REVIEW ARTICLE

The location of physical activity determines its efficacy on Vitamin D status: Evidence from a meta-analysis

Mahdi Vajdi[1], Sahar Golpour-Hamedani[1], Reyhane Mokhtari Hemami[2], Shirin Hassanizadeh[1], Melika Darzi[3], Gholamreza Askari[4]

[1]Student Research Committee, Department of Clinical Nutrition, School of Nutrition and Food Science, Isfahan University of Medical Sciences, Isfahan, Iran, [2]Department of Community Nutrition, Faculty of Nutrition, Tabriz University of Medical Sciences, Tabriz, Iran, [3]Department of Nutrition, School of Medicine, Urmia University of Medical Sciences, Urmia, Iran, [4]Nutrition and Food Security Research Center, Isfahan University of Medical Sciences, Isfahan, Iran

Background: Numerous epidemiological studies have identified a positive correlation between increased physical activity and raised levels of serum 25-hydroxyvitamin D (25(OH)D). However, it remains uncertain whether this correlation implies a cause-and-effect relationship. The aim of this systematic review and meta-analysis was to analyze the effects of physical activity on serum 25(OH)D concentrations in humans. **Materials and Methods:** Interventional studies examining the effect of physical activity on serum 25(OH) D and published before July 2025 were detected by searching online databases, including PubMed, Embase, Scopus, and Web of Sciences, using a combination of suitable keywords. The heterogeneity among the included trials was evaluated using *I2* statistics. Data were pooled using a random-effects model, and the weighted mean difference (WMD) was considered as the overall effect size. **Results:** Thirty eligible studies were included in the final analysis. Pooling effect sizes from studies demonstrated a significant increase in serum 25(OH)D levels following physical activity (WMD = 4.08 nmol/L; 95% confidence interval [CI]: 2.05, 6.11). Moreover, in subgroup analysis, the outdoor setting of the intervention resulted in a large and statistically significant difference in the serum Vitamin D levels, compared to the control groups (WMD: 17.23 nmol/L, 95% CI: 14.54, 19.92). However, the indoor setting of the physical activity intervention had a negligible effect on the serum Vitamin D levels (WMD: 0.37 nmol/L, 95% CI: −0.38, 1.14), compared to the control groups. **Conclusion:** These results propose that prescribing outdoor physical activity may be an effective clinical strategy for improving Vitamin D levels, primarily mediated through sunlight exposure.

Key words: 1,25(OH)2D3, meta-analysis, physical activity, Vitamin D

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INTRODUCTION

Vitamin D is a vital nutrient that plays a significant role in important body processes such as maintaining strong bones and supporting a healthy immune system. The primary sources of this nutrient are sunlight exposure and various dietary options, including fatty fish, enriched dairy products, and supplements.[1] However, a significant portion of the population, especially those living in areas with limited sunlight or dietary restrictions, may be at risk of Vitamin D deficiency.[2] Research has indicated that Vitamin D insufficiency is linked with several adverse health conditions, including musculoskeletal disorders, autoimmune diseases, cardiovascular disorders, and certain types of cancer.[3] Vitamin D deficiency is a prevalent concern globally, and maintaining sufficient levels of serum 25-hydroxyvitamin D (25(OH)D) is essential for both overall health and disease prevention.[4] The measurement of serum 25(OH)D concentrations is the most common and accurate assessment of Vitamin D

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Address for correspondence: Prof. Gholamreza Askari, Nutrition and Food Security Research Center, Isfahan University of Medical Sciences, Isfahan, Iran.
E-mail: askari@mui.ac.ir

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status in individuals, serving as a clinical research standard to identify and address Vitamin D concentrations.[5]

Engaging in physical activity is crucial for promoting overall health and well-being, and it is widely acknowledged for its numerous advantages, such as enhancing cardiovascular function, managing weight, and improving mental health.[6] Several studies have explored the potential impact of physical activity on serum Vitamin D levels, aiming to elucidate the underlying mechanisms and provide insights into the overall health benefits of exercise. Physical activity has been explored as a potential modifiable factor to improve Vitamin D status.[7] Various studies have evaluated the impacts of different types, frequencies, intensities, and durations of physical activity on serum Vitamin D levels. Several potential mechanisms have been proposed regarding how exercise could influence circulating 25(OH)D concentrations. These mechanisms include increased sun exposure during outdoor physical activities, which can boost the cutaneous synthesis of Vitamin D in the body,[7] the mobilization of Vitamin D from adipose tissue and muscle stores into the bloodstream during physical activity, and enhanced intestinal absorption via insulin sensitivity pathways.[8] Furthermore, physical activity may influence serum Vitamin D levels by promoting weight management. Vitamin D is a fat-soluble vitamin that can accumulate in adipose tissue. Consequently, individuals with higher body fat percentages may have lower bioavailability of Vitamin D, leading to decreased serum levels.[9] The existing literature on the relationship between physical activity and Vitamin D levels has shown heterogeneous findings, with some studies demonstrating significant increases in serum 25(OH)D while others have found no effect. Previous systematic reviews and meta-analyses in this field have reported conflicting results with substantial heterogeneity. Several key studies have provided important insights into this relationship. For instance, Wanner *et al*. demonstrated that outdoor exercisers had significantly higher 25(OH)D3 levels compared to indoor exercisers, highlighting the potential importance of sun exposure during physical activity,[10] while Webb noted that artificial indoor lighting does not provide the wavelengths required for cutaneous Vitamin D synthesis, explaining the negligible effect of indoor physical activity on Vitamin D levels.[11] However, earlier reviews have been constrained by key methodological limitations, including mixing observational studies with intervention trials, failure to distinguish between indoor and outdoor exercise settings, and a focus on specific populations such as athletes, rather than the general population. These constraints have limited the ability to establish clear causal relationships between physical activity and Vitamin D status.

Given the global burden of Vitamin D deficiency and its adverse outcomes, along with the increasing prevalence of sedentary lifestyles in many societies, there is a pressing requirement to identify modifiable factors that can increase Vitamin D levels and thereby potentially mitigate the risk of associated disorders.[12] This study presents the first systematic comparison of indoor versus outdoor physical activity interventions on Vitamin D status, drawing exclusively from controlled trials to strengthen causal inference. By isolating the contribution of sunlight exposure while controlling for physical activity variables, we address longstanding uncertainties regarding their independent and combined effects. Our comprehensive subgroup analyses specifically address the unexplained heterogeneity that has plagued previous reviews and focus on the general population rather than athletic cohorts, offering broader public health applicability. We hypothesized that outdoor physical activity interventions would demonstrate superior increases in serum 25(OH)D levels compared to indoor interventions due to concurrent sunlight exposure, and that the magnitude of Vitamin D improvement would vary significantly based on baseline Vitamin D status and intervention duration. This meta-analysis aimed to systematically review all published trials, investigating the effect of physical activity on serum 25(OH)D levels. The results of this study could assist policy-makers in better managing the associated disorders and preventing further increases in Vitamin D insufficiency among different populations.

