Abstract

Introduction Reducing sedentary time is associated with improved postprandial glucose regulation. However, it is not known if the timing of sedentary behavior (i.e., pre- versus post-meal) differentially impacts postprandial glucose in older adults with overweight or obesity.

Methods In this secondary analysis, older adults (≥ 65 years) with overweight, and obesity (BMI ≥ 25 kg/m^2) wore a continuous glucose monitor and a sedentary behavior monitor continuously in their real-world environments for four consecutive days on four separate occasions. Throughout each four-day measurement period, participants followed a standardized eucaloric diet and recorded mealtimes in a diary. Glucose, sedentary behavior, and meal-intake data were fused using sensor and diary timestamps. Mixed-effect linear regression models were used to evaluate the impact of sedentary timing relative to meal intake.

Results Pre-meal sedentary time was significantly associated with both the increase from pre-meal glucose to the post-meal peak (ΔG) and the percent of pre-meal glucose increase that was recovered one-hour post-meal glucose peak (% Baseline recovery) ($p < 0.05$), with higher levels of pre-meal sedentary time leading to both a larger ΔG, and a smaller % Baseline recovery. Post-meal sedentary time was significantly associated with the time from meal intake to glucose peak (ΔT) ($p < 0.05$), with higher levels of post-meal sedentary time leading to a longer time to peak.

Conclusions Pre- versus post-meal sedentary time differentially impacts postprandial glucose response in older adults with overweight or obesity. Findings suggest that relatively low intensity and short duration changes to sedentary behavior that are strategically positioned within the one-hour prior to, and/or immediately post energy intake might meaningful benefit long-term glycemic control.

New and Noteworthy

This investigation provides novel findings indicating that the timing of sedentary behavior relative to energy intake influences postprandial glycemia.

Introduction

The high prevalence of sedentary lifestyles and the overabundance of energy-dense foods has contributed to a global rise in overweight, obesity and cardiometabolic disease(Saklayen, 2018; Sattar et al., 2020). This trend is particularly concerning for older adults as aging is independently associated with cardiometabolic disease, and older adults tend to be overweight or obese(Fakhouri et al., 2012; Wang et al., 2007). Further, physical activity is a cornerstone of cardiometabolic disease prevention and treatment, but only 2.4% of adults 65 y are physically active, and the interaction of aging- and obesity-related declines in physical function make adding structured exercise particularly challenging for this group(Troiano et al., 2008).

A body of evidence has amassed over recent years to support the cardiometabolic benefits of reducing and interrupting sedentary time, independent of physical activity(Bankoski et al., 2011; Bull et al., 2020; Chastin & Skelton, 2012; Chomistek et al., 2013). Given the challenges with initiating and maintaining physical activity in older adults, lifestyle interventions that target sedentary behavior have emerged, and national physical activity guideline recommendations now include specific recommendations to reduce sedentary time(*24-Hour Movement Guidelines – Canadian 24-Hour Movement Guidelines*, n.d.; Bull et al., 2020; Health, 2021; Piercy & Troiano, 2018). While broad consensus on the exact amount and type of sedentary behavior that impacts health has yet to be reached, experts, including The American Diabetes Association, agree that reducing sedentary time is a major modifiable risk factor for cardiometabolic disease (American Diabetes Association, 2017; Piercy & Troiano, 2018; *Sedentary Behavior and Cardiovascular Morbidity and Mortality*, n.d.).

In addition to evidence from large-scale epidemiologic studies(Dunstan et al., 2021), findings from laboratory-based experiments indicate that reducing and interrupting sedentary time positively impacts cardiometabolic health by reducing blood glucose levels(Dunstan et al., 2012). Specifically, research indicates that modifications to sedentary behavior can be used to manage post-meal hyperglycemia, which is important given that high postprandial (post-meal) glucose is specifically correlated with cardiometabolic risk(O'Keefe & Bell, 2007) and is a major risk factor for the development of type 2 diabetes in at-risk populations(Bell et al., 2008; Ceriello, 2005; Monnier et al., 2003). However, several gaps in knowledge remain. For example, older adults with overweight or obesity at risk for cardiometabolic disease have not been studied, and the optimal timing of reductions to sedentary time (pre- vs. post-meal) is not known. Further, existing evidence is limited to in-laboratory testing where participants follow a strict, standardized protocol to interrupt sedentary time. It is not known how non-prescribed behaviors performed in real-world environments interact to influence postprandial glucose levels.

