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Evening regular activity breaks extend subsequent free-living sleep time in healthy adults: a randomised crossover trial

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ABSTRACT

Objective To determine if performing regular 3-min bouts of resistance exercise spread over 4 hours in an evening will impact subsequent sleep quantity and quality, sedentary time and physical activity compared with prolonged uninterrupted sitting.

Methods In this randomised crossover trial, participants each completed two 4-hour interventions commencing at approximately 17:00 hours: (1) prolonged sitting and (2) sitting interrupted with 3 min of bodyweight resistance exercise activity breaks every 30 min. On completion, participants returned to a free-living setting. This paper reports secondary outcomes relating to sleep quality and quantity, physical activity and sedentary time which were assessed using wrist-worn ActiGraph GT3+ accelerometers paired with a sleep and wear time diary.

Results A total of 28 participants (women, n=20), age 25.6±5.6 years, body mass index 29.5±6.7 kg/m^2 (mean±SD) provided data for this analysis. Compared with prolonged sitting, regular activity breaks increased mean sleep period time and time spent asleep by 29.3 min (95% CI: 1.3 to 57.2, p=0.040) and 27.7 min (95% CI: 2.3 to 52.4, p=0.033), respectively, on the night of the intervention. There was no significant effect on mean sleep efficiency (mean: 0.2%, 95% CI: −2.0 to 2.4, p=0.857), wake after sleep onset (1.0 min, 95% CI: −9.6 to 11.7, p=0.849) and number of awakenings (0.8, 95% CI: −1.8 to 3.3, p=0.550). Subsequent 24-hour and 48-hour physical activity patterns were not significantly different.

Conclusions Performing bodyweight resistance exercise activity breaks in the evening has the potential to improve sleep period and total sleep time and does not disrupt other aspects of sleep quality or subsequent 24-hour physical activity. Future research should explore the longer-term impact of evening activity breaks on sleep.

Trial registration number Australian New Zealand Clinical Trials Registry (ACTRN12621000250831).

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Evidence indicates that evening exercise sessions have no disruptive effects and, in some cases, positive impacts on elements of sleep quality, however, current recommendations discourage exercise prior to bedtime. The regular activity breaks protocol has been shown to improve postprandial metabolism, however, the impact on subsequent sleep is unknown.

WHAT THIS STUDY ADDS

⇒ Interrupting evening sedentary time with 3 min of light-intensity to moderate-intensity bodyweight resistance exercises every 30 min extends subsequent free-living time spent asleep by 27 min and has no disruptive effects on other elements of sleep and 24-hour physical activity patterns in healthy adults.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ Sleep hygiene recommendations should be reviewed to better reflect the current pool of evidence. Regularly interrupting prolonged sitting with short bouts of activity breaks is a promising intervention that may improve cardiometabolic health through multiple mechanisms (postprandial metabolism and sleep).

INTRODUCTION

Insufficient sleep can adversely affect diet[1] and has been associated with an increased risk of cardiometabolic diseases including incident coronary heart disease[2–4] and type 2 diabetes.[3 4] Other components of sleep are also important; difficulty with initiating and maintaining sleep also increases the risk of type 2 diabetes,[5] and disrupted sleep has been associated with a greater risk of coronary heart disease[6] and other cardiometabolic risk factors such as elevated blood pressure and blood lipid levels.[7]

Although higher levels of daytime physical activity generally promote better sleep, current sleep hygiene recommendations discourage high-intensity exercise prior to bed because exercise-induced elevations in body temperature and heart rate can result in poorer sleep quality.[8] However, these recommendations do not appear widely supported by current evidence, with many

experimental studies reporting no significant negative effects of late-night exercise on sleep quality[9 10] and some reporting favourable effects.[11–13] It may also be important to consider if changing activity patterns in the evening impacts overall physical activity and 24-hour activity patterns with existing data limited to children.[14] To date, no study appears to have investigated the impact of breaking up sedentary time in the evening by performing short bouts of light-intensity to moderate-intensity resistance exercises on subsequent sleep and physical activity patterns.

The evening period is a prime time to target behaviours that influence cardiometabolic health. Adults accrue the longest periods of uninterrupted sitting[15–17] and consume almost half their daily energy intake during this time.[18] Insulin sensitivity is also diminished in the evening[19] and together, these factors promote elevated postprandial responses, which can be detrimental to cardiometabolic health over time.[20] This activity breaks protocol, which interrupts evening prolonged sitting with 3 min of simple resistance exercises every 30 min, has shown to positively affect postprandial metabolism.[21] However, how this protocol, which increases the amount of activity participants are doing in the hours immediately preceding bedtime, influences subsequent sleep is unknown.

Therefore, the aims of this study were to determine the effect of performing regular resistance exercise breaks compared with prolonged sitting in the evening over 4 hours in a laboratory setting on the secondary outcomes sleep quantity and quality (sleep period time, efficiency and wake after sleep onset), sedentary time and physical activity over the subsequent free-living 48 hours.

METHODS

Study design

This study was a randomised crossover trial. This manuscript focuses on secondary outcomes related to sleep quantity and quality and patterns of physical activity and sedentary time. The primary outcome has been published previously, see Gale *et al*.[21] For further details, see attached the study protocol in online supplemental file 1.

Participants

This study was conducted in Dunedin, New Zealand. Thirty participants aged 18–40 years were recruited by word of mouth. A sample size of 30 participants was estimated to provide 80% power (5% significance) to detect a difference of 0.4 SD in glucose total area under the curve (which was the primary outcome of this study). Eligible participants were: non-smokers, not taking medications or supplements known to impact glucose or triglyceride metabolism, able to speak and understand English, without intolerances or allergies to gluten or dairy (these components were present in the test meals) and those who self-reported habitual sedentary time of more than 5 hours (work) and 2 hours (evening) per day. Participants were asked to obtain medical clearance if their responses to the Physical Activity Readiness Questionnaire indicated that physical activity may not be appropriate (n=1). Participants from across the body mass index categories (minimum 18.5 kg/m^2, no upper limit) were recruited to ensure representation from all groups given the relationship between obesity and glycaemic control. All participants provided written informed consent.

Preliminary measures

Participants attended an introductory session at the University of Otago to confirm eligibility for enrolment. Blood pressure was measured using an automated sphygmomanometer (OMRON HEM-907; Omron Healthcare; Kyoto, Japan) and a correctly sized cuff. Participants were excluded if their systolic or diastolic blood pressure readings were greater than 130 mm Hg and 90 mm Hg, respectively. Standard height and weight were measured in duplicate following standard procedures. Experimental protocols were discussed, and participants watched a video that demonstrated the exercises. Participants practiced the required exercises under supervision from the study research assistant (Registered Dietitian) who was instructed on how to observe and correct technique by a member of the research team who has a degree in Exercise Science (MCP). On completion of primary measurements, participants were fitted with an ActiGraph GT3X+ (ActiGraph, Pensacola, Florida, USA) accelerometer to be worn continuously (24 hours per day) on their non-dominant wrist for seven consecutive days to capture habitual physical activity and sleep patterns. Participants were provided with a wear time diary to record non-wear time, what times they retired to bed, attempted to sleep and woke up. Participants were also asked to record any physical activity performed while not wearing the accelerometer (eg, swimming or contact sport) or to record activities known to be inaccurately identified by the accelerometer (eg, stationary cycling, certain resistance-based exercises or yoga).