MATERIALS AND METHODS

This meta-analysis adhered to the reporting standards set out in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses statement[13] [Supplementary Table 1]. Prior to conducting the review and analysis, the study protocol was registered on the PROSPERO database (CRD42023488967).

Search strategy

A comprehensive search for relevant studies was performed through July 2025 using scholarly research databases, including PubMed, Cochrane, Embase, Scopus, Web of Science, and Google Scholar. The search incorporated key terms include (exercise OR physical fitness OR sport OR physical activities OR physical activity OR sports OR walk OR run OR athlete OR outdoor physical activity OR outside physical activity OR outdoor exercise OR indoor physical activity OR indoor exercise) AND (Vitamin D OR Vit D OR calcitriol OR cholecalciferol OR hydroxycholecalciferols OR dihydroxycholecalciferols OR ergocalciferol). In addition to the database searches, supplemental manual checking of reference lists from pertinent studies was done to help ensure the most complete collection of relevant papers. Two researchers (M.V. and S.G.) independently performed the search process to ensure comprehensive study identification. Any differences in study selection were resolved through group discussion.

Study selection

Following the removal of duplicates, two authors (M.V. and R.MH.) independently screened the remaining articles by title, abstract, and full text. Eligibility was restricted to randomized controlled trials that met the following criteria: (a) the study assessed the impact of physical activity on serum Vitamin D levels; and (b) sufficient statistical information was provided (standard deviation [SD], standard error, or 95% confidence interval [CI]) for each group at baseline and at the end of the study or reported changes in the outcome. Studies were excluded if they (a) lacked an appropriate control group, (b) were not original clinical trials (e.g., animal studies, reviews), and (c) combined physical activity with other active treatment agents. Both authors systematically searched the literature databases independently. Any uncertainty regarding the study's inclusion/exclusion was resolved through discussion between the two authors.

Data extraction

To extract the relevant data, two independent authors (M.V and S.GH) systematically assessed all studies and recorded information, such as publication year, country of the study, study characteristics (such as design, duration, sample size, and participant health details), intervention specifics (including the physical activity type, intensity, and controls), and main outcome measures with a particular focus on the longest follow-up Vitamin D levels when reported at multiple time points. If any essential data were not provided in the article, the corresponding authors were contacted by E-mail for clarification. To ensure accuracy, the authors double-checked the compiled data. Any inconsistencies were resolved through discussion with the corresponding author (G.A.) until reaching a consensus.

Risk of bias assessment

To evaluate the study quality and potential bias, two independent (M.V and M.D) utilized the Cochrane risk of bias tool[14] which assessed the following domains: (a) the adequacy of random sequence generation; (b) the concealment of allocation sequences; (c) the blinding of study participants and investigators; (d) the blinding of outcome assessors; (e) the completeness of outcome data; (f) the evidence of selective reporting; and (g) the presence of any additional risk of bias. Each study received a ranking by the reviewers of "low," "high," or "unclear" about bias per Cochrane guidelines. Reviewers compared their ratings after independent evaluation and resolved any disagreements through discussion to reach consensus assessments for each study.

Statistical analysis

Statistical analyses were performed using STATA version 16.0 (Stata Corporation, College Station, TX, USA). Significance was defined as $P < 0.05$. The effect size was determined by comparing average Vitamin D levels between groups. The pooled weighted mean difference (WMD) and its 95% CI were used to evaluate the impact of physical activity on serum Vitamin D levels. To measure the SD of the mean change, the following formula was applied: $SD^2 = ([SD\ baseline^2 + SD\ final^2] - [2\ R \times SD\ baseline + SD\ final])$. Heterogeneity among studies was assessed using the I^2 statistic and Cochrane's Q test. I^2 over 50% or a Q test P value under 0.1 indicated significant between-study heterogeneity.[15] If significant heterogeneity was present, a random-effects model was used. To investigate potential sources of heterogeneity, subgroup analyses were conducted based on physical activity location, sample size, participant age, intervention duration, study location, gender, baseline Vitamin D status, health status, and adjustment for baseline serum Vitamin D levels. Sensitivity analyses were also performed to evaluate the influence of individual studies on the overall effect size. Small-study effects were estimated using Begg's rank correlation and Egger's regression asymmetry tests.[16],[17] Publication bias was assessed through a visual examination of funnel plots. If publication bias was detected, a trim and fill analysis was conducted to create a new model and effect size that accounted for the bias.

RESULTS

Search results

After searching the databases, a total of 1321 studies were identified, but 295 of them were duplicate studies and were removed. Then, we carefully reviewed the titles and abstracts of 1026 the remaining studies; 972 studies were excluded because they did not meet the inclusion criteria. The full texts of the remaining 54 studies were further reviewed, and 24 studies were excluded [Figure 1]. Finally, 30 eligible studies were included in this meta-analysis.[18-47]

Study characteristics

The detailed characteristics of the 32 studies are shown in Table 1. Data were collected from 32 eligible studies, including 46 arms, comprising a total of 3,526 participants, with 1823 individuals in the intervention and 1703 in the control group. These studies were published from 1999 to 2022 and conducted in Iran,[26,35,36,43] China,[37,40,44,47] Brazil,[21,25] Poland,[28,42] the United States,[20,27] The Netherlands,[18] Australia,[19] Spain,[29] Iraq,[30] Austria,[31] India,[32] Norway,[33] Switzerland,[34] Denmark,[38] Portugal,[39] South Korea,[41] Egypt,[45] and Indonesia.[46] All studies were published from 1999 to 2022. Six studies were performed in men, 14 in both genders, and 12 in females. The mean age of the participants was between 10 and 83 years. The interventions were reported as resistance training and weight-bearing ($n = 12$); aerobic ($n = 9$); moderate or moderate-to-vigorous