The goal of this secondary analysis was to investigate the effects of real-world sedentary behavior on postprandial glucose control in older adults with overweight or obesity. In this ecologically valid analysis, we leveraged objective data collected from two different wearable sensors (an actigraphy-based sedentary behavior monitor and a continuous glucose monitor) worn by participants in real-world environments. Data were collected passively and continuously for four consecutive days as participants went about their daily lives. We hypothesized that lower amounts of sedentary time would be associated with a lower magnitude of postprandial glucose excursion and a shorter time to recover to baseline glucose levels.

Methods

The current study was a secondary analysis of a study investigating the cardiometabolic effects of interrupting sedentary time in older adults. The study was conducted at the University of Colorado Anschutz Medical Campus (CU-AMC) and approved by the Colorado Multiple Institutional Review Board (COMIRB).

Participants

Older adults (≥ 65 years) were recruited from CU-AMC and the surrounding communities. Interested volunteers completed a telephone screen to determine initial eligibility (self-reported overweight or obesity, no diagnosed chronic disease, ambulatory, sedentary (<150 m/wk of moderate to vigorous physical activity) and non-smoking). Eligible volunteers were invited to an in-person screening visit to learn more about the study and confirm eligibility. After providing consent, medical history was reviewed, and weight, height and fasting glucose were measured using standard procedures. Participants with overweight or obesity (BMI ≥ 25 kg/m^2), no contraindications to exercise, fasting glucose <126 mg/dl, and resting systolic and diastolic blood pressure <160- and 100-mm HG, respectively were enrolled in the study.

Real-World Measurement

Participants were monitored in their real-world environment at four different time points for four consecutive days each. During the measurement periods, glucose and activity were continuously measured. Participants were instructed to maintain their typical active and sedentary behavior and followed a standardized meal intake protocol.

Continuous Glucose Monitoring

Throughout each measurement period, participants wore the Medtronic iPro®2 Professional Continuous Glucose Monitor (CGM)**(*iPro®2 Professional GCM*, 2016)**. Briefly, a sensor was inserted at a 45° angle just under the skin on the participant's hip using a removable introducer needle. A small, flexible electrode was embedded in the skin to obtain continuous measurements in mg/dL (every 10 seconds) using the glucose oxidase method. The system stores an average value every 5 minutes (total of up to 288 measurements per day).

Activity and Sedentary Behavior

Sedentary behavior was measured using the activPAL™ (PALTechnologies: Glasgow, Scotland) monitor. The activPAL™ is a small (53 x 35 x 7 mm) and light (15 grams) device that uses accelerometer-derived information about thigh position to estimate time spent in different body positions (i.e., sitting/lying, standing), and activities (i.e., stepping). The device was attached using a non-allergenic adhesive pad and positioned on the midline of the thigh, one-third of the way between the hip and knee. Participants wore the monitor on their right leg 24 hours per day. At least 10 hours of waking wear time was required for a day to be considered valid and included in the analyses(Tudor-Locke et al., 2012).

Standardized Meal Intake

To ensure consistent macronutrient intake during the real-world measurement periods, participants were provided a standardized, eucaloric diet (including meals, snacks, and beverages) from the CU-AMC Clinical and Translational Research Center metabolic kitchen. Daily energy requirements for each participant were determined using participants' measured resting metabolic rate (RMR) and an activity factor of 1.4(Black et al., 1996). Briefly, RMR was measured via indirect calorimetry using the ventilated hood method (Parvo Medics metabolic

cart). After lying quietly for 30 min, RMR was measured for 15-20 minutes following standard procedures. The macronutrient breakdown of the provided diet was 50% carbohydrate, 34% fat, and 16% protein. Timing of energy intake was not controlled and therefore participants used a diet diary to record the time each meal was consumed.

Data Cleaning and Processing

All data cleaning and processing procedures were performed using custom R (cran.r-project.org) programs.

Real-World Data Synchronization

The activPAL™ "events" files were generated from PALTechnologies™ proprietary software (PALTechnologies.com). Custom R (cran.r-project.org) programs were used to adapt events files and CGM glucose data to second-by-second data and then synchronized using dataset timestamps. To ensure consistent timestamps between the activPAL™ and CGM data, devices were managed on the same desktop computer and at the same time prior to distribution and download. Timestamp consistency was further verified via visual inspection of the data. Meal intake times from the diet diaries were integrated and aligned with the activPAL™ and CGM data.