Randomisation

Participants were randomised to complete the two experimental conditions in one of two possible orders (figure 1), stratified by weight status. The randomisation sequence was generated by MCP prior to recruitment using Stata (V.16; StataCorp, College Station, Texas, USA) and concealed electronically. The randomisation sequence was revealed and assigned on the afternoon prior to each participant beginning their first experimental condition. Participants were informed of their allocated sequence on arrival.

Pre-intervention standardisation protocols

To minimise diet-induced variability on experimental days, participants were provided with a standardised breakfast, morning tea, lunch and additional snacks to be consumed before 14:00 hours on each experimental day. A detailed summary of the standardised meal protocol

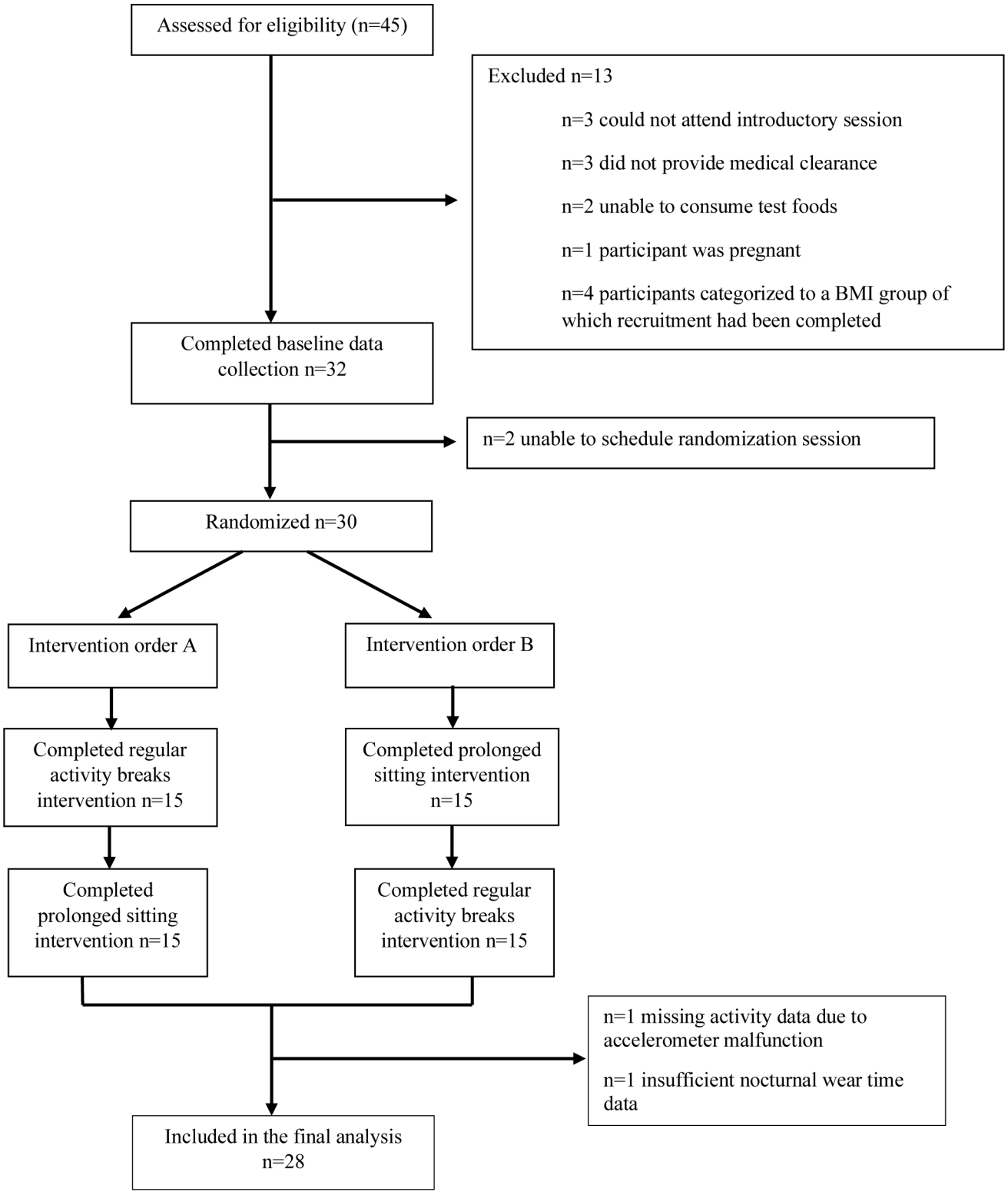

Figure 1 CONSORT study flow chart. BMI, body mass index; CONSORT, Consolidated Standards of Reporting Trials.

is reported elsewhere.[21] Participants were fitted with an ActiGraph GT3X+ accelerometer for continuous wear on their non-dominant wrist from the morning of the intervention day to 48 hours after the intervention. In the 24 hours prior to the first experimental condition, participants were asked to avoid all moderate-intensity to vigorous-intensity physical activity. Participants verbally self-reported compliance with all pre-intervention protocols before each experimental session.

Intervention protocol

Details of the laboratory intervention sessions have been described previously.[21] Each participant completed two 4-hour sessions, on the same day of the week,

from 17:00–17:30 to 21:30–22:00 hours, separated by a minimum 6-day washout to eliminate carry-over effects (median 6 days, IQR 6–12 days). The intervention sessions were conducted on either Tuesday or Thursday evenings, to ensure the next day was a 'typical' weekday, rather than a weekend day. In the prolonged sitting condition, participants remained seated for the duration of the session. The regular activity breaks condition was identical, except participants interrupted sitting with 3 min of simple resistance exercises every 30 min. Each break involved three exercises (chair squats, calf raises and standing knee raises with straight leg hip extensions) for 20 s each over three rounds. Participants performed exercises in time with a video recording of a person performing the exercises in a time standardised manner, and included reminders about form and a timer. These simple, body weight resistance exercises were chosen as the mode of activity breaks for this study as they do not require equipment, can be performed on the spot and have been used previously.[22] During the first session, participants were permitted to get up and use the bathroom as required and bathroom breaks were replicated during the subsequent session. While seated participants were able to watch television, read or work on a portable device during both conditions. Two standardised meals were provided during each condition at baseline and 2 hours. Sessions were supervised by two members of the research team. All participants completed every activity break, and no adverse events were reported during the breaks. Following the sessions, participants returned to their normal free-living environment with no further standardisation.

Physical activity and sleep data processing

For both periods of physical activity assessment (pre-trial habitual physical activity and the assessment of activity immediately prior to, during and after each intervention) time-stamped activity data were downloaded using ActiLife software (ActiLife V.6.13.4), saved in 15 s epoch and imported into Stata. Self-reported sleep and wake times were entered manually into ActiLife to constrain the Cole-Kripke algorithm[23] that determined sleep period time (time between self-reported time attempted sleep and the wake time), wake after sleep onset (WASO (minutes spent awake between sleep onset determined by algorithm and end of sleep)), total sleep time (amount of time spent sleeping during sleep period time for example, sleep period time minus WASO), number of awakenings and sleep efficiency (how consolidated the sleep was). The intensity and duration of activity performed during self-reported non-wear time (eg, contact sport) were identified and manually overwritten in Stata. Sedentary time was classified as <2860 counts/min, with total physical activity represented by over this cut point (ie, ≥2860), which therefore combines light, moderate and vigorous activity.[24] Valid wear time was classified as wear time ≥10 hours during waking hours.