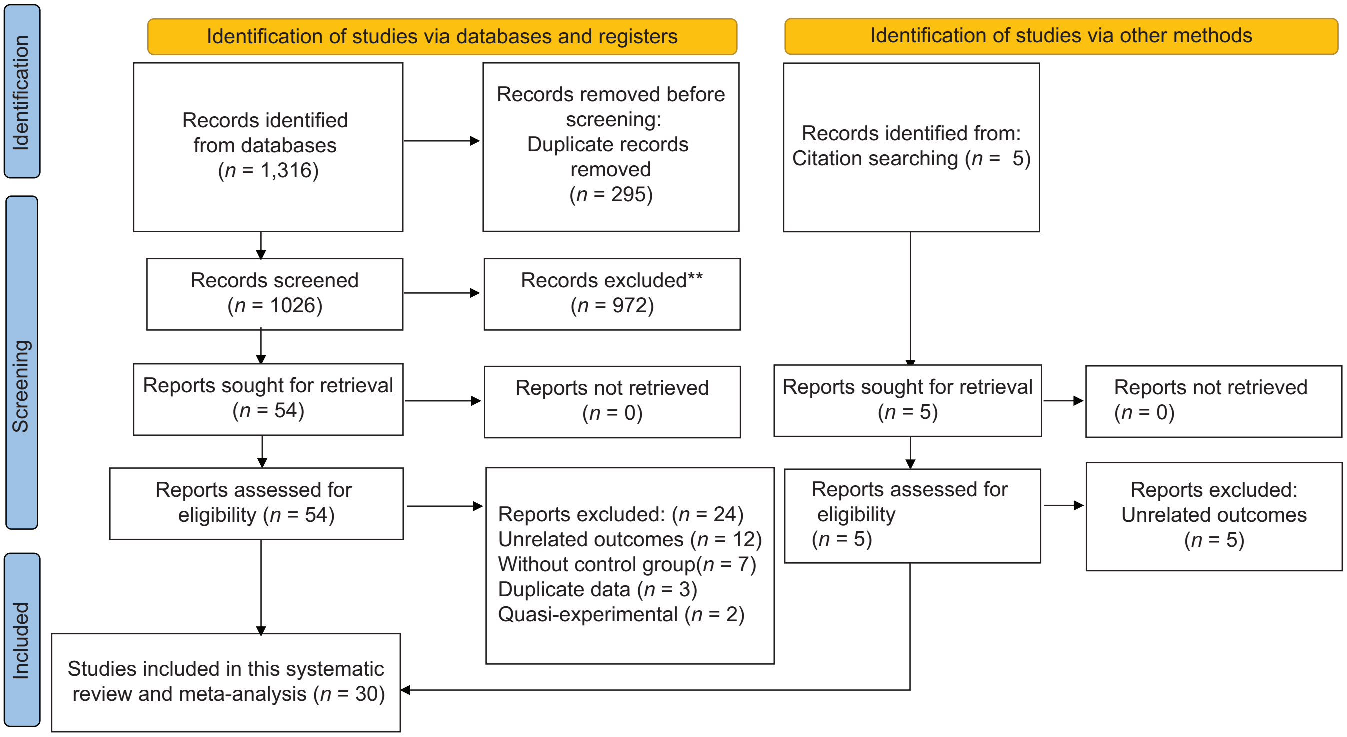

Figure 1: Flowchart of the number of studies identified and selected for the meta-analysis

intensity (*n* = 5); aquatic (*n* = 2); Yijinjing combined with resistance training (*n* = 1); and dynamic flamingo exercise, walking, and Tai Chi (*n* = 1). Human populations included premenopausal women, postmenopausal women, healthy men, athletes, breast cancer survivors, pregnant women, type 2 diabetes, multiple sclerosis, metabolic syndrome (MetS), acute hip fracture patients, obesity, autism spectrum disorder, cystic fibrosis, and hemodialysis patients. The interventions varied in physical activity frequency from daily to weekly and in session duration from 30 to 75 min, and the duration of intervention ranged from 4 weeks to 72 weeks. Three studies explicitly indicated that the sessions of physical activity were conducted indoors.[26,30,42] Furthermore, it can be reasonably deduced from an additional 23 studies that the physical activity took place outdoors. However, for six studies, the location of the intervention could not be determined from the descriptions provided.[27,28,32,35,40,43] Two studies specifically designed the intervention to take place outdoors,[30,42] and one study had separate intervention arms for outdoor and indoor physical activity.[26] The details of the risk of bias assessment are shown in Supplementary Table 2. Among the included studies, three had a high risk of bias,[22,30,39] and 27 studies had some concerns.

The effect of physical activity on Vitamin D levels

Thirty studies with 3526 participants provided data for the meta-analysis of Vitamin D levels. We found that Vitamin D levels were significantly increased in physical activity group compared to the control (WMD = 4.08 nmol/L; 95% CI: 2.05, 6.11; $P < 0.001$) [Figure 2]. The amount of heterogeneity was high ($I^2 = 85.5\%$, $P < 0.001$), which sample size, study location, gender, duration, physical activity location, baseline Vitamin D levels, mean age, health status, and duration of studies were recognized as sources of it.

Subgroup analysis

Results of the subgroup analyses are shown in Supplementary Table 1. Twenty-one were indoors or presumed to be indoors, three of the interventions occurred outdoors, and six were not reported. The indoor setting of the physical activity intervention had a negligible effect on the serum Vitamin D levels of the participants (WMD: 0.37 nmol/L, 95% CI: −0.38, 1.14, $P = 0.327$; $I^{2:}$ 62.3%), compared to the control groups. However, the outdoor setting of the intervention resulted in a large and statistically significant difference in the serum Vitamin D levels, compared to the control groups (WMD: 17.23 nmol/L, 95% CI: 14.54, 19.92, $P < 0.001$; $I^{2:}$ 0%). Studies that were conducted on women revealed a greater increase in Vitamin D levels (WMD: 7.49 nmol/L, 95% CI: 6.17, 8.81, $P < 0.001$; $I^{2:}$ 84.8%) than those performed on both sexes (WMD: 1.22 nmol/L, 95% CI: −0.004, 2.41, $P = 0.051$; $I^{2:}$ 78.4%). Regarding subgroup analysis, increase in Vitamin D levels was significant in participants who had baseline serum Vitamin D 30–50 nmol/L (WMD: 1.65 nmol/L, 95% CI: 0.74, 2.25, $P < 0.001$; $I^{2:}$ 93.8%) and 50–125 nmol/L (WMD: 6.07 nmol/L, 95% CI: 4.44, 7.70, $P < 0.001$; $I^{2:}$ 66%). Moreover, Vitamin D levels significantly increased in studies with duration of 12 weeks or less (WMD: 5.02 nmol/L, 95% CI: 3.93, 6.11, $P < 0.001$; $I^{2:}$ 89.9%), while studies with