To demonstrate the methods used to integrate behavioral data from the activPAL™ and glucose data from the CGM, Figure 1 illustrates four days of continuous, real-world data fused for one example participant. This example further demonstrates how within a single individual pre- and post-meal sedentary time (blue box) versus either post-meal sedentary time only (red box) or pre-meal sedentary time only (green box) might differentially impact the postprandial glucose response.

Continuous Glucose Monitoring

For each glucose curve associated with meal intake, three glucose metrics were derived and evaluated: (i) the increase in glucose from pre-meal to the post-meal peak ($\Delta G = gl_{\{peak\}} - gl_{\{pre\text{-}meal\}}$); (ii) the time from meal intake to glucose peak ($\Delta T = t_{\{peak\}} - t_{\{meal\}}$); (iii) percent of meal-induced glucose increase that is recovered 1 hour post-meal glucose peak (% Baseline recovery = $(gl_{\{peak\}} - gl_{\{1\ hr\ post\text{-}peak\}})/\Delta G$). The pre-meal glucose, $gl_{\{pre\text{-}meal\}}$, was calculated as the mean glucose value in the one-hour window preceding meal intake. Peak glucose, $gl_{\{peak\}}$, was calculated as the maximal glucose value in the three-hour window post-meal intake, with the corresponding time assigned as $t_{\{peak\}}$. The glucose value one hour after the peak, $gl_{\{1\ hr\ post\text{-}peak\}}$, was calculated as the glucose value at time $t_{\{1\ hr\ post\text{-}peak\}} = t_{\{peak\}} + 1$ hour. All three metrics were calculated using the R package *iglu*(Broll et al., 2021). Glucose measures are illustrated in Figure 2 using the breakfast meal curve for one example participant. The vertices of the shaded triangle correspond to the start of meal intake ($t_{\{meal\}}$, $gl_{\{pre\text{-}meal\}}$), peak ($t_{\{peak\}}$, $gl_{\{peak\}}$) and one hour post-peak ($t_{\{1\ hr\ post\text{-}peak\}}$, $gl_{\{1\ hr\ post\text{-}peak\}}$) time points.

Sedentary Behavior

For each meal, two metrics of sedentary behavior were evaluated: (i) the percentage of time the subject was sedentary (sitting or lying) during the one-hour window pre-meal intake (*Pre-Meal Sedentary Time*); (ii) the percentage of time the subject was sedentary during the one-hour window post-meal intake (*Post-Meal Sedentary Time*).

Statistical Analysis

To evaluate the impact of sedentary time on glucose levels associated with meal intake, mixed-effect linear regression models, treating each of the three glucose meal metrics as a

response, were used. Fixed covariates included: Pre-Meal Sedentary Time, Post-Meal Sedentary Time, BMI, and Fasting Glucose Level. Subject ID was treated as a random intercept. To assess the significance, p-values based on the likelihood ratio tests (with $p < 0.05$ significance threshold) were evaluated. For significant covariates, the effect sizes were determined based on estimated model coefficients. Linear mixed models were fit using the R package lme4, version 1.1-27**(Bates et al., 2022)**. All statistical analyses were performed in R, version 4.1.0.

Results

Three subjects did not have meal data to match with the CGM and activity data, and thus were excluded from the analyses. Additionally, after calculation of glucose meal metrics, ten meals in total were identified as outliers (five meals with negative ΔG indicating no rise in glucose; one meal with $\Delta T = 3$ hours indicating no fall in glucose during the three-hour window post-meal intake; four meals with non-wear time for the sedentary behavior monitor). These 10 meals were removed from all further analyses. Table 1 shows the descriptive characteristics of the final sample of 15 subjects with a total of 558 meals.

BMI was not significantly associated with any of the three meal glucose metrics, which is likely due to the fact that all participants were overweight or obese. In contrast, fasting glucose was significantly associated with ΔG, such that higher levels of fasting glucose corresponded to a larger glucose increase in response to meal intake (increase of 6.2 mg/dL ΔG for 10mg/dL increase in fasting glucose value, Table 2).

Pre-meal sedentary time was significantly associated with both ΔG and % Baseline recovery ($p < 0.05$ in Table 2), with higher levels of pre-meal sedentary time leading to both a larger ΔG (increase of 6.7 mg/dL from 0 min to 60 min sedentary time), and a smaller %

Baseline recovery (decrease of 47.5% from 0 min to 60 min sedentary time). The effect of pre-meal sedentary time on ΔT was not significant.