Physical activity and sleep data were separated into two distinct time periods: intervention and post-intervention (online supplemental figure 1). The post-intervention period was defined as the 48-hour period following the end time of the experimental condition although each nocturnal period (defined based on self-reported attempted sleep and wake times) during the post-intervention period was analysed separately.

Statistical analysis

Thirty participants completed the study, however, two participants with missing data were excluded (n=1: accelerometer malfunction, n=1: removed accelerometer overnight). Twenty-eight participants were included in the analyses. To investigate differences between conditions, mixed-effects regression models were used with sleep and activity variables as outcomes, intervention condition as the independent variable and participant as a random effect. Mean differences, 95% CIs and p values were calculated. Residuals of models were plotted and visually assessed for homoskedasticity and normality. A p value of <0.05 was considered statistically significant. All

Table 1 Participant characteristics* (n=28)

	All
Age, years	25.6 (5.6)
Gender, n (%)	
Male	8 (29)
Female	20 (71)
Ethnicity, n (%)	
New Zealand European	21 (75)
Other	7 (25)
Anthropometric measures	
Weight, kg	84.6 (19.8)
Height, cm	169.5 (10.7)
BMI, kg/m^2	29.5 (6.7)
Weight status, n (%)	
Healthy weight	8 (28)
Overweight	10 (36)
Obese	10 (36)
Blood pressure, mm Hg	
Systolic	121.6 (8.6)
Diastolic	74.9 (9.0)
Activity, min/day	
Total physical activity	295.4 (79.5)
Sedentary behaviour	631.3 (86.5)
Sleep period time	467.3 (73.0)
Non-wear time	46.1 (43.5)

*Values reported as mean (SD), unless otherwise stated.
BMI, body mass index.

analyses were carried out in Stata V.17.0 (StataCorp LLC, College Station, Texas, USA).

Time spent in physical activity and sedentary behaviour were reported in (1) absolute minutes and (2) proportions of the waking day. Both are reported because if sleep period time is different between conditions, then absolute minutes in activity and sedentary time would necessarily be different due to the 24-hour constraint of the day. In this situation, the difference in activity or sedentary time may not represent the effect of the intervention directly, but rather represent displacement of other time because of a change in sleep period time. Proportions, however, describe differences in time-use composition of the waking day, independent of sleep period time. Both are informative.

The first 24 hours was analysed as the primary time period to assess the acute effects of regular activity breaks in the evening. The full post-intervention period (48 hours) was analysed as the secondary time period to determine if any acute effects were apparent over 2 days.

As an increase in these sleep and activity variables can be either health promoting (sleep period time, total sleep time, sleep efficiency and physical activity) or not health promoting (WASO, number of night awakenings and sedentary time), a forest plot was created so that direction and strength of effects could be visually assessed more easily. For this, all mean differences and 95% CIs were standardised to be in units of SD.

Equity, diversity and inclusion statement

Our research and author team consist of women, junior, mid-career and senior researchers from different disciplines (Human Nutrition & Dietetics, Biostatistics Sleep and Exercise Sciences); however, all members are based at one University. We acknowledge that our study population is mostly well-educated, white women. We did not purposefully recruit marginalised communities, nor did we investigate the effects of merorganisation on the observed responses.

RESULTS

This study was commenced in March 2021 and ended in October 2021 when the intended sample size was reached (n=30). Participants were mostly women, of New Zealand European ethnicity, and 19–39 years of age (table 1). Based on habitual accelerometry prior to intervention, participants spent 7 hours 47 min (SD 1 hour 13 min) asleep, 10 hours 31 min (1 hour 27 min) sedentary and 4 hours 55 min (1 hour 20 min) engaged in total (light and moderate-to-vigorous) physical activity on average. Three-quarters of participants had an optimal sleep duration, 21% were short sleepers (<7 hours) and 4% were long sleepers (>9 hours).

In the first nocturnal period, regular activity breaks increased sleep period time (the quantity of time between sleep onset and end of sleep) by 29.3 min (95% CI: 1.3 to 57.2, p=0.040, table 2) compared with prolonged sitting. There were no significant differences in sleep efficiency, WASO and number of awakenings. Total sleep time (amount of time a person spends sleeping during sleep period) was 27.7 min longer (95% CI: 2.3 to 52.4, p=0.033) following the regular activity breaks intervention (7 hours 12 min, SD 48 min) compared with prolonged sitting (6 hours and 45 min, SD 82 min) (table 2). Time that sleep was attempted did not significantly differ between conditions (11:56 pm for prolonged sitting and 11:58 pm for regular activity breaks) whereas mean wake times the following morning were different (7:35 am for prolonged sitting, 8:06 am for regular activity breaks (online supplemental table 1).

Table 2 The effect of regular activity breaks and prolonged sitting in the evening on sleep, physical activity and sedentary time in the following 24 hours (n=28)

	Prolonged sitting	Regular activity breaks	Mean difference* (95% CI)	P value
Sleep†				
Sleep period time, min	456 (87)	485 (49)	29 (1 to 57)	**0.040**
Sleep efficiency, %	89 (7)	89 (7)	0 (–2 to 2)	0.857
Wake after sleep onset, min	45 (30)	46 (32)	1 (–10 to 12)	0.849
Number of awakenings, n	17 (9)	17 (8)	1 (–2 to 3)	0.550
Total sleep time, min	405 (82)	432 (48)	27 (2 to 52)	**0.033**
Activity				
Total activity, min	299 (101)	281 (76)	–18 (–50 to 14)	0.265
Total activity as a percent of waking time, %	31 (10)	29 (8)	–2 (–5 to 1)	0.289
Sedentary time, min	646 (126)	641 (92)	–6 (–52 to 40)	0.806
Sedentary time as a percent of waking time, %	67 (10)	67 (8)	0 (–3 to 4)	0.933

*Mean difference, 95% CI and p values calculated using a mixed-effects regression model with participant as a random effect.
†Sleep n=27 as one participant removed accelerometer during sleep time.