Table 1: Characteristics of the included studies

First author, year	Location	Participants		Gender (male/female)	Mean age		Design	Intervention	Comparator	Duration (week)	Main results
		Case	Control		Case	Control					
Sun, 2022	China	14	15	Both	47.9±8.6	50.6±7.0	RCT	Progressive cycling training classes	Placebo	12	No significant difference
Gupta, 2019	India	25	27	Both	12.26±2.83	12.68±3.33	RCT	Home-based resistance and plyometric jumping program plus Vitamin D and calcium supplements	Vitamin D and calcium supplements	48	Significant difference
de Jong, 1999	Netherlands	35	34	Both	76.5±4.5	78.7±6.8	RCT	Moderate intensity exercise	No intervention	17	No significant difference
Irandoust, 2017	Iran	15	15	Women	43.2±12.4	43.2±12.4	RCT	Outdoor jogging and stretching	No intervention	12	Significant difference
Kukuljan, 2011	Australia	46	44	Men	60.7±7.1	59.9±7.4	RCT	Stationary cycling, resistance training, weight-bearing exercises	No intervention	72	No significant difference
Mason, 2011	United States	117	87	Women	58.1±5.0	57.4±4.4	RCT	Moderate to vigorous intensity aerobic exercise	No intervention	48	No significant difference
Moreira, 2013	Brazil	64	44	Women	58.6±6.71	59.3±6.07	RCT	Aquatic exercise sessions and Vitamin D supplements	Vitamin D supplements	24	No significant difference
Kim H, 2016	Japan	35	34	Women	81.4±4.3	81.1±5.1	RCT	Stationary cycling, resistance training, weight bearing exercises	Health education classes	12	Significant difference
Kim SH, 2016	South Korea	23	20	Women	55.7±5.3	56.3±6.7	RCT	Home based weight bearing and resistance exercises and calcium and Vitamin D supplements	Calcium and Vitamin D supplements	24	No significant difference
Marinho, 2016	France	6	7	Both	72.18	73.5	RCT	Resistance exercise training program	No intervention	8	No significant difference
Freitas, 2017	Brazil	26	25	Both	45.9±7.7	48.5±9.6	RCT	Aerobic and resistance training, plus nutrition counseling	Sham plus nutrition counseling	12	Significant difference
Hossain, 2018	United States	7	7	Both	NR	NR	RCT	Brisk walking	No intervention	12	No significant difference
Prusik, 2018	Poland	35	48	Women	68.4±5.0	68.4±5.0	RCT	Nordic walking and Vitamin D supplementation	Vitamin D supplement	12	Significant difference
Vlachopoulo, 2018	Spain	19	18	Male	14.5±0.9	14.7±1.1	RCT	Swimming/football/Cycling	No intervention	36	-
Farag, 2019	Iraq	21	24	Both	40.42±5.89	40.54±5.94	RCT	Endurance training plus Vitamin D supplementation	Vitamin D supplementation	12	Significant difference
Franzke, 2019	Austria	34	32	Both	83.1±6.1	83.1±6.1	RCT	Resistance training	Cognitive training	24	No significant difference
Gustafsson, 2019	Norway	381	343	Women	30.5±4.4	30.4±4.3	RCT	Moderate-intensity exercise program	No intervention	12	No significant difference
Stemmle, 2019	Switzerland	43	44	Both	83.2±7.4	85.5±6.0	RCT	Simple home exercise program and Vitamin D supplementation 800 IU	Vitamin D supplementation 800 IU	48	No significant difference
Ansari-Kolachahi, 2020	Iran	10	10	Men	9.8±2.0	9.8±2.0	RCT	Aquatic exercise	No intervention	10	No significant difference
Malandish, 2020	Iran	13	13	Women	53.36±3.98	53.00±3.26	RCT	Moderate intensity aerobic exercise on a treadmill	No intervention	12	Significant difference
Sun, 2020	China	9	9	Men	24.2±3.1	26.7±6.2	RCT	Progressive resistance training from light to heavy	No intervention	12	No significant difference
Tanvig, 2020	Denmark	143	151	Women	29.25±3.70	28.75±3.70	RCT	Encouraged to be moderately active and given pedometer	No intervention	15	Significant difference

Contd...

Table 1: Contd...

First author, year	Location	Participants		Gender (male/female)	Mean age		Design	Intervention	Comparator	Duration (week)	Main results
		Case	Control		Case	Control					
Diniz-Sousa, 2021	Portugal	41	20	Both	41.6±10.5	46.5±8.5	RCT	Multicomponent exercise training program along with usual medical care	Usual medical care after BS	44	No significant difference
Feng, 2021	China	97	98	Both	70.2±5.8	70.7±6.8	RCT	Dynamic Flamingo exercise, tai chi, walking, and nonactive Vitamin D supplementation	Nonactive Vitamin D supplementation	48	No significant difference
Kim, S-W, 2021	South Korea	14	17	Women	40.3±4.23	40.4±3.31	RCT	High impact weight-bearing exercise	Maintain regular lifestyle	16	-
Podsiadło, 2021	Poland	20	17	Women	68.77±5.42	67.38±4.21	RCT	Nordic walking training	No intervention	12	Significant difference
Bahmani, 2022	Iran	10	9	Women	27.70±2.68	25.44±2.29	RCT	Aerobic training plus Vitamin D supplement	Vitamin D supplement	8	No significant difference
Huang, 2022	China	26	21	Both	62.0±5.0	63.5±4.7	RCT	Yijinjing combined with elastic band exercise	Maintain original living without any exercise intervention	24	No significant difference
Lasheen, 2022	Egypt	15	15	Both	29.4±6.37	30.06±4.77	RCT	Conventional medical treatment, Vitamin D supplementation and aerobic, stretching and strengthening exercises	Conventional medical treatment, Vitamin D supplementation	6	Significant difference
Mudjanarko, 2022	Indonesia	10	10	Men	51±4.84	47±4.84	RCT	Moderate intensity aerobic exercise	Maintained lifestyle	4	No significant difference

RCT: Randomized controlled trials, NR: Not reported

duration of more than 12 weeks showed a slight (but not significant) decrease in Vitamin D levels. Subgroup analysis based on the age of participants indicated that physical activity significantly increased Vitamin D levels only in participants with 18–65 years (WMD: 5.00 nmol/L, 95% CI: 3.93, 6.06, $P < 0.001$; $I^{2:}$ 89.2%). A subgroup analysis further revealed that physical activity was associated with a significant increase in serum Vitamin D levels among the studies conducted in Asian countries (WMD: 2.96 nmol/L, 95% CI: 2.08, 3.85, $P < 0.001$; $I^{2:}$ 91.3%). Finally, the studies that adjusted for the baseline serum Vitamin D levels showed a larger increase in Vitamin D levels 5.08 (2.69, 7.47) (WMD: 5.08 nmol/L, 95% CI: 2.69, 7.47, $P < 0.001$; $I^{2:}$ 74.7%) than the studies that did not control for the baseline serum Vitamin D levels [Supplementary Table 3].