Post-meal sedentary time was significantly associated with ΔT ($p < 0.05$ in Table 2), with higher levels of post-meal sedentary time leading to a longer time to peak (increase of 25.5 minutes from 0 min to 60 min sedentary time), thus effectively extending the time during which glucose rose before peaking and beginning to drop. The effects of post-meal sedentary time on ΔG and % Baseline recovery were not significant.

The results are summarized visually using a forest plot of the three models (Figure 3).

Discussion

The overall goal of this secondary analysis was to investigate the effects of real-world sedentary behavior on postprandial glucose control in older adults with overweight or obesity. The primary finding and novel contribution of this investigation was that timing of sedentary behavior (pre- versus post-meal intake) is an important determinant of postprandial glucose. Specifically, higher pre-meal sedentary time was associated with higher postprandial glucose excursions and longer baseline recovery, while higher post-meal sedentary time was associated with longer time needed to attain the postprandial peak and begin returning to baseline.

In particular, if the entire pre-meal hour was spent sedentary, then ΔG was estimated to increase by 6.7 mg/dL, and % Baseline Recovery was estimated to decrease by 47.5% compared to the entire hour being non-sedentary. Thus, even cutting sedentary time in half before a meal would be expected to shorten the glucose peak by over 3.3 mg/dL and improve % baseline recovery by almost 24%. For the post-meal period, if the entire hour after meal intake was spent sedentary then the time to peak was estimated to increase by 25.5 minutes. Therefore, cutting sedentary time

in half after a meal, for example by taking a 30-minute walk, would be expected on average to shorten the time to peak and start the recovery to baseline about 12 minutes sooner. While these effects are moderate in size, they are estimated in the context of a single postprandial glucose excursion, and thus accumulation of these effects over many meals would likely contribute to meaningful improvements in hyperglycemia, however this requires further investigation.

An additional contribution of this investigation was the demonstration of a pragmatic, real-world study design. We synchronized continuous, real-world data from a wearable actigraphy-based sedentary behavior monitor and a continuous glucose monitor to construct a contextually rich and ecologically valid dataset.

The widespread and growing prevalence of diabetes and cardiometabolic disease makes identifying modifiable risk factors that counteract glucose dysregulation a major public health concern(Home et al., n.d.). Given that postprandial glucose levels are reported to be a significant contributor to glycated hemoglobin (HbA1c)(Chen et al., 2011; Solomon et al., 2018), the gold standard measure of glucose control, strategies that target postprandial glucose levels could prove particularly relevant. Findings from this study suggest that in older adults with overweight or obesity, modifications to pre- and/or post-meal sedentary time could be an effective lifestyle change to manage meal-induced hyperglycemic events. Specifically, it is reasonable to deduce from these cross-sectional data that reductions in pre-meal sedentary time would lead to improved HbA1c through reduced peak glucose excursions and improved return to baseline levels. Our results suggest that while reductions in post-meal sedentary time might not decrease the magnitude of glucose excursions, they might shorten the time needed for glucose to begin to return to baseline levels and thereby reduce HbA1c.

Our findings complement the existing evidence in the literature. Glucose levels are known to be highly influenced by bioenergetic factors, including diet and physical activity. On the one hand, sedentary behavior has been linked to poor glucose control, while on the other hand, non-sedentary behavior and physical activity have been found to reduce the risk of diabetes(Balk et al., 2015; Herbst et al., 2015; Hu, 2003, 20030509 DCOM- 20030702). While these studies demonstrate the benefits of less sedentary and more physically active lifestyles on glucose control, many of them investigate physical activity in conjunction with dietary interventions(Balk et al., 2015). As the quantity and composition of meals are known to strongly influence glucose levels, the effects solely due to physical behavior have been less clear. By standardizing meal intake, findings from the current study advance our understanding of the independent effects of physical behavior on glucose control.

Several studies have considered the association between physical activity and postprandial glucose levels. Reynolds et al. found that walking post-meal was more beneficial than walking at unspecified times in relation to meals; however, the subjects' diets were not standardized, creating potential confounding(Reynolds et al., 2016). Additionally, since the alternative to post-meal activity was unspecified timing, the differences between pre- versus post-meal activity could not be assessed. Fletcher et al. considered standardized meals and found that physical activity, that is interrupted sitting, reduced the area under the glucose curve from the pre-meal fasting baseline (Fletcher et al., 2018). However, only adolescent subjects were included in the study, and the timing of physical activity in relation to meal intake (pre- versus post-meal) was not investigated. The main differences between our work and existing studies are an investigation of sedentary behavior timing (pre- versus post-meal), and study design (older, overweight adults with a controlled diet in a free-living, non-laboratory environment).