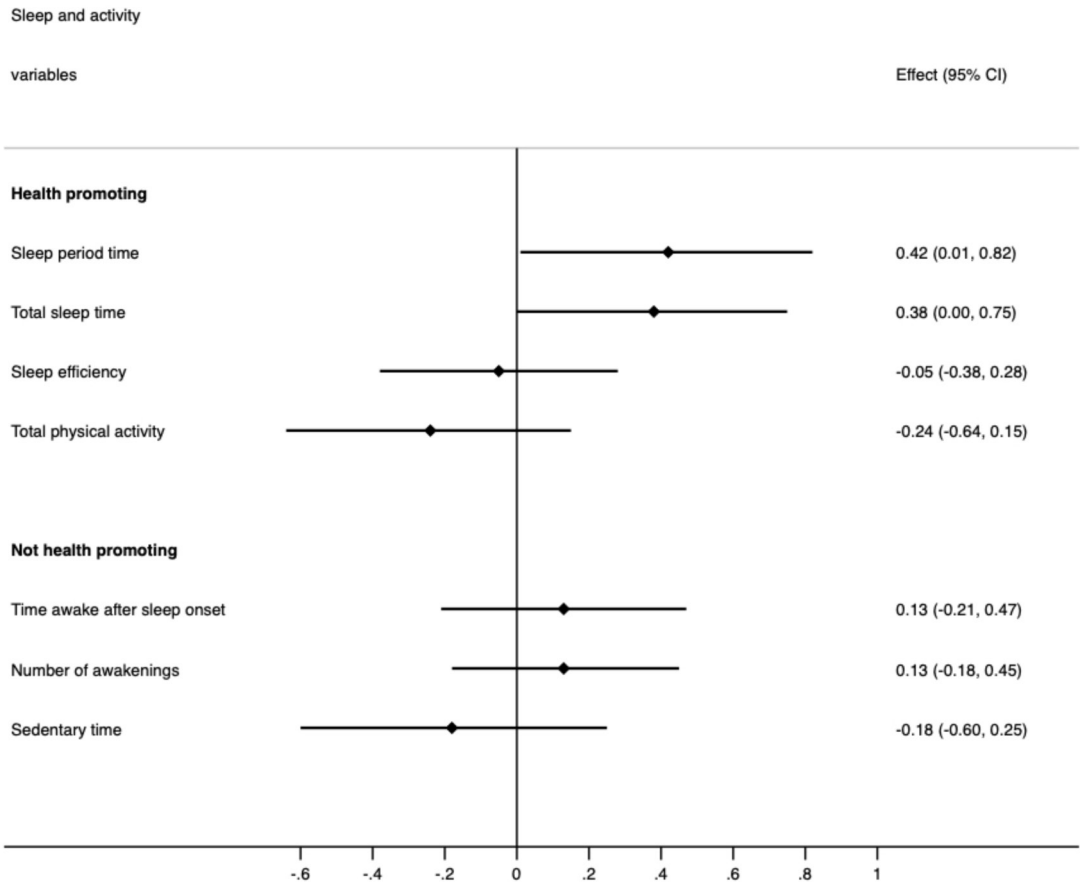

Figure 2 Standardised effect sizes for sleep and physical activity variables for night one following the regular activity breaks intervention compared with prolonged sitting, grouped as either health promoting or not health promoting.

There were no statistically significant differences in activity patterns in the 24 hours following each intervention. However, compared with prolonged sitting, the regular activity breaks intervention resulted in 18 min (95% CI: −50.3 to 13.8, p=0.265) less total physical activity and 1.6% (95% CI: −4.6 to 1.4, p=0.289) less waking time being active, in the 24-hour period following intervention.

Figure 2 shows health-promoting effects of regular activity breaks in the evening with increased sleep period time (effect size 0.42 SD, 95% CI: 0.01 to 0.82) and total sleep time (effect size 0.38 SD, 95% CI: 0.01 to 0.75), as well as a (small, non-significant) decrease in sedentary time. Decreases in sleep efficiency and total physical activity and increases in WASO and number of awakenings were all small (effect size <0.3) and non-significant.

There were no significant differences in measures of sleep or activity over the entire 48 hours following each intervention (table 3). The mean difference in sleep period time for regular activity breaks compared with prolonged sitting in the subsequent 48-hour period was 0 min (−20.5 to 20.5, p>0.999). Mean bedtime, sleep onset and wake times for each nocturnal period by intervention can be found in online supplemental eTable 1.

DISCUSSION

This study appears to be the first to explore the effect of evening resistance exercise breaks on subsequent sleep quality and physical activity patterns in healthy adults. Our results indicate that performing regular activity breaks in the evening in a laboratory setting significantly improves free-living sleep period time and total sleep time. Furthermore, this pattern of activity does not appear to disrupt other measured components of free-living sleep quality, nor does it negatively impact subsequent free-living physical activity.

These results add to a growing body of evidence that indicates evening exercise does not disrupt sleep quality, despite current sleep recommendations to the contrary. A meta-analysis of 23 experimental studies reported that, compared with no-exercise, performing one bout of physical activity ending within 4 hours prior to bedtime had no effect on total sleep time, WASO, sleep onset latency and efficiency.[10] Most of these studies used high-intensity cardiovascular physical activity protocols such as cycling or running, usually as a singular bout. Much less research has employed resistance exercise protocols[11 25 26] which may also be a more pragmatic and simple choice for evening activity breaks protocols as individuals can perform the breaks on the spot without interrupting evening activities, such a streaming, thus improving adherence. Our

Table 3 The effect of regular activity breaks and prolonged sitting in the evening on sleep, physical activity and sedentary time in the following 48 hours (n=28)

	Prolonged sitting	Regular activity breaks	Mean difference* (95% CI)	P value
Sleep†				
Sleep period time, min	478 (59)	478 (70)	0 (–20 to 20)	>0.999
Sleep efficiency, %	87 (6)	88 (6)	1 (–1 to 3)	0.236
Wake after sleep onset, min	54 (26)	52 (32)	–2 (–10 to 6)	0.638
Number of awakenings, n	19 (8)	19 (8)	0 (–2 to 2)	0.748
Total sleep time, min	416 (64)	420 (58)	5 (–13 to 23)	0.614
Activity‡				
Total activity, min	568 (183)	561 (166)	–8 (–58 to 42)	0.757
Total activity as a percent of waking time, %	30 (9)	28 (9)	–0 (–3 to 2)	0.727
Sedentary time, min	1274 (204)	1289 (208)	15 (–52 to 82)	0.661
Sedentary time as a percent of waking time, %	66 (10)	67 (9)	1 (–3 to 4)	0.761

*Mean difference, 95% CI and p values calculated using a mixed-effects regression model with participant as a random effect.
†Sleep n=25 as n=1 participant removed accelerometer during sleep time and n=2 participants did not have night two sleep data.
‡Activity n=26 as n=2 participants did not have sufficient wear time during day 2.

study extends these findings by showing that short bouts of resistance activity performed throughout the evening also do not disrupt sleep quality, and in fact may be beneficial to total sleep time.

While existing research indicates that evening exercise may not adversely impact sleep, the mechanisms by which evening exercise influences sleep quality remain unclear. Increases in core temperature and extended periods of heart rate elevation which can influence melatonin production and increase neurological activity are unlikely with regular activity breaks using resistance exercises[25 27] performed in short bouts, which may explain why there were no differences in sleep quality in the present study. However, the mechanisms behind sleep extension observed in the current study are harder to explain and require further mechanistic data to elucidate.

It is important to note that after completing the prolonged sitting intervention, more than half of our participants (57%) slept <7 hours that night. Therefore, regular bodyweight resistance exercise breaks in the evening have the potential to help individuals meet optimal sleep recommendations and, over the long term, reduce cardiometabolic disease risk. Furthermore, previous research indicates that 30 additional minutes of sleep time have been found to have a positive impact of clinical well-being, thus suggesting our results are clinically relevant, especially so if the benefit could be extended over the long-term.[28]

Over the subsequent two nocturnal periods, the mean difference in sleep period time between interventions was 0 min which could indicate some degree of compensation for the additional sleep accrued in the first nocturnal period. Interestingly, as studies often assess compensation for sleep loss rather than sleep extension,[29] explanations of this effect will require further research. Although not statistically significant, there was a reduction in total physical activity of 18 min in the 24 hours following the regular activity breaks intervention compared with prolonged sitting. However, as the proportion of waking time spent in total activity did not change, it seems likely that the additional sleep has, in this case, displaced some total activity.

Research and policy implications

These results provide further evidence that the prevailing guidance to avoid physical activity in the hours before sleep should be removed from sleep hygiene recommendations. To better assess compensatory effects, future studies should assess the impact of performing evening regular activity breaks on sleep quality and activity patterns over a longer period. Additionally, future research should investigate the mechanisms driving evening regular activity breaks induced sleep extension.

