. Two-way ANOVA analyzed multiple group comparisons. Blood glucose levels were measured using CGM throughout the study, and hourly averages were calculated. Differences were considered statistically significant at $P<0.05$.

Result

Baseline characteristics of participants

The flow of participants is illustrated in Figure 1. Initially, 140 individuals were evaluated at baseline, among which 110 fulfilled the inclusion criteria and consented to enroll in the study. These participants were then randomly assigned in a 1:1 ratio to two groups: outdoor and indoor Tai Chi groups. In the outdoor Tai Chi group, two participants refused cooperation, two lost interests, and one became unreachable, leading to their withdrawal from the study. Three participants exhibited poor compliance in the indoor Tai Chi group, and two lost interests, resulting in their dropout. In the end, there were 50 participants in each outdoor and indoor Tai Chi group. These participants were included in the subsequent analysis. As demonstrated in Table 1, all baseline indicators were comparable among the two groups, with no significant differences observed.

Primary Outcomes

When comparing the primary outcomes at 12 weeks, we found a significant difference in the outdoor and indoor Tai Chi groups in HbA1c. The interaction effect was significant ($p = 0.012$). (Table 2)

Secondary Outcomes

Waist circumference decreased significantly in the outdoor Tai Chi group and to a lesser but non-significant extent in the indoor Tai Chi group, with a significant time effect but not a significant group effect. BMI decreased significantly in the outdoor Tai Chi group and also decreased but not significantly in the indoor Tai Chi group, with significant time and group effects. (Table 2)

Fasting and 2-hour plasma glucose decreased significantly in both groups, and the group effect was significant. HOMA-IR decreased significantly in the outdoor Tai Chi group and decreased but not significantly in the indoor Tai Chi group, with a significant time effect and a significant group effect. TIR increased significantly in both groups, with a significant group effect. (Table 2)

The outdoor Tai Chi group showed significant improvement in PSQI, Total sleep time, and Sleep efficiency, and the indoor Tai Chi group showed insignificant changes. Still, the time effect and group effect were significant. (Table 2)

There was a significant increase in sun exposure time in the outdoor Tai Chi group and a nonsignificant change in the indoor Tai Chi group. Both time and group effects were significant. (Table 2)

It is noteworthy that the outdoor exercise group showed a more pronounced decrease in blood glucose during the 7:00-9:00 and 20:00-21:00 time periods, while the indoor and outdoor exercise groups were very close to each other during the 13:00-17:00 time period. (Figure 2)

Subgroup Analysis

Subgroup analyses at 12 weeks showed that in females (mean difference, 1.33 [95%CI, 0.70~2.05), age≤67 years (mean difference, 1.11[95%CI, -0.25~2.14), educational level ≤10 years (mean difference, 1.80 [95% CI, -0.02~2.35), body mass index of 24.00 or less (mean difference, 1.52 [95% CI, -0.41~2.61), and 1 or fewer comorbidities (mean difference, 1.55 [95% CI, -0.31~2.08]) in the subgroups, the outdoor Tai Chi group, compared with the indoor Tai Chi group, had a better effect on improving the HbA1c. (Figure 3)

Discussion

This randomized clinical trial demonstrated that outdoor Tai Chi was more effective in improving waist circumference, BMI, glycosylated hemoglobin, FPG, 2hPG, insulin resistance index, triglycerides, sleep quality, total sleep time, sleep efficiency, and TIR. The time effects were significant across multiple metrics, suggesting that consistent long-term practice of Tai Chi, whether outdoors or indoors, can provide health benefits.

Both groups showed significant decreases in HbA1c, FPG and 2hPG with significant group effects. This indicates that outdoor and indoor Tai Chi can effectively improve blood glucose levels. Notably, the outdoor Tai Chi group showed a more significant decrease in HOMA-IR, whereas the indoor Tai Chi group also showed a decrease but not to a significant level. This suggests that outdoor Tai Chi may be more effective in improving insulin resistance[12]. It has been demonstrated that the combination of the Mediterranean diet and outdoor walking may indeed provide an effective non-pharmacological treatment strategy for elderly diabetic patients, helping to reduce the intensity of their need for medication to treat comorbidities[13]. TIR increased significantly in both groups with a significant group effect, further demonstrating the positive effect of Tai Chi practice on glycemic control[14]. CGM data showed that patients' blood glucose levels became smoother after performing outdoor exercise. Despite the fact that the exercise was scheduled in the morning, this positive effect extended to blood glucose levels in the evening and even at night, showing a significant trend of improvement.Of note, blood glucose was very similar indoors and outdoors from 13:00-17:00, which may be related to the recovery of skeletal muscle tone and mitochondrial function in the afternoon after exercise in the morning, suggesting a circadian rhythm in oxidative metabolism[15].