Sensitivity analysis

To assess the effect of each study on the overall effect size, we removed every study one by one from the analysis. We did not notice any significant effect for any individual study on the pooled effect sizes of meta-analysis results [Supplementary Figure 1].

Publication bias

Funnel plot and Begg's linear regression test ($P = 0.146$) showed no publication bias for meta-analysis of physical activity and its effects on Vitamin D levels. However, there was a significant publication bias in the Egger test for Vitamin D ($P = 0.032$). The trim-and-fill analysis did not impute any additional studies, and the pooled effect size remained unchanged, indicating that the observed publication bias did not substantially affect the overall results [Figure 3].

DISCUSSION

The effect of physical activity on Vitamin D levels was examined for the first time in this systematic review and meta-analysis of interventional studies. Physical activity was shown to increase Vitamin D levels in a pooled analysis. Based on the sensitivity analysis, no individual study has a significant impact on the pooled effect sizes in meta-analyses. Subgroup analysis revealed that studies involving outdoor physical activity, focusing on women, conducted in Asia, lasting less than 12 weeks, including participants aged 18–65 years, with a baseline Vitamin D level of 30–125 nmol/L, and a sample size smaller than 50 were more effective in increasing Vitamin D levels. These findings are in line with several studies. These variations across subgroups contributed to the considerable heterogeneity observed ($I^2 = 84.8\%$), reflecting differences in intervention duration, participant characteristics, and baseline Vitamin D levels. Although subgroup analyses helped identify potential sources of variability, high

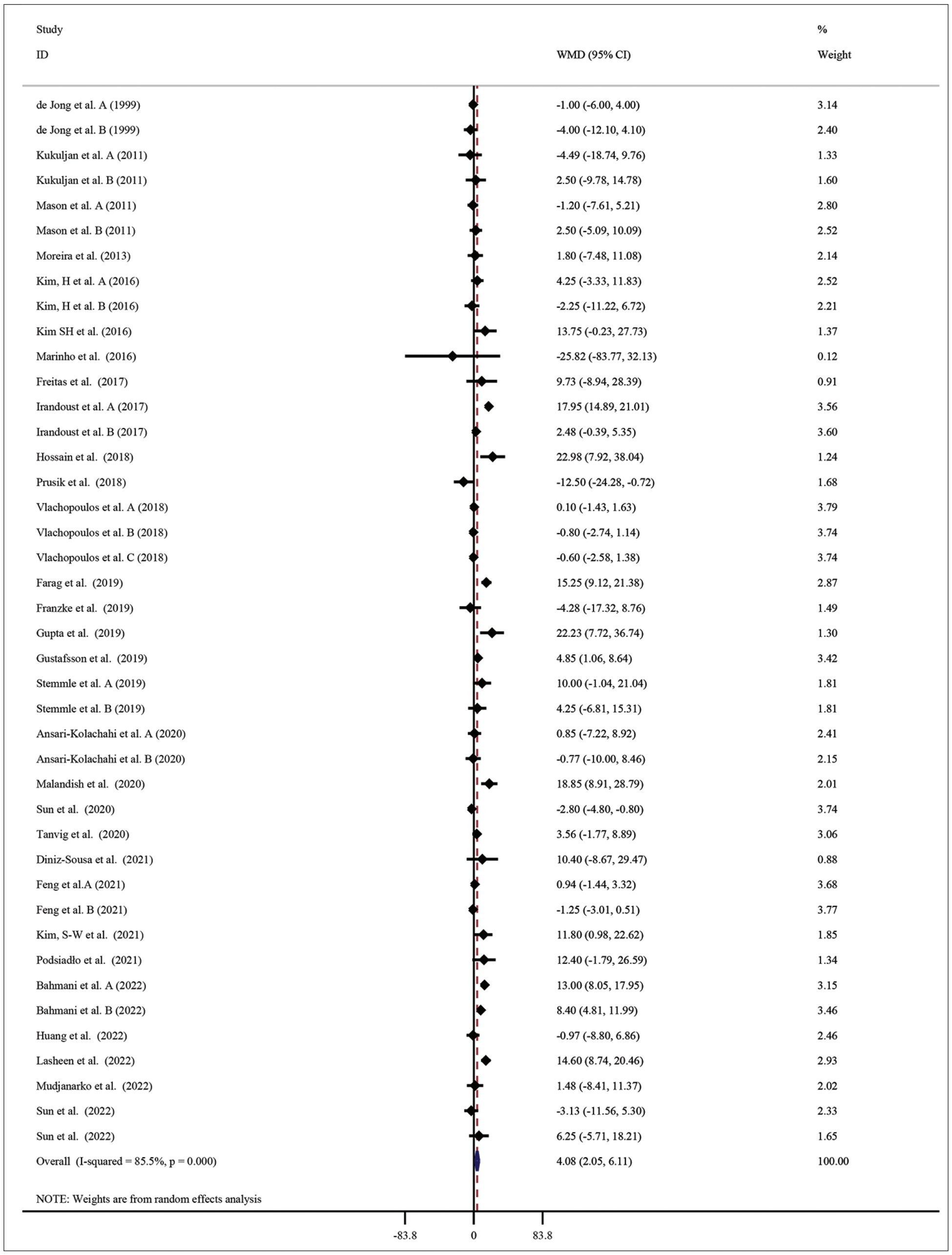

Figure 2: Forest plot illustrating weighted mean difference and 95% confidence intervals for the impact of physical activity on circulating Vitamin D levels. This plot presents pooled estimates from studies assessing the impact of various physical activity interventions on serum 25-hydroxyvitamin D concentrations. WMD = Weighted mean difference; CI = Confidence interval

heterogeneity persisted in some subgroups. This highlights the need for standardized protocols in future research and suggests that contextual factors may play a critical role in moderating the impact of physical activity on Vitamin D status.