Strengths and limitations

Key strengths of the study include its crossover design, which controls for individual variability, and our examination of both the immediate effects of the exercise protocols on sleep and the longer-term examination on activity patterns. Rigorous standardisation protocols were employed for food and physical activity. These strengths elevate the likelihood that the increase in sleep observed can be attributed to the regular activity breaks. Word of mouth recruitment resulted in a sample that was mostly young adult women, which limits the generalisability of the findings. However, participants self-reported spending large parts of their day (at least 5 hours) and evening (at least 2 hours) sedentary. This probably reflects the activity patterns of a wider portion of the population as it is estimated that adults spend more than

half of the day engaged in sedentary behaviour.[30] There is limited nationally representative data on sedentary behaviour among New Zealand adults, however, habitual sedentary time of participants in the current study (65% of waking time) is slightly more than larger samples of adults from the USA (58% of monitored wake time).[31] Although participants were not screened for sleep disorders/complaints, objectively measured baseline sleep duration was somewhat similar to national data (collected via self-report) which indicated that ~68% of adults met sleep guidelines (75% in the current study) while 27% were short sleepers (21% in the current study).[32] As sleep was the main outcome, accelerometers were worn on the wrist, rather than on the waist (which is more appropriate for measurement of physical activity). As differentiating between moderate-to-vigorous and light-intensity physical activity can be difficult using existing wrist-worn accelerometry cut points,[33] only total physical activity was reported. As with all laboratory studies, the highly controlled setting may not reflect behaviour in a free-living setting. Thus, further research is required to assess whether activity breaks performed in the evening in a free-living setting can replicate beneficial impacts on sleep as reported here.

CONCLUSION

Evidence indicates that regular evening activity breaks have a positive effect on acute postprandial glucose and insulin responses in healthy adults.[21] The current study shows that this same protocol also extends subsequent sleep. Future research should explore the acceptability of performing regular evening activity breaks in a free-living setting to inform further intervention development. Additionally, future health initiatives could include tools (eg, a mobile application) to break up evening sedentary time with activity, which hold promise in improving cardiometabolic health via multiple targets (postprandial metabolism and sleep).

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Contributors MCP, JJH and RT contributed to conceptualisation. JJH and MCP contributed to methodology. JTG and JJH contributed to formal analysis. MCP, JJH and JTG contributed to investigation. MCP contributed to resources. JJH contributed to data curation. JTG contributed to writing—original draft preparation. JTG, DLW, JJH, RT and MCP contributed to writing—review and editing. JJH and MCP contributed to supervision. JTG contributed to project administration. MCP contributed to funding acquisition. All authors have read and agreed to the published version of the manuscript.

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Disclaimer MCP is the guarantor of this work and, as such, had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

Competing interests None declared.

Patient and public involvement Patients and/or the public were not involved in the design, or conduct, or reporting, or dissemination plans of this research.

Patient consent for publication Not applicable.

Ethics approval This study involves human participants. The study was approved by the University of Otago Ethics Committee (Health; H20/161, December 2020). Participants gave informed consent to participate in the study before taking part.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement Data are available upon reasonable request. Data described in the manuscript will be made available upon reasonable request to the corresponding author.

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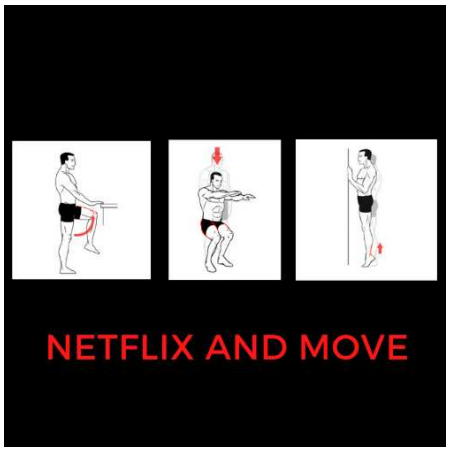

Netflix and Move: Does interrupting streaming in the evening with short bouts of activity impact postprandial glycemia and sleep?

A randomised crossover study.

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1. Project Summary

This study will provide important evidence around how reducing sedentary behaviour in the evening by regularly performing short bouts of resistance activity may improve postprandial metabolism and sleep, both of which are important for cardio-metabolic health. We will conduct a randomised crossover study involving 30 participants. The study will include two experimental intervention sessions each performed in the evening between 5:30 pm and 10:00 pm: 1) uninterrupted sitting; and 2) regular activity breaks, separated by a minimum six-day washout period. Blood samples will be collected intermittently across the intervention session and used to measure glucose, insulin, and triglyceride responses. Sleep duration, efficiency and onset latency will be measured via accelerometry in the 48 h after each intervention session is completed. Mixed model regression will be used to examine differences in the effect of the two interventions in these outcomes.

2. Background

Sedentary behaviour activities performed in a seated or reclining position that involve very low energy expenditure (1) is associated with increased incidence of diabetes, cardiovascular disease, some cancers and overall mortality (2-4). Results from observational studies using accelerometers as an objective measure of sedentary behaviour indicate that the *pattern* in which total sedentary time is accumulated is related to markers of cardio-metabolic health, over and above the total amount of sedentary time (5, 6). Individuals who accumulate sedentary time in long continuous bouts have higher waist circumference, body mass index (BMI), fasting glucose and triglyceride concentrations than those with a similar total sedentary time that is frequently interrupted with light physical activity (5, 6). These associations appear to be consistent across age, sex and ethnic groups (6), and occur even in those who engage in large amounts of leisure time moderate-to-vigorous physical activity (5, 6). Intervention studies have demonstrated that performing regular activity breaks (~ 2 min walking, arm cranking, or 3 min of simple resistance exercises every 20-30 min) reduces glucose and insulin concentrations by up to 39% (7-9) and may also reduce triglyceride concentrations and improve non-esterified fatty acid concentrations (10). Having higher concentrations of postprandial glucose, insulin and triglycerides promote oxidative stress, inflammation and endothelial dysfunction (11-14), all of which contribute to the development of atherosclerosis and cardiovascular disease (14, 15). Non-fasting glucose (16), insulin (17) and triglyceride concentrations (18, 19) also independently predict cardiovascular morbidity and mortality. Regular activity breaks have been shown to reduce postprandial glucose and insulin concentrations in young healthy adults (20), as well as those with obesity (21) and type 2 diabetes (7). These improvements have been shown to persist 24 h after the laboratory based intervention (22), and it is currently unknown when they dissipate. Interestingly, to date, no studies have been performed in a sample which includes participants across the spectrum of BMI categories, even though there has been some suggestion that

the effects of regular activity breaks may differ in individuals with different weight status (23).
For many individuals, the greatest accumulation of sedentary time occurs in an occupational setting. However, recent research indicates that in office workers (24), retired people (25), and those with type two diabetes, (26) the most prolonged, uninterrupted periods of sitting happen *in the evening*. In addition, the average adult also consumes ~45% of their daily energy intake in the evening (27). Elevations in postprandial glucose concentrations associated with both prolonged sitting (20) and higher energy intake may be further exacerbated by the circadian rhythm in insulin sensitivity, with poorer insulin response occurring in the evening compared to the morning (28). To date, a single small study (n=9) has found that performing regular activity breaks in the evening produces reductions in postprandial glycemia and insulinemia (29) that are similar to those observed in the morning (21). However, participants in this study were exclusively obese (29).