The outdoor exercise group showed significant improvement in the total Pittsburgh Sleep Quality Index (PSQI) scores compared to the indoor exercise group. These findings are consistent with a meta-analysis reporting that different types of exercise, including single-component and combined exercise, were associated with improvements in PSQI[16]. Participation in regular exercise training has been shown to have beneficial effects on overall sleep quality and sleep efficiency[17]. This result is consistent with our finding that both the indoor and outdoor groups improved objective sleep quality and quantity at baseline levels, including total sleep time and efficiency. Exercise may improve sleep by reducing psychological factors such as stress, anxiety and depression[18]. Exercise has been shown to reduce stress levels and release chemicals such as endorphins that contribute to relaxation and pleasure[19]. Exercise may also indirectly improve sleep quality by improving physical fitness[19].

While exercise has been widely shown to improve sleep quality significantly, its underlying mechanisms are still unclear. One proposed mechanism is physical activity's ability to influence melatonin levels [20]. Melatonin is a key hormone that regulates circadian rhythms and sleep [21]. Research shows that exercise can regulate melatonin levels [22, 23].

Decreased sleep quality may lead to autonomic nervous system disorders, causing increased sympathetic excitability and adrenocorticotropic hormone secretion, affecting blood glucose levels[24].A meta-analysis (meta-analysis) of recent cross-sectional studies explored the relationship between sleep duration and HbA1c in patients with T2DM. According to the results of this meta-analysis, there was a significant association between sleep duration and HbA1c levels. In studies exploring the relationship between patients with T2DM (type 2 diabetes mellitus) and sleep duration, a notable finding was that T2DM patients with habitually short sleep (usually defined as less than 7 hours per night) tended to have higher levels of glycated hemoglobin (HbA1c), compared to patients with normal sleep duration (usually 7-8 hours per night) who demonstrated lower levels of HbA1c. This finding reveals that sleep deprivation may negatively affect glycemic control in diabetic patients [25].

The outdoor exercise group spent significantly more time in the sun each day than the other two. Outdoor exercise is practiced in a warm and sunny environment, and this contact with nature brings a sense of relaxation and pleasure, helping to relieve tension and stress [26]. Outdoor activities also provide exposure to landscapes of different colors (e.g., greens, blues, and browns) and additional sensory stimulation [27] [28]. These sensory stimuli may also positively affect stress reduction [29]. Sunlight during the day promotes melatonin secretion by the brain's pineal gland, which increases alertness and activity [30] [31].

Moderate sunlight exposure is associated with improved insulin sensitivity and may help improve glycemic control in diabetics [32]. In the present study, we found that the outdoor exercise group spent significantly more time under sunlight than the indoor exercise group. Although there was a significant decrease in fasting blood glucose in the outdoor exercise group compared with the indoor exercise group, we have not yet confirmed a substantial correlation between sunlight exposure time and blood glucose.

Subgroup analyses were performed in our study and showed that the outdoor Tai Chi group was superior to the indoor Tai Chi group in terms of HbA1c improvement in female patients and in patients with a BMI of 24.00 or less, who have had T2DM for more than 10 years, and who have fewer or equal to 1 comorbidity. Although aerobic exercise can help manage T2DM, our data suggests that the exercise venue should be considered. Different exercise venues may affect blood glucose and related metabolic responses differently. Findings on T2DM duration, BMI, and comorbidities suggest that interventions may be more effective in the early or mild stages of T2DM[33].