Physical activity is a well-established lifestyle intervention that positively impacts blood glucose control. However, incorporating physical activity regimens into a daily routine can be challenging for older adults with overweight or obesity, and this population is generally at a higher risk for developing diabetes. Given poor adherence to physical activity regimens, the benefits of physical activity may not be easily attained by this population. In contrast, a reduction in sedentary behavior could be viewed as a less strenuous, more easily achievable goal. Further, we chose to focus on the one hour pre- and post-meal because in addition to the less strenuous change of moving from sedentary to non-sedentary we were most interested in 1) the acute effects of relatively small duration changes in sedentary behavior. In this regard, the findings from the current study highlight the impact seemingly small behavior change can have on glycemic control in the postprandial period, and while future studies with larger sample sizes and longer follow up are needed to confirm and expand the current study, our results suggest that simple behavior change strategies that are pragmatically anchored to an individual's pre- and/or post-meal routine might be an effective modification for chronic glycemic control.

This study has several strengths, including a novel study design that combines an ecologically valid assessment of real-world physical behavior and glucose, the standardization of meals to eliminate the confounding effects of energy intake, the continuous measurement of outcomes for four continuous days, and the investigation in an at-risk population. This design is not only scientifically relevant to real-world scenarios but also demonstrates how in the current Covid-19 era, pragmatic trial designs that are less reliant on traditional in-clinic measures are feasible.

The main limitation of this study is the small, non-diverse sample. The analyses were based on fifteen subjects with a total of 558 meals across subjects, limiting statistical power. In

particular, there was insufficient power to assess additional features of physical behavior across participants and the sample was predominantly female, preventing exploration of potential sex differences. Additionally, the analyses focused on only three postprandial glucose metrics. Many other glucose measures could be clinically important in assessing the benefit of reducing sedentary behavior. Finally, although both pre- and post-meal sedentary time were significantly associated with at least one measure of glucose control, neither was associated with all three. The precise clinical effects of improving these three metrics on diabetes diagnosis and resulting health complications are also hard to assess due to the relative newness of CGM technology, and thus lack of consensus on which measures predict long-term complications from the cardiometabolic disease.

Compared to an increase in physical activity, a reduction in sedentary time may be more accessible and directly modifiable for older adults with overweight or obesity. This study suggests that lifestyle interventions that target pre- and post-meal sedentary behavior in this population may effectively improve glycemic control. While both pre- and post-meal sedentary behavior are important for the postprandial glycemic response, the timing of sedentary behavior has a differential effect on meal-related glycemic measures. Long-term prospective and randomized controlled trials are needed to elucidate the precise relationship between each metric and long-term diabetes complications. Additionally, larger sample studies in a free-living environment with controlled meals are needed to evaluate the potential benefits of other components of physical behavior beyond those obtained by modifications in sedentary behavior.

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References

24-Hour Movement Guidelines – Canadian 24-Hour Movement Guidelines. (n.d.). Retrieved February 6, 2022, from https://csepguidelines.ca/

American Diabetes Association. (2017). 4. Lifestyle Management. *Diabetes Care*, *40*(Suppl 1), S33–S43. https://doi.org/10.2337/dc17-S007

Balk, E. M., Earley, A., Raman, G., Avendano, E. A., Pittas, A. G., & Remington, P. L. (2015). Combined Diet and Physical Activity Promotion Programs to Prevent Type 2 Diabetes Among Persons at Increased Risk: A Systematic Review for the Community Preventive Services Task Force. *Annals of Internal Medicine*, *163*(6), 437–451. https://doi.org/10.7326/M15-0452

Bankoski, A., Harris, T. B., McClain, J. J., Brychta, R. J., Caserotti, P., Chen, K. Y., Berrigan, D., Troiano, R. P., & Koster, A. (2011). Sedentary activity associated with metabolic syndrome independent of physical activity. *Diabetes Care*, *34*, 497–503. https://doi.org/10.2337/dc10-0987