Uninterrupted screen time in the evenings may not only result in poorer glycemic control, but also poorer sleep (30, 31). Poor sleep is, in turn, also associated with increased risk of cardio-metabolic disease, poorer mental health and earlier mortality (32). Physical activity, on the other hand has been shown to improve sleep (33). The effects of performing regular activity breaks on sleep has not been investigated.

3. Aim of Study

To investigate the efficacy of performing regular activity breaks during prolonged sitting in the evening as a means of improving postprandial metabolism and overall sleep quality.

4. Objectives

To compare the effects of 4 h of uninterrupted sitting to 4 h of sitting interrupted with 3 min of resistance exercises every 30 min, both during prolonged screen time in the evening, on postprandial glucose, insulin and triglyceride response and sleep duration, efficiency, and onset latency, in a sample of 30 participants across the spectrum of BMI categories.

5. Hypothesis

That performing 3 min of resistance exercise every 30 min to interrupt prolonged sitting during screen time in the evening will improve postprandial metabolism and sleep when compared to uninterrupted sitting.

6. Study Design

This study will be a randomised, crossover trial, in which each participant will complete two 4 h intervention sessions: 1) uninterrupted sitting; and 2) sitting but with a 3 min bout of simple resistance exercise every 30 min. Each intervention session will be separated by 6 days, so they are repeated on the same days of the week.

7. Study Setting/Location

This single site study will be conducted in the Department of Human Nutrition Research Clinic at the University of Otago, Dunedin.

8. Study Population

A total of 30 participants between the ages of 18 to 40 y will be recruited to participate. To provide an even distribution of participants across BMI categories: 10 participants will be normal weight (BMI 20-24.9 $kg \cdot m^{-2}$); 10 participants will be overweight (BMI 25 – 29.5 $kg \cdot m^{-2}$); and 10 will be obese (BMI ≥30 $kg \cdot m^{-2}$)

9. Eligibility Criteria

Participants in this study are required to be predominantly sedentary during the day, therefore we will require participants to:

- Self-report spending, on average, more than 5 h per day (at work or at home), and 2 h in the evening engaged in sedentary behaviour.

Other research indicates that smoking impacts postprandial metabolism, therefore, participants will only be included in the study if they are a non-smoker.

Because we are measuring postprandial metabolism, which can be affected by medications and dietary supplements, participants will only be included if they are not taking any medication or dietary supplements that are known to impact postprandial metabolism, including metformin and niacin.

We will also ask participants not to take part if:

- They have been told by a doctor or other medical professional (such as a physiotherapist) that they should avoid doing physical activity or any of the specific movements used in the simple resistance exercises.
- They have an intolerance or allergy to dairy or gluten as the test meal and snack will contain these foods.

Participants will be asked to gain clearance from their General Practitioner to participate in this study if their responses to the Physical Activity Readiness Questionnaire (PAR-Q) indicate that participating in physical activity may not be medically appropriate.

10. Study Outcomes

Primary Outcome:

The difference in glucose total area under the curve (tAUC) and incremental area under the curve (iAUC) measured over 4 h between the two interventions.

Secondary Outcomes

The difference in insulin total area under the curve (tAUC) and incremental area under the curve (iAUC) measured over 4 h between the two interventions.

The difference in triglyceride total area under the curve (tAUC) and incremental area under the curve (iAUC) measured over 4 h between the two interventions.

The difference in nocturnal mean and tAUC interstitial glucose in each of the two nights following the interventions.

The difference in activity patterns (sleep, physical activity, and sedentary behaviour) in the 48-h following the interventions.

The difference in sleep duration (time spent asleep) in each of the two nights following the intervention.

The difference in sleep efficiency (percentage to time spent asleep between sleep onset and sleep offset) in each of the two nights following the intervention.

The difference in sleep onset latency (the duration from the time sleep was attempted until the onset of sleep is detected) in each of the two nights following the intervention.

11. Study Procedures

Recruitment of participants

Paper and electronic copies of the recruitment flyers advertising the study will be distributed around the university campus, including on Dunedin based/focused social media. Individuals interested in participating will be asked to indicate interest by emailing activitybreaks-study@otago.ac.nz.

Randomisation

Participants will be block randomised (block size n=6) to complete the two interventions in 1 of 2 possible orders. Randomisation will be stratified by weight status. The randomisation sequence will be generated by MCP using Stata software and concealed electronically. The evening before each participant begins his or her first intervention session, MCP will reveal and assign the next sequential allocation. Participants will not be notified of which intervention session they are completing until they arrive at the clinic on the evening of each intervention session. However, by a process of elimination, they will obviously know what their second intervention will be as soon as they begin their first intervention session.

Gale JT, *et al. BMJ Open Sp Ex Med* 2024; 10:e001774. doi: 10.1136/bmjsem-2023-001774

Study procedures

Consent and screening

The postgraduate research students/research assistant or the PI (MCP) will respond to email enquiries providing the information sheet and a link to the REDCap consent and demographic questionnaire. Once the participants have completed the consent and demographic questionnaire, the responses to the PAR-Q will be checked. If medical clearance is required, the participant will be emailed and asked to contact their GP to gain clearance to participate in the study. Once medical clearance is obtained, or if it is not required, participants will be scheduled to attend an initial introductory session.

At this introductory session, the participant will be asked if they have any further questions about the study. Once any questions have been addressed, they will have their height, weight, and blood pressure (in triplicate 1 min apart; after 15-min seated rest) measured. If blood pressure is greater than 140/90 mmHg and participants have not already obtained medical clearance, then they will be asked to contact their GP to gain clearance to participate in the study. Participants will then be shown a video of the exercises they will be asked to perform in the regular activity breaks intervention and asked to practise these movements with the investigator. Technique will be corrected as necessary. To assess the usual sleep and activity patterns of participants before they start the intervention, participants will be fitted with an ActiGraph or AX3 accelerometer (depending on availability – all participants will be fitted with the same model), at the end of this session, which they will be asked to wear for a seven-day period (24 h a day). Participants will also be asked to complete a sleep and wear time diary over this time.

Standardisation of prior physical activity and diet

The afternoon prior to each intervention session, participants will collect food for their breakfast, morning tea and lunch for the following day. Participants will also be, fitted with both an ActiGraph (worn at the wrist to measure sleep and physical activity) and a continuous glucose monitor which they will continue to wear through the intervention session and for the following 48 h. They will also be provided with a sleep and wear-time diary, which they are to complete (by recording times of accelerometer removal and bed and attempted sleep times each day). To minimise the influence of previous activity on outcome measures, participants will be required to avoid all intentional moderate-to-vigorous intensity physical activity and be largely sedentary for 24 h prior to each intervention.

Providing food to participants ensures their food intake is standardised before arriving at the clinic. The breakfast, morning tea and lunch together will provide 55% of each participant's estimated energy requirements (Schofield equation (34), using a physical activity factor of 1.5), with a macronutrient profile of 55% carbohydrate, 15% protein, and 30% fat. Participants will be asked to ensure that all provided food is consumed prior to 2 pm, and to replicate the timing of consumption prior to both intervention sessions. Following 2 pm, participants will refrain from eating until they arrive at the clinic.