Limitations

First, although the study was designed as a randomized controlled trial with data monitoring by means of wearable devices, it required patients to be proficient in operating electronic devices, and these limitations may impact the accuracy and generalizability of the findings. Second, the study may have focused only on short-term effects, while the long-term effects of outdoor exercise on blood glucose and sleep in patients with T2DM are unknown. Thus, the applicability of the study's findings to long-term effects is limited.

Conclusions

In summary, this study demonstrated that outdoor Tai Chi significantly improves waist circumference, BMI, blood glucose levels, sleep quality and sun exposure. In contrast, indoor Tai Chi was relatively weak but also provided some health benefits. Therefore, outdoor Tai Chi may be a better option for people who wish to improve their health through Tai Chi practice. Future studies could further explore the specific mechanisms by which the outdoor environment affects the effectiveness of Tai Chi practice, and how outdoor Tai Chi could be better integrated into daily life and health management programs.

Declarations

Ethics approval and consent to participate

Research was conducted in accordance with the Declaration of Helsinki. The study protocol was approved by the Ethics Committee of Shanghai Yangpu District Shidong Hospital. All participants signed an informed consent form, and the Institutional Review Boards of all participating institutions approved the study (2024-013-01). The study was registered on the Chinese Clinical Trial Register, number ChiCTR2200057863(19/03/2022).

Human and animal rights

No animals were used for the study. All human procedures were followed in accordance with the Helsinki Declaration of 1975 as revised in 2013.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests

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Data availability

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

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10

Table 1. Baseline demographic characteristics of study participants.

	Outdoor Tai Chi group	Indoor Tai Chi group	
Variables	n (%) or M±SD	n (%) or M±SD	P-value
Age, years	65.2 ± 8.7	66.5 ± 5.1	0.723
Education			
Primary	2 (4.0)	3 (6.0)	0.451
Secondary	33 (66.0)	35 (70.0)	
High school	5 (10.0)	5 (10.0)	
University or above	10 (20.0)	7 (14.0)	
Alcohol drinking behavior[a]			
Yes	2 (4.0)	1 (2.0)	0.886
No	48 (96.0)	49 (98.0)	
Duration of disease (years)	6.5 ± 1.2	7.1 ± 1.0	0.331
Number of comorbidities	2 ± 1	2 ± 1	0.638

[a] Self-reported as drinking 3 or more alcoholic drinks (can/bottle) per typical week.

11

Table 2 Changes of indicators before and after intervention in the two groups

project	Outdoor Tai Chi group		Indoor Tai Chi group		P-value		
	Before the intervention	After 12 weeks of intervention	Before the intervention	After 12 weeks of intervention	Interaction effect	Time effect	Group effect
WC (cm)	105.9 ± 5.6	94.4 ± 8.1*	106.5 ± 8.5	103.8 ± 7.0	0.651	0.033	0.778
BMI (kg/m2)	27.7 ± 3.8	25.4 ± 3.7*	28.0 ± 3.3	27.5 ± 2.6	0.002	0.002	0.021
HbA1C (%)	8.8 ± 1.6	7.1 ± 2.0*	8.9 ± 1.2	7.9 ± 1.5	0.012	0.001	0.022
FPG (mmol/L)	8.6 ± 1.0	6.2 ± 1.6	8.9 ± 1.0	6.7 ± 0.9	0.038	0.003	0.031
2h PG (mmol/L)	10.5 ± 1.2	8.2 ± 0.5	11.5 ± 1.3	8.2 ± 0.7	0.022	<0.001	0.010
HOMA-IR	2.5 ± 1.7	2.0 ± 0.8*	2.6 ± 1.8	2.4 ± 1.5	0.061	0.001	0.035
TC (mmol/L)	5.6 ± 1.2	5.4 ± 1.1	5.7 ± 1.6	5.5 ± 1.4	0.045	0.439	0.478
TG (mmol/L)	1.5 ± 0.8	1.1 ± 0.8*	1.6 ± 0.9	1.5 ± 1.1	0.003	0.112	0.016
HDL-C (mmol/L)	1.4 ± 0.2	1.3 ± 0.7	1.5 ± 0.4	1.3 ± 0.5	0.356	0.002	0.441
LDL-C (mmol/L)	3.4 ± 0.8	3.5 ± 0.4	3.3 ± 1.0	3.2 ± 0.8	0.268	0.399	0.521
PSQI global score	7.5 ± 4.0	6.5 ± 5.1†	7.7 ± 4.6	7.5 ± 3.2	0.002	0.021	0.001
Total sleep time (min)	367.8 ±50.4	399.5 ±44.2*	360.3 ±49.9	365.5 ±50.0	0.331	0.002	0.003
Sleep efficiency (%)	82.1 ± 5.5	91.9 ± 4.7*	81.8 ± 6.0	82.5 ± 5.0	0.324	0.021	0.019
Wake after sleep onset (min)	60.5 ± 22.3	59.1 ± 20.1	62.9 ± 23.9	61.9 ± 22.8	0.273	0.127	0.445
TIR (%)	72.2 ± 10.3	89.9 ± 16.4	69.3 ± 13.6	88.1 ± 12.5	0.021	0.011	0.001
Time under the sun (min)	66.8 ± 10.3	87.0 ± 16.1*	65.2 ± 11.1	68.3 ± 15.8	0.011	0.001	0.034