A study conducted by Wanner *et al*. found significantly higher 25(OH)D3 levels in outdoor exercisers than in indoor exercisers.[10] There is evidence that exercising outdoors may be more effective than exercising indoors due to both the physical benefits of exercise and the benefits of sun exposure.[48] As previously confirmed, Vitamin D is synthesized primarily from sunlight on the skin, where it is activated to perform its primary function.[49] However, in order to increase plasma Vitamin D levels by exposure to the sun, many factors must be considered, such as melanin content, type of clothing, sunscreen use, latitude, time of day, and age of the individual.[50] Therefore, it is important to recognize that the increase in 25(OH)D levels may also be influenced by environmental factors independent of physical activity. The negligible effect of indoor physical activity on Vitamin D levels can be attributed to the lack of sufficient ultraviolet B (UVB) exposure in indoor settings. Artificial indoor lighting does not provide the

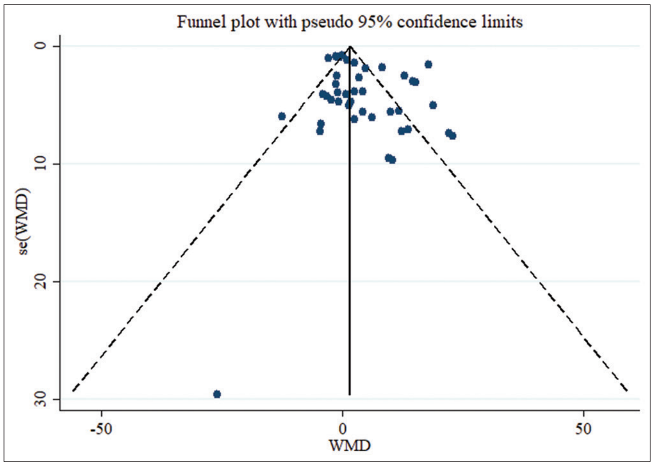

Figure 3: Funnel plot (with pseudo 95% confidence intervals) of the weighted mean difference (WMD) versus the standard error (WMD) for studies evaluating the association between physical activities on circulating Vitamin D levels. WMD = Weighted mean difference

wavelengths required for cutaneous Vitamin D synthesis, limiting the potential for endogenous production.[11] This highlights a key methodological challenge in disentangling the independent effects of physical activity from those of sun exposure. Future studies should consider controlling for UVB exposure using objective tools such as personal dosimeters or matching participants based on outdoor time, in order to better isolate the true impact of physical activity on Vitamin D status.

Physical activity may have a positive effect on Vitamin D levels in participants with overweight, obesity, and MetS since these individuals often suffer from hypovitaminosis D[9] and altered Vitamin D metabolism.[51] It is also possible that obese individuals experience insufficient UVB exposure, which may contribute to their low levels of Vitamin D.[51] Wortsman *et al*. found that obese individuals had a 57% lower increase in 25(OH)D concentration after sun exposure than normal-weight individuals, even though the amount of Vitamin D precursor in the skin was similar to normal-weight individuals.[9] As a result, obese individuals have been shown to have 71% reductions in 25-hydroxylase gene expression in subcutaneous adipose tissue.[9] Furthermore, obese individuals are less likely to expose larger areas of their body to sunlight than normal-weight individuals.[52] Thus, physical activity, especially outdoors, is a way to get sun exposure and increase the synthesis of Vitamin D. Physical activity can decrease body weight while increasing lipolysis. Hence, Vitamin D levels may increase due to increased mobilization of Vitamin D from adipose tissue. It has been shown in previous research that women have higher rates of induced systemic lipolysis than men.[53] Therefore, women may benefit more from physical activity than men. Another important determinant of 25(OH)D was age; older adults may have lower levels of Vitamin D due to reduced cutaneous synthesis and lower dietary intake.[54] For this reason, our results may not be significant in individuals over 65 years old. Since there are few studies on individuals under the age of 18 years, the results should be interpreted cautiously in this age group. Furthermore, Vitamin D levels differ across continents due to different factors such as air pollution,[55] and different levels of Vitamin D deficiency, especially among Asians.[56] However, more studies need to be conducted in America and Australia. The results of subgroups based on baseline Vitamin D levels should also be interpreted cautiously because of the small number of studies with baseline levels <30 nmol/L and more than 125 nmol/L. Other possible explanations for the role of physical activity in increasing Vitamin D levels are that it is associated with an increase in anti-inflammatory markers and a reduction in pro-inflammatory markers such as interleukin-6 and tumor necrosis factor-alpha.[45] It has also been found that physical activity improves Vitamin D status by increasing Vitamin D receptors in muscles, pancreas, and adipose tissue.[8] Finally, from a public health perspective, these findings highlight the value of promoting outdoor physical activity as a dual-benefit intervention to enhance both physical fitness and Vitamin D status. Given the well-established association between low Vitamin D levels and increased risk of various chronic diseases,[57] encouraging regular outdoor activity could serve as a feasible and cost-effective strategy to reduce the burden of these conditions. Health authorities and policymakers should consider integrating outdoor physical activity recommendations into national health guidelines, especially in regions with a high prevalence of Vitamin D deficiency. Nevertheless, further research involving diverse populations, larger cohorts, extended intervention durations, and varied baseline Vitamin D statuses is needed to refine these recommendations and ensure their broad applicability.

Strengths and limitations

Several strengths of this meta-analysis are: first, subgroup analyses were conducted using a variety of confounders, and second, a thorough sensitivity analysis was conducted to ensure stable results. However, there are some limitations to be considered. The sample size of most studies was small. Measurement error may have reduced the ability of studies to detect the effect of physical activity intervention due to variability in the laboratory assays used to determine 25(OH)D concentrations. Some studies did not describe whether the physical activity intervention occurred indoors or outdoors; we were able to infer the location from the intervention description in some cases. There was no blinding of participants to the intervention or control groups, and it is possible that the physical activity intervention might have caused other changes that affected 25(OH)D concentrations. Furthermore, there was heterogeneity among the included studies. However, subgroup analysis was conducted based on multiple variables to identify heterogeneity sources.

CONCLUSION

Vitamin D levels significantly increase after physical activity, particularly when performed outdoors, due to enhanced exposure to sunlight and UVB radiation. However, indoor physical activity alone does not appear to exert a comparable effect. Given the close relationship between meta-analyses and evidence-based management practices, future clinical trials should examine different types of physical activity over longer durations and in larger populations to better understand the therapeutic effects of exercise on Vitamin D status. Furthermore, future research should explore the mechanisms underlying the limited efficacy of indoor activity and investigate whether UVB-simulating technologies or combined nutritional strategies can enhance outcomes.

Ethical consideration

The study protocol was approved and registered by the ethics committee of Isfahan University of Medical Sciences (IR.MUI.PHANUT.REC.1403.036). The protocol of the current study has been registered in the PROSPERO system (registration number: CRD42023488967).

Data availability

Data will be made available on request.

Authors’ contribution statement

All authors have reviewed and approved the final manuscript. MV and GA were the primary researchers responsible for formulating the hypothesis and overseeing the project. SGH, MD, RMH, and SH conducted the literature search and data screening. Data extraction and quality assessment were performed independently by MV, SGH, and MD. MV, RMH, and SGH analyzed and interpreted the data and wrote the manuscript.

Acknowledgments

The study protocol was approved by the ethics committee of Isfahan University of Medical Sciences (IR.MUI.PHANUT.REC.1403.036). We would like to express our sincere gratitude to the Student Research Committee of Isfahan University of Medical Sciences for their invaluable support.