Bates, D., Maechler, M., Bolker [aut, B., cre, Walker, S., Christensen, R. H. B., Singmann, H., Dai, B., Scheipl, F., Grothendieck, G., Green, P., Fox, J., Bauer, A., & simulate.formula), P. N. K. (shared copyright on. (2022). *lme4: Linear Mixed-Effects Models using "Eigen" and S4* (1.1-29) [Computer software]. https://CRAN.R-project.org/package=lme4

Bell, D. S. H., O'Keefe, J. H., & Jellinger, P. (2008). Postprandial dysmetabolism: The missing link between diabetes and cardiovascular events? *Endocrine Practice: Official Journal of the American College of Endocrinology and the American Association of Clinical Endocrinologists*, *14*(1), 112–124. https://doi.org/10.4158/EP.14.1.112

Black, A. E., Coward, W. A., Cole, T. J., & Prentice, A. M. (1996). Human energy expenditure in affluent societies: An analysis of 574 doubly-labelled water measurements. *European Journal of Clinical Nutrition*, *50*(2), 72–92.

Broll, S., Buchanan, D., Chun, E., Muschelli, J., Fernandes, N., Seo, J. H., Shih, J., Urbanek, J., Schwenck, J., Hicban, M., Martin, M., Patel, P., Ashok, M., Nguyen, N., & Gaynanova, I. (2021). *iglu: Interpreting Glucose Data from Continuous Glucose Monitors* (3.3.0) [Computer software]. https://CRAN.R-project.org/package=iglu

Bull, F. C., Al-Ansari, S. S., Biddle, S., Borodulin, K., Buman, M. P., Cardon, G., Carty, C., Chaput, J.-P., Chastin, S., Chou, R., Dempsey, P. C., DiPietro, L., Ekelund, U., Firth, J., Friedenreich, C. M., Garcia, L., Gichu, M., Jago, R., Katzmarzyk, P. T., … Willumsen, J. F. (2020). World Health Organization 2020 guidelines on physical activity and sedentary behaviour. *British Journal of Sports Medicine*, *54*(24), 1451–1462. https://doi.org/10.1136/bjsports-2020-102955

Ceriello, A. (2005). Postprandial hyperglycemia and diabetes complications: Is it time to treat? *Diabetes*, *54*(1), 1–7. https://doi.org/10.2337/diabetes.54.1.1

Chastin, S. F., & Skelton, D. A. (2012). Minimise sedentary behaviour at all ages for healthy ageing. *BMJ*, *344*, e2451. https://doi.org/10.1136/bmj.e2451

Chen, L., Magliano, D. J., & Zimmet, P. Z. (2011). The worldwide epidemiology of type 2 diabetes mellitus—Present and future perspectives. *Nature Reviews. Endocrinology*, *8*(4), 228–236. https://doi.org/10.1038/nrendo.2011.183

Chomistek, A. K., Manson, J. E., Stefanick, M. L., Lu, B., Sands-Lincoln, M., Going, S. B., Garcia, L., Allison, M. A., Sims, S. T., LaMonte, M. J., Johnson, K. C., & Eaton, C. B. (2013). Relationship of sedentary behavior and physical activity to incident

cardiovascular disease: Results from the Women's Health Initiative. *Journal of the American College of Cardiology*, *61*, 2346–2354. https://doi.org/10.1016/j.jacc.2013.03.031

Dunstan, D. W., Dogra, S., Carter, S. E., & Owen, N. (2021). Sit less and move more for cardiovascular health: Emerging insights and opportunities. *Nature Reviews Cardiology*, *18*(9), Article 9. https://doi.org/10.1038/s41569-021-00547-y

Dunstan, D. W., Kingwell, B. A., Larsen, R., Healy, G. N., Cerin, E., Hamilton, M. T., Shaw, J. E., Bertovic, D. A., Zimmet, P. Z., Salmon, J., & Owen, N. (2012). Breaking up prolonged sitting reduces postprandial glucose and insulin responses. *Diabetes Care*, *35*, 976–983. https://doi.org/10.2337/dc11-1931

Fakhouri, T. H. I., Ogden, C. L., Carroll, M. D., Kit, B. K., & Flegal, K. M. (2012). Prevalence of obesity among older adults in the United States, 2007-2010. *NCHS Data Brief*, *106*, 1–8.