Values are expressed as mean ± SD

12

WC = waist circumference;BMI = body mass index; ; FPG = fasting plasma glucose; 2hPG = 2-hour plasma glucose; HbA1c = glycosylated hemoglobin; TC = total cholesterol; TG = triglyceride; HDL-C = high-density lipoprotein cholesterol; LDL-C = low-density lipoprotein cholesterol; PSQI = Pittsburgh Sleep Quality Index; TIR = time in range
*Significant differences between groups ($P < 0.05$).
†Significant differences between groups ($P < 0.01$).

13

14

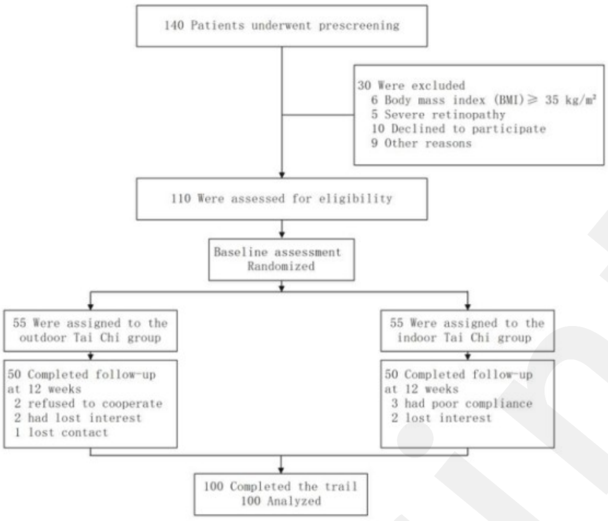

FIG.1. Flow diagram of the study participants

15

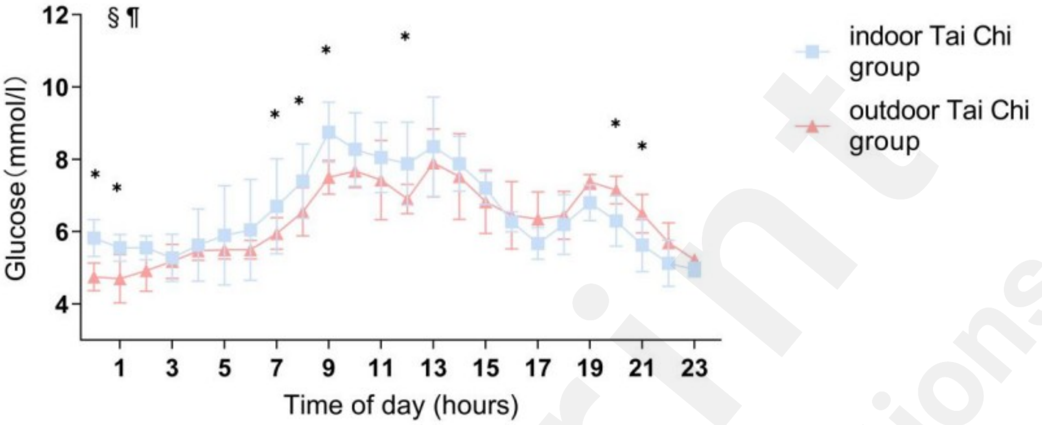

Fig. 2 CGM-based glucose levels in indoor and outdoor Tai Chi groups in the 12th week.
Using two-way ANOVA: § $p < 0.05$ for the effect of time; ¶ $p < 0.05$ for the interaction between exercise and time. Using Tukey's multiple comparison test: $^{*}p < 0.05$ for the difference between indoor and outdoor Tai Chi groups. Values are means + SEM.