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Conflicts of interest

There are no conflicts of interest.

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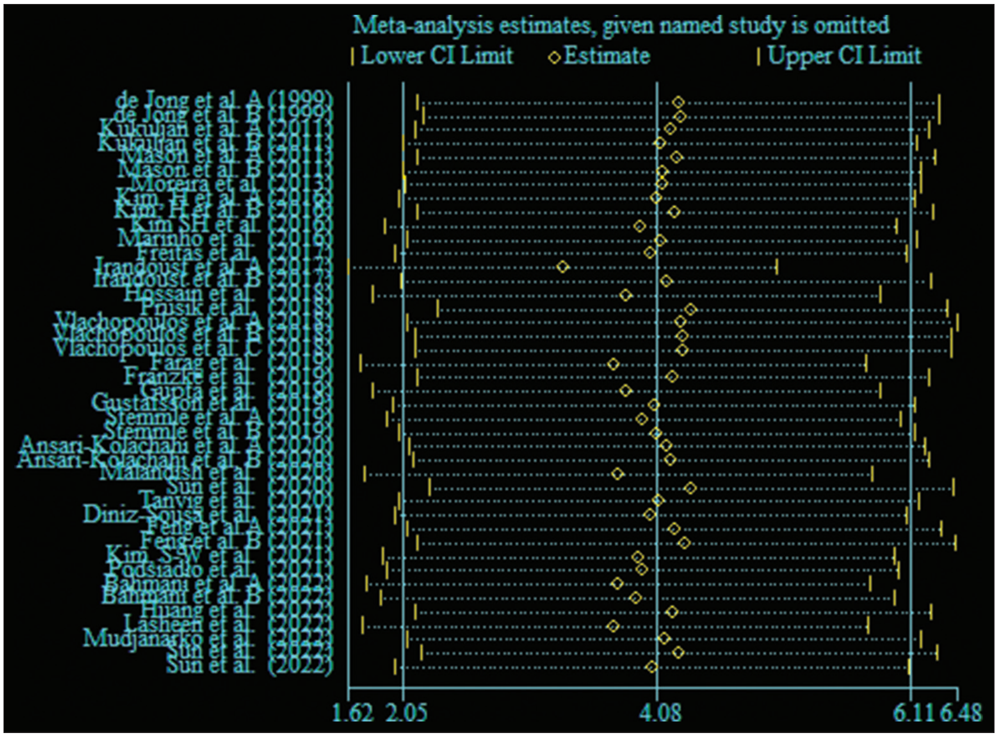

Supplementary Figure 1: Sensitivity analysis of physical activity on Vitamin D levels. CI = Confidence interval

Supplementary Table 1: Preferred Reporting Items for Systematic Reviews and Meta-Analyses checklist

Section/topic	Number	Checklist item	Reported on page number
		Title	
Title	1	Identify the report as a systematic review, meta-analysis, or both	Page 1
		Abstract	
Structured summary	2	Provide a structured summary including, as applicable: background; objectives; data sources; study eligibility criteria, participants, and interventions; study appraisal and synthesis methods; results; limitations; conclusions and implications of key findings; systematic review registration number	Page 1
		Introduction	
Rationale	3	Describe the rationale for the review in the context of what is already known	Page 1
Objectives	4	Provide an explicit statement of questions being addressed with reference to PICOS	Page 2
		Methods	
Protocol and registration	5	Indicate if a review protocol exists, if and where it can be accessed (e.g., Web address), and, if available, provide registration information including registration number	Page 2
Eligibility criteria	6	Specify study characteristics (e.g., PICOS, length of follow-up) and report characteristics (e.g., years considered, language, publication status) used as criteria for eligibility, giving rationale	Page 3
Information sources	7	Describe all information sources (e.g., databases with dates of coverage, contact with study authors to identify additional studies) in the search and date last searched	Page 2
Search	8	Present full electronic search strategy for at least one database, including any limits used, such that it could be repeated	Page 2
Study selection	9	State the process for selecting studies (i.e., screening, eligibility, included in systematic review, and, if applicable, included in the meta-analysis)	Page 2
Data collection process	10	Describe method of data extraction from reports (e.g., piloted forms, independently, in duplicate) and any processes for obtaining and confirming data from investigators	Page 3
Data items	11	List and define all variables for which data were sought (e.g., PICOS, funding sources) and any assumptions and simplifications made	Page 3
Risk of bias in individual studies	12	Describe methods used for assessing risk of bias of individual studies (including specification of whether this was done at the study or outcome level), and how this information is to be used in any data synthesis	Page 3
Summary measures	13	State the principal summary measures (e.g., risk ratio, difference in means)	Page 3
Synthesis of results	14	Describe the methods of handling data and combining results of studies, if done, including measures of consistency (e.g., I^2) for each meta-analysis	Page 3
Risk of bias across studies	15	Specify any assessment of risk of bias that may affect the cumulative evidence (e.g., publication bias, selective reporting within studies)	Page 3
Additional analyses	16	Describe methods of additional analyses (e.g., sensitivity or subgroup analyses, meta-regression), if done, indicating which were pre-specified	Page 3
		Results	
Study selection	17	Give numbers of studies screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally with a flow diagram	Page 3
Study characteristics	18	For each study, present characteristics for which data were extracted (e.g., study size, PICOS, follow-up period) and provide the citations	Page 4 and Table 1
Risk of bias within studies	19	Present data on risk of bias of each study and, if available, any outcome level assessment (see item 12)	Supplementary Table 2
Results of individual studies	20	For all outcomes considered (benefits or harms), present, for each study: (a) simple summary data for each intervention group (b) effect estimates and confidence intervals, ideally with a forest plot	Page 4
Synthesis of results	21	Present results of each meta-analysis done, including confidence intervals and measures of consistency	Figure 2
Risk of bias across studies	22	Present results of any assessment of risk of bias across studies (see Item 15)	Supplementary Table 2
Additional analysis	23	Give results of additional analyses, if done (e.g., sensitivity or subgroup analyses, meta-regression [see Item 16])	Page 4
		Discussion	
Summary of evidence	24	Summarize the main findings including the strength of evidence for each main outcome; consider their relevance to key groups (e.g., healthcare providers, users, and policy makers)	Page 6
Limitations	25	Discuss limitations at study and outcome level (e.g., risk of bias), and at review-level (e.g., incomplete retrieval of identified research, reporting bias)	Page 8
Conclusions	26	Provide a general interpretation of the results in the context of other evidence, and implications for future research	Page 9
		Funding	
Funding	27	Describe sources of funding for the systematic review and other support (e.g., supply of data); role of funders for the systematic review	Page 9