Intervention sessions

Uninterrupted sitting intervention: Participants will arrive at the clinic at 5:30 pm. A cannula will be inserted into a forearm vein to allow collection of multiple blood samples. The participant will then rest comfortably for at least 15 min before a baseline sample will be collected. At ~6:00 pm participants will be fed a standardised dinner providing 35% of their estimated energy requirements, with a macronutrient profile of 55% carbohydrate, 15% protein and 30% fat. Participants will be required to consume this meal in 15 min. A snack/dessert will be provided at 8:00 pm, providing the final 10% of the participant's estimated energy intake. Blood samples will be collected hourly for 4 h with additional samples collected 30 and 45 min after each feeding. A total of nine blood samples will be collected (Figure One). During the postprandial period, participants will be required to remain as sedentary as possible, only leaving their chair to use the bathroom when required (timing and duration of bathroom breaks will be recorded by an investigator). Upon completion of the intervention session, participants will return home by car (taxis will be arranged and paid for those who do not have their own transport). Participants will continue to wear the continuous glucose monitor and accelerometers for 48 h. Participants will also be asked to record the times they went to bed, started trying to go to sleep and got up for the day for the two nights directly following each intervention session in the sleep and wear-time diary they will be provided with.

Regular Activity Breaks Intervention: This intervention will follow the same protocol as for the prolonged sitting intervention. However, in addition, participants will perform 3 min of simple resistance exercises every 30 min. Simple resistance exercises will consist of calf raises, half squats, knee raises, and straight leg hip extensions. These exercises will be performed in time with a prepared video with technique cuing commentary. In addition, the investigator will accompany the participant in the activity breaks to provide support and monitor safe technique.

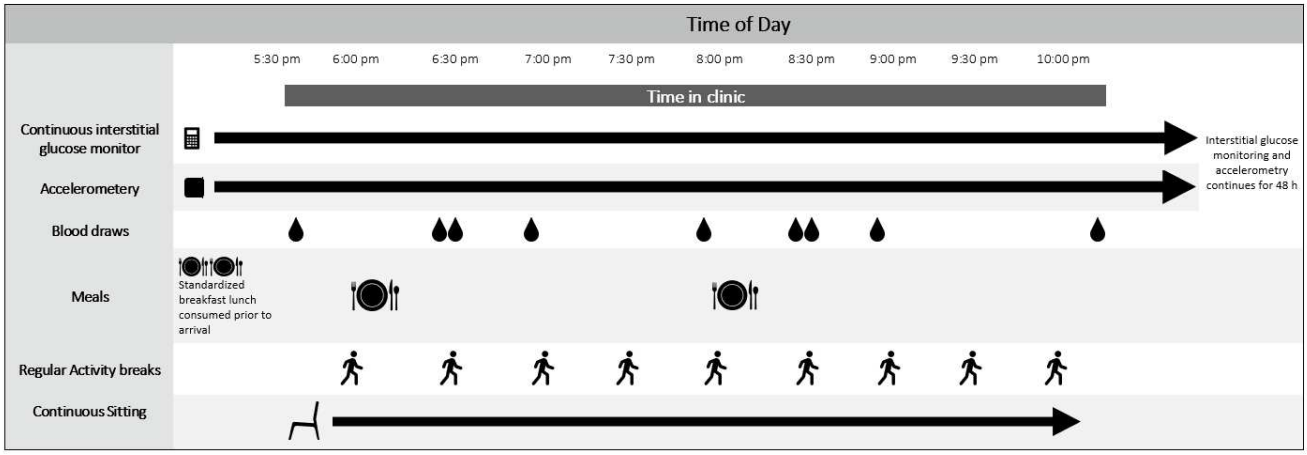

Figure 1: Intervention Day timeline

Analytical Methods

Blood samples collected for the analysis of glucose, insulin and triglycerides will be centrifuged within an hour of collection and plasma stored at -80°C until analysis. Insulin analysis will be carried out using the Electrochemiluminescent Immunoassay (1010 Immunoassay System, Roche Diagnostic Elecsys®, Mannheim, Germany). Blood glucose, and triglycerides will be determined using enzymatic colorimetric methods (Roche diagnostics). All analysis will be carried out in the Department of Human Nutrition Diabetes and Lipid Laboratory at the University of Otago. The individual conducting the analysis will be blinded to intervention.

Accelerometer data processing

Usual activity patterns - From the 7-day wear period prior to completing the intervention sessions, an estimate of habitual time spent sedentary, and in light and moderate-to-vigorous physical activity and asleep will be calculated. These variables will be used to describe the baseline characteristics of the population and investigated as moderators in exploratory analysis, as it is possible that baseline physical activity status impacts the effects of regular activity breaks on glycemic control (35).

Sleep - Accelerometer data, including data from the sleep and wear time diaries will be used to investigate the acute effects of uninterrupted sitting and regular activity breaks on sleep duration (time spent asleep), sleep efficiency (ratio of total time spent asleep compared to the total amount of time spent in bed, between sleep onset and sleep offset) and sleep onset latency (the duration from the onset of self-reported attempted sleep time, to the onset of sleep) for two nights after the intervention.

Qualitative Assessment of Practicality of Performing Regular Activity Breaks in the Evening

Participants who complete the intervention study will be invited to participate in focus group discussions or individual interviews to investigate their experiences of performing regular activity breaks in the evening in a laboratory setting and their opinions about how transferable this behavior would be to real life. They will also be encouraged to identify barriers and facilitators that they foresee to performing regular activity breaks in the evening. Consent to participate in these focus groups will be obtained separately from the intervention study. Each focus group will include a maximum of 6 people and would likely last 45-60 min. The discussions will be scheduled at times that suit participants. Where participants completing the study cannot be scheduled into a focus group at a convenient time, individual interviews may be conducted. Focus groups/interviews will be recorded, and transcripts analyzed using inductive thematic analysis (36).

Data Monitoring and Quality Control

No formal data monitoring will take place.

Quality control will be ensured by developing standard operating procedures for all data collection, including:

- The introductory session (anthropometry and blood pressure measurements)
- Procedures around standardisation of diet and exercise prior to each intervention
- All measurements conducted during each of the two intervention sessions (meal preparation and timing of administration, timing of blood collection, timing of activity breaks)
- Biological specimen management and analysis (tube labelling, centrifuging, separating of serum for storage in freezer, analysis of glucose and insulin concentrations)

All student researchers/research assistants involved in the research will be thoroughly trained in all operating procedures and the PI (MP) will perform periodic checks throughout data collection to ensure protocols are being adhered to.

12. Statistical Considerations and Data Analysis

Sample size and statistical power

Using variances calculated for the first four hours of our previous study (20), a sample size of 30 participants will give 80% power to the 5% significance level to detect a difference of 0.4 standard deviations. A sample of this size will also allow us to detect differences in the secondary outcomes in the order of 0.4 standard deviations of insulin and triglyceride AUC, and 20 min of sleep duration.

Statistical methods

Statistical analysis will be performed using Stata version 16. As a crossover design, each person will be compared to themselves and the mean difference between the uninterrupted sitting and regular activity breaks interventions for the whole group is determined. The mean difference in outcome variables between the two interventions will be estimated, along with 95% confidence intervals, using mixed effects regression models, with intervention condition as the exposure variable, participant ID as a random effect, and controlling for randomisation order.

Exploration of effect moderation by weight status and by sedentary and physical activity patterns will be undertaken by running the mixed effects regression models stratified by these moderating variables. While not powered to detect significant differences in these smaller groups, effect sizes will be compared to see if moderation is indicated.