Fletcher, E. A., Salmon, J., McNaughton, S. A., Orellana, L., Wadley, G. D., Bruce, C., Dempsey, P. C., Lacy, K. E., & Dunstan, D. W. (2018). Effects of breaking up sitting on adolescents' postprandial glucose after consuming meals varying in energy: A cross-over randomised trial. *Journal of Science and Medicine in Sport*, *21*(3), 280–285. https://doi.org/10.1016/j.jsams.2017.06.002

Health, A. G. D. of. (2021, January 14). *Physical activity and exercise guidelines for all Australians* [Text]. Australian Government Department of Health; Australian Government Department of Health. https://www.health.gov.au/health-topics/physical-activity-and-exercise/physical-activity-and-exercise-guidelines-for-all-australians

Herbst, A., Kapellen, T., Schober, E., Graf, C., Meissner, T., Holl, R., & for the DPV-Science-Initiative. (2015). Impact of regular physical activity on blood glucose control and cardiovascular risk factors in adolescents with type 2 diabetes mellitus—A multicenter study of 578 patients from 225 centres. *Pediatric Diabetes*, *16*(3), 204–210. https://doi.org/10.1111/pedi.12144

Home, Resources, diabetes, L. with, Acknowledgement, FAQs, Contact, & Policy, P. (n.d.). *IDF Diabetes Atlas | Tenth Edition*. Retrieved May 21, 2022, from https://diabetesatlas.org/

Hu, F. B. (2003). Sedentary lifestyle and risk of obesity and type 2 diabetes. *Lipids*, *38*, 103–108.

Hu, F. B. (20030509 DCOM- 20030702). Overweight and obesity in women: Health risks and consequences. *Journal of Women's Health*, *12*, 163–172.

iPro®2 Professional GCM. (2016, August 17). Medtronic Diabetes. https://www.medtronicdiabetes.com/download-library/ipro-2

Monnier, L., Lapinski, H., & Colette, C. (2003). Contributions of fasting and postprandial plasma glucose increments to the overall diurnal hyperglycemia of type 2 diabetic patients: Variations with increasing levels of HbA(1c). *Diabetes Care*, *26*(3), 881–885. https://doi.org/10.2337/diacare.26.3.881

O'Keefe, J. H., & Bell, D. S. H. (2007). Postprandial hyperglycemia/hyperlipidemia (postprandial dysmetabolism) is a cardiovascular risk factor. *The American Journal of Cardiology*, *100*(5), 899–904. https://doi.org/10.1016/j.amjcard.2007.03.107

Piercy, K. L., & Troiano, R. P. (2018). Physical Activity Guidelines for Americans From the US Department of Health and Human Services. *Circulation. Cardiovascular Quality and Outcomes*, *11*(11), e005263. https://doi.org/10.1161/CIRCOUTCOMES.118.005263

Reynolds, A. N., Mann, J. I., Williams, S., & Venn, B. J. (2016). Advice to walk after meals is more effective for lowering postprandial glycaemia in type 2 diabetes mellitus than advice that does not specify timing: A randomised crossover study. *Diabetologia*, *59*(12), 2572–2578. https://doi.org/10.1007/s00125-016-4085-2

Saklayen, M. G. (2018). The Global Epidemic of the Metabolic Syndrome. *Current Hypertension Reports*, *20*(2), 12. https://doi.org/10.1007/s11906-018-0812-z

Sattar, N., Gill, J. M. R., & Alazawi, W. (2020). Improving prevention strategies for cardiometabolic disease. *Nature Medicine*, *26*(3), Article 3. https://doi.org/10.1038/s41591-020-0786-7

Sedentary Behavior and Cardiovascular Morbidity and Mortality. (n.d.). Professional.Heart.Org. Retrieved February 6, 2022, from https://professional.heart.org/en/science-news/sedentary-behavior-and-cardiovascular-morbidity-and-mortality

Solomon, T. P. J., Eves, F. F., & Laye, M. J. (2018). Targeting Postprandial Hyperglycemia With Physical Activity May Reduce Cardiovascular Disease Risk. But What Should We Do, and When Is the Right Time to Move? *Frontiers in Cardiovascular Medicine*, *5*, 99. https://doi.org/10.3389/fcvm.2018.00099

Troiano, R. P., Berrigan, D., Dodd, K. W., Masse, L. C., Tilert, T., & McDowell, M. (2008). Physical activity in the United States measured by accelerometer. *Medicine and Science in Sports and Exercise*, *40*, 181–188. https://doi.org/10.1249/mss.0b013e31815a51b3