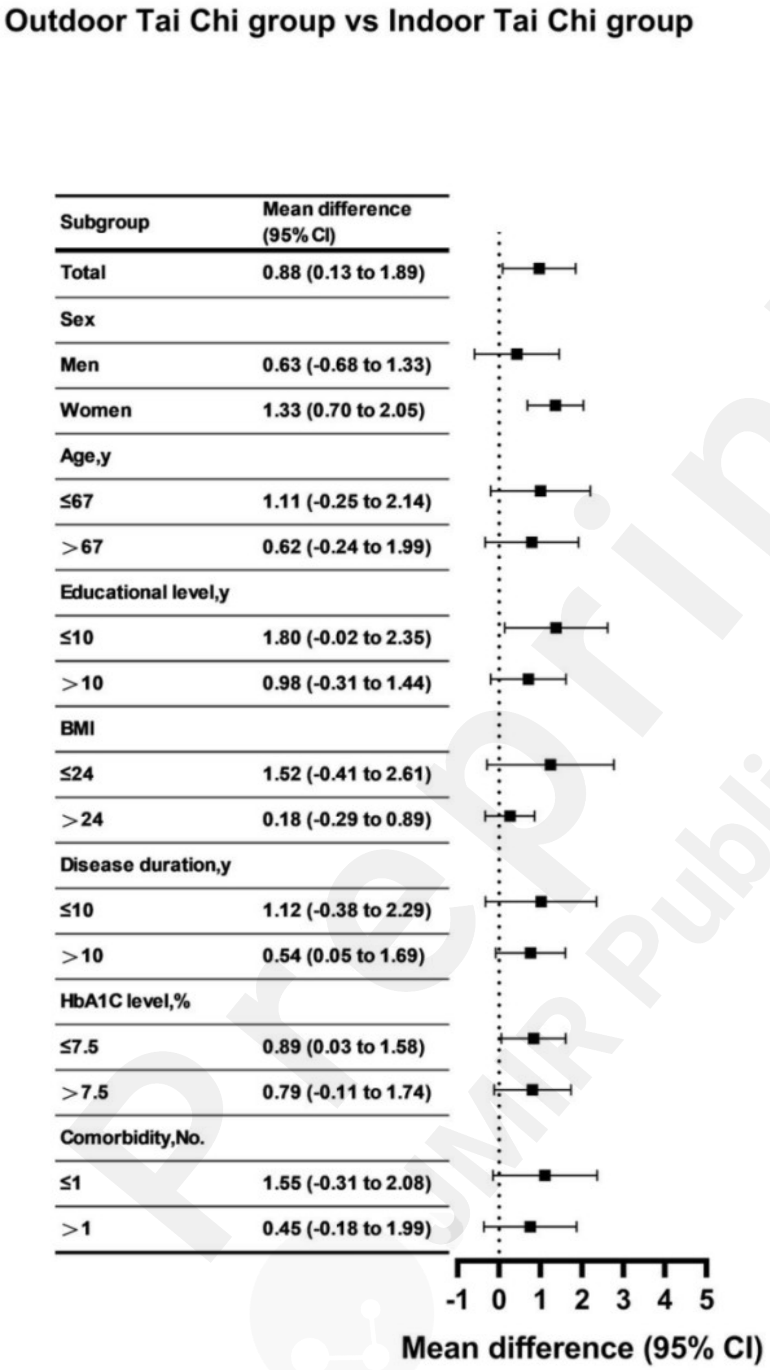

Figure 3. Subgroup Analysis of HbA1c levels at 12 Weeks

BMI = body mass index (calculated as weight in kilograms divided by height in meters squared); HbA1c = glycated hemoglobin (to convert to proportion, multiply by 0.01).