13. Ethical Considerations

The study will be conducted in full conformance with the most current revision of the Declaration of Helsinki, the International Conference for Harmonization of Good Clinical Practice Regulations and Guidelines and the laws and regulations of New Zealand.

Quality assurance

This research will be conducted by researchers who are skilled in the technical aspects of this research study. Students/research assistants working on the research project will be carefully trained and overseen by the named investigators. Standard operating procedures will be developed and adhered to at all times.

Risks/safety considerations

Cannula insertion and blood collection.

There is a risk of discomfort, pain and bruising from the cannula insertion. Participants will be informed of the risks. An experienced nurse or phlebotomist will insert the cannula and ensure strict aseptic technique is followed during blood collection from the cannula to minimise any risk of infection.

While most participants tolerate blood collection from a cannula very well, there are a small percentage of participants who may feel faint during and after collection. All blood samples will be collected with the participant sitting in a recliner, which allows for the participant to be reclined with feet elevated should they feel unwell during cannula insertion or blood collection.

Performing Regular Activity Breaks

There is a small risk of loss of balance when performing exercises which require participants to balance on one leg (such as the knee raises and hip extensions). Participants will be encouraged to perform these exercises within arm's reach of the back of their chair, so they have something to grab onto if they do lose their balance (although most will simply be able to place both feet on the floor to regain their balance).

Over the course of the regular activity breaks intervention, participants will perform upwards of 200 repetitions of each exercise. If they are not used to performing these movements, they may experience a small amount of delayed onset muscle soreness in the days immediately following the intervention. This type of muscle soreness is common after the initiation of any new activity programme, is unlikely to be severe, and should only last for a few days.

Participants will be free to withdraw from the study at any time without any disadvantage to them.

Potential Benefits

Very little is understood about how performing regular activity breaks in the evening will affect postprandial metabolism and sleep. This study will provide high quality experimental evidence around the effects of interrupting sedentary behaviour with short bouts of resistance activity on glucose and lipid metabolism and sleep. This will inform the development of future public health and physical activity guidelines.

Informed Consent

Individuals who have indicated they are interested in participating will be emailed an information sheet and an online consent, screening, and demographic questionnaire. Participants will be asked to read the information sheet before completing online consent. Participants will be encouraged to contact the study investigators at any time if they have any questions about the study.

Online informed consent will be collected from the participant before the begin any screening procedures.

Consent information will be stored electronically on REDCap.

Participant Confidentiality

Upon enrolment, the participant will be assigned a unique identifying code consisting of "NET" at the beginning, followed by 2 numbers (e.g., NET01). To preserve confidentiality during data-collection, all data will be recorded against this ID number. Any information linking the participant's identity to the ID number will be kept in a password-protected computer file.

Responses to questionnaires will be electronically linked to study ID number, as will accelerometry data. Study ID numbers will also be written on all biological sample tubes, sleep and wear time diaries and the recording sheets for anthropometry and blood pressure.

Participant Follow-up

Once the data from the study have been analysed, the participants will be provided with an overall summary of the results. Participants are also free to request a copy of their individual data once the summary of results has been provided to them.
Any participant who is identified as having a blood pressure above 140/90 or a baseline (non-fasting) glucose concentration above 7.8 $mmol \cdot L^{-1}$ during the study will be provided a written copy of these results and advised to see their general practitioner to discuss their results.

Data Management

Data will be collected as per Standard Operating Procedures and cleaned as per standard data entry procedures. Data quality checks will be run on all entered data to check for accuracy, consistency, and completeness.

In the database that contains the results of the study, each participant will be represented by an ID number. This database will be stored on the investigators' computers, all of which are password-protected. A backup copy may also be stored on the University's shared server space, but only the PI (MCP) will have the password that will enable access to the data stored on the server.

The file linking participants to their ID number will be stored in a separate password-protected file that only the PI (MCP) will have access to. The only reason this information will be accessed once the study is completed is if the participant requests their individual results. This file will be destroyed once all participants have been given the opportunity to request individual information. The deidentified information collected as part of this research will be retained for at least 10 years in secure storage.

14. Outcomes and Significance

Completion of study proposed here will provide important high-quality evidence around how reducing sedentary behaviour by performing short bouts of regularly performed activity may facilitate improvements in both postprandial metabolism and sleep, both of which are established risk factors for cardio-metabolic disease.

The USA 2018 Physical Activity Guidelines Advisory Committee have recently highlighted the lack of high-quality evidence currently available around the interactions between sedentary behaviour and light- and moderate- intensity physical activity on health (37). This research clearly fills a gap in the literature that is of high importance to policy makers. In addition, similar research has recently been used to inform the development of the Canadian 24 h movement guidelines for adults (38). It is, therefore, anticipated that the outcomes of this research will help to inform public health messages and physical activity guidelines both in New Zealand and internationally.

Gale JT, *et al*. *BMJ Open Sp Ex Med* 2024; 10:e001774. doi: 10.1136/bmjsem-2023-001774

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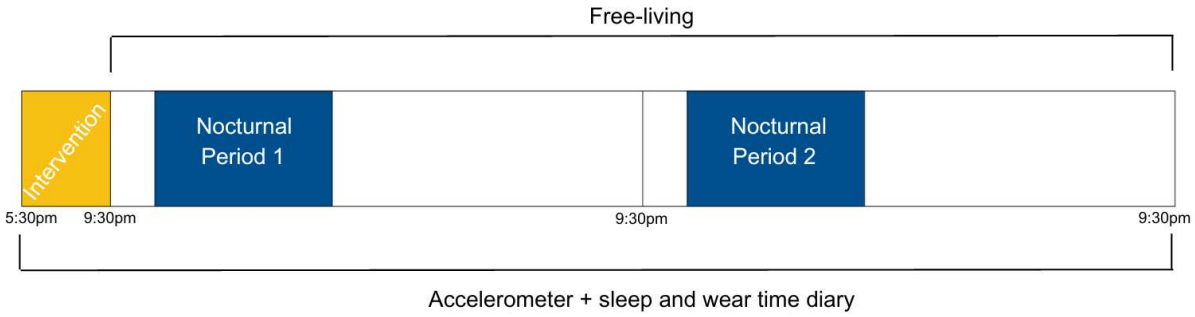
Supplemental Material

eFigure 1. Intervention timeline

eTable 1. Mean bed time, sleep onset and sleep wake times[a] following regular activity breaks and prolonged sitting in in the following two nights (n=28)


Free-living
Intervention
Nocturnal Period 1
Nocturnal Period 2
5:30pm
9:30pm
9:30pm
9:30pm
Accelerometer + sleep and wear time diary

Supplemental Table 1. Mean bed time, sleep onset, and sleep wake times[a] following regular activity breaks and prolonged sitting for the following two nights (n=28)

	Prolonged Sitting	Regular Activity Breaks
Night 1	**24-h time (SD, min)**	**24-h time (SD, min)**
Bed time	23:56 (67.8)	23:58 (86.4)
Sleep onset	00:04 (64.2)	00:05 (85.2)
Sleep wake time	07:35 (79.2)	07:59 (78.6)
Night 2[b]		
Bed time	23:44 (89.4)	00:14 (105.6)
Sleep onset time	23:54 (91.2)	00:20 (103.8)
Sleep wake time	08:06 (77.4)	08:11 (84.0)

[a] Bedtime, sleep onset and sleep wake time reported as 24-hour time, (minutes)
[b] Night 2, prolonged sitting n=27 as n=1 participant removed accelerometer during sleep time.