Tudor-Locke, C., Camhi, S. M., & Troiano, R. P. (2012). A catalog of rules, variables, and definitions applied to accelerometer data in the National Health and Nutrition Examination Survey, 2003-2006. *Preventing Chronic Disease*, *9*, E113. https://doi.org/10.5888/pcd9.110332

Wang, Y. C., Colditz, G. A., & Kuntz, K. M. (2007). Forecasting the obesity epidemic in the aging U.S. population. *Obesity (Silver Spring, Md.)*, *15*(11), 2855–2865. https://doi.org/10.1038/oby.2007.339

Figure Titles and Footnotes

Figure 1: Example Real-World Data Fusion

Four continuous days of fused data from the glucose monitor, sedentary behavior monitor, and meal intake diary from one example participant. Glucose concentration is depicted in grayscale with higher concentrations shown in darker gray and higher vertical. Physical behavior is shown below glucose data in the colored bar. Timing of meal intake is depicted with vertical black and purple bars. This example demonstrates how within a single individual pre- and post-meal sedentary time (blue box) versus either post-meal sedentary time only (red box) or pre-meal sedentary time only (green box) might differentially impact the postprandial glucose response.

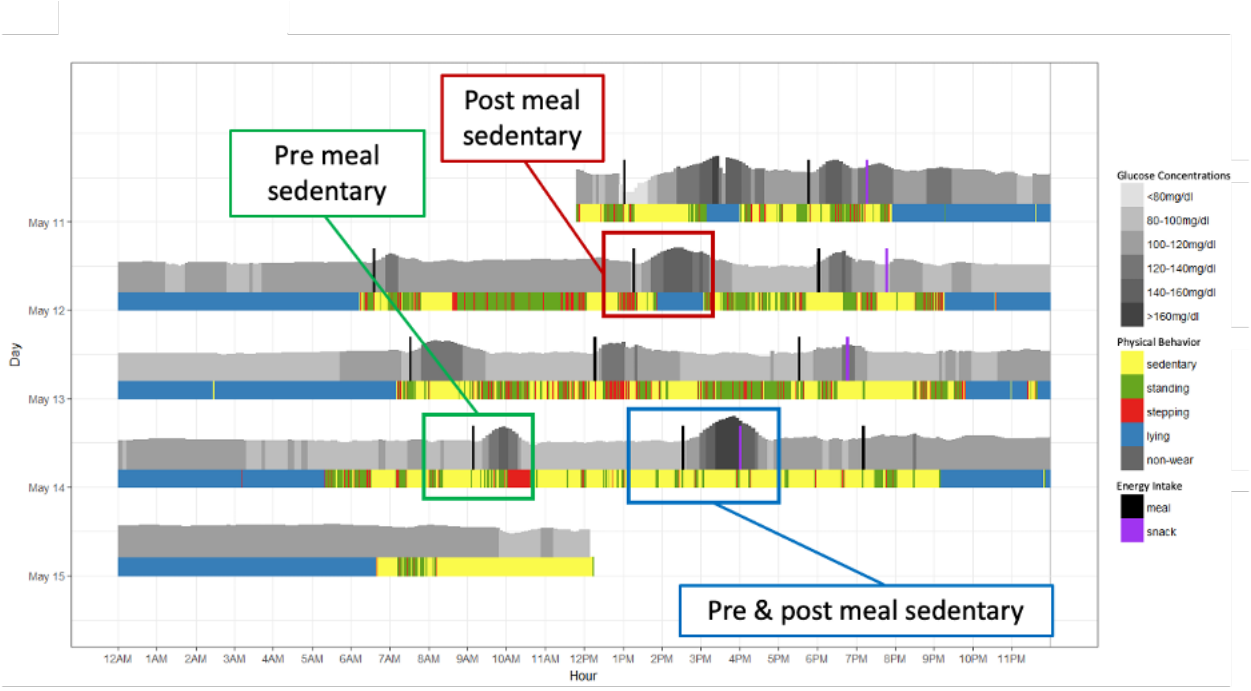


Figure 2: Example Glucose Curve

Glucose curve corresponding to breakfast for one example participant. The black line corresponds to the measured glucose values, the vertical red dashed line corresponds to the mealtime, and the blue horizontal line corresponds to the pre-meal glucose level (an average of glucose values over the hour pre-meal intake). The purple triangle connects the pre-meal glucose value with the glucose value at the peak, and the glucose value one hour after the peak. The three meal metrics, ΔG, ΔT, and % Baseline Recovery, are illustrated by the black brackets.