Supplementary Table 2: Quality assessment of studies (according to the Cochrane risk-of-bias tool for randomized trials) investigating the associations between physical activity on Vitamin D levels

Study	Allocation concealment	Random sequence generation	Blinding of participant and personnel	Blinding of outcome assessment	Incomplete outcome data	Selective reporting	Other sources of bias	Overall risk of bias
Kim H, 2016	L	H	H	L	L	U	L	Low
Farag, 2019	L	U	H	U	H	U	L	Low
Diniz-Sousa, 2021	L	U	H	U	H	U	L	Low
de Jong, 1999	L	U	H	U	L	U	L	Some concerns
Marinho, 2016	L	U	H	U	L	U	L	Some concerns
Kukuljan, 2011	L	U	H	U	L	U	L	Some concerns
Mason, 2011	L	U	H	L	L	U	L	Some concerns
Moreira, 2013	L	U	H	L	L	U	L	Some concerns
Kim SH, 2016	L	L	H	U	U	U	L	Some concerns
Vlachopoulo, 2018	L	U	H	U	L	U	L	Some concerns
Freitas, 2017	L	L	H	L	L	U	L	Some concerns
Irandoust, 2017	L	L	H	U	L	U	L	Some concerns
Hossain, 2018	L	L	H	U	L	U	L	Some concerns
Prusik, 2018	L	U	H	U	L	U	L	Some concerns
Franzke, 2019	L	U	H	L	U	U	L	Some concerns
Gupta, 2019	L	L	H	L	L	U	L	Some concerns
Gustafsson, 2019	L	L	H	H	U	U	L	Some concerns
Stemmle, 2019	L	U	H	L	L	U	L	Some concerns
Ansari-Kolachahi, 2020	L	U	H	U	L	U	L	Some concerns
Malandish, 2020	U	U	H	U	L	U	L	Some concerns
Sun, 2020	L	U	H	U	L	U	L	Some concerns
Tanvig, 2020	L	L	H	H	L	U	L	Some concerns
Feng, 2021	L	U	H	U	L	U	L	Some concerns
Kim, S-W, 2021	L	U	H	U	L	U	L	Some concerns
Podsiadło, 2021	L	U	H	U	L	U	L	Some concerns
Bahmani, 2022	L	U	H	L	L	U	L	Some concerns
Huang, 2022	L	L	H	U	L	U	L	Some concerns
Lasheen, 2022	L	U	H	L	L	U	L	Some concerns
Mudjanarko, 2022	L	U	H	U	L	U	L	Some concerns
Sun, 2022	L	L	H	L	L	U	L	Some concerns

H=High risk of bias; L=Low risk of bias; U=Unclear risk of bias

Supplementary Table 3: Results of subgroup analyses for the effects of physical activity on vitamin D levels according to intervention or participant characteristics

Study group	Number of effect sizes	WMD (95%CI)	*P*-effect	*P*-heterogeneity	I^2 (%)	*P* for between subgroup heterogeneity
Sample size						
<50	22	2.18 (1.41 to 2.94)	<0.001	<0.001	91.4	0.013
≥50	20	0.45 (−0.66 to 1.58)	0.424	0.022	43.0	
Continent						
Asia	21	2.96 (2.08 to 3.85)	<0.001	<0.001	91.3	0.001
Europe	14	0.10 (−0.82 to 1.04)	0.823	0.038	44.3	
America	3	2.50 (−2.15 to 7.16)	0.292	0.015	76.2	
Australia	2	−0.48 (−9.78 to 8.82)	0.920	0.466	0.0	
South America	2	3.37 (−4.93 to 11.67)	0.427	0.456	0.0	
Gender						
Male	9	−0.80 (−1.70 to 0.08)	0.077	0.636	0.0	<0.001
Female	16	7.49 (6.17 to 8.81)	<0.001	<0.001	84.8	
Both	17	1.20 (−0.004 to 2.41)	0.051	<0.001	78.4	
Duration (week)						
≤12	21	5.02 (3.93 to 6.11)	<0.001	<0.001	89.9	<0.001
>12	21	−0.07 (−0.85 to 0.70)	0.849	0.067	33.8	
Physical activity location						
Indoor	30	0.37 (−0.38 to 1.14)	0.334	<0.001	62.3	<0.001
Outdoor	3	17.23 (14.54 to 19.92)	<0.001	0.589	0.0	
NR	9	1.61 (0.38 to 2.84)	0.010	<0.001	87.8	
Age (year)						
<17	6	−0.21 (−1.22 to 0.79)	0.673	0.077	49.7	<0.001
18–65	21	5.00 (3.93 to 6.06)	<0.001	<0.001	89.2	
66–79	9	−0.54 (−1.85 to 0.76)	0.413	0.064	45.7	
>80	5	2.64 (−1.73 to 7.02)	0.237	0.382	4.4	
NR	1	22.98 (7.92 to 38.03)	0.003	-	-	
Baseline Vitamin D						
<30	8	−0.28 (−1.38 to 0.82)	0.619	<0.001	87.6	<0.001
30–50	9	1.65 (0.74 to 2.55)	<0.001	<0.001	93.8	
50–125	18	6.07 (4.44 to 7.70)	<0.001	<0.001	66.0	
>125	1	−25.82 (−83.76 to 32.12)	0.383	-	-	
NR	6	0.30 (−3.01 to 3.62)	0.856	0.318	15.0	
Participants						
Healthy	5	−0.78 (−2.50 to 0.93)	0.371	0.001	77.9	<0.001
Diabetes	4	−0.01 (−4.60 to 4.56)	0.993	0.632	0.0	
Overweight and obesity	7	8.74 (6.98 to 10.50)	<0.001	<0.001	91.2	
Adolescents and children	7	−0.11 (−1.12 to 0.89)	0.825	0.004	68.4	
Postmenopausal	4	3.55 (−0.41 to 7.52)	0.079	0.010	73.7	
Hip fracture	2	7.13 (−0.68 to 14.94)	0.074	0.471	0.0	
MS	3	10.90 (8.29 to 13.50)	<0.001	0.130	51.0	
Others	3	11.17 (0.11 to 22.24)	0.048	0.427	0.0	
Elderly	7	−0.68 (−2.00 to 0.63)	0.309	0.114	41.5	
Adjustment for baseline serum Vitamin D						
Yes	8	5.08 (2.69 to 7.47)	<0.001	<0.001	74.7	0.003
No	34	1.37 (0.72 to 2.03)	<0.001	<0.001	86.6	

CI=Confidence interval; NR=Not reported; MS=Multiple sclerosis; WMD=Weighted mean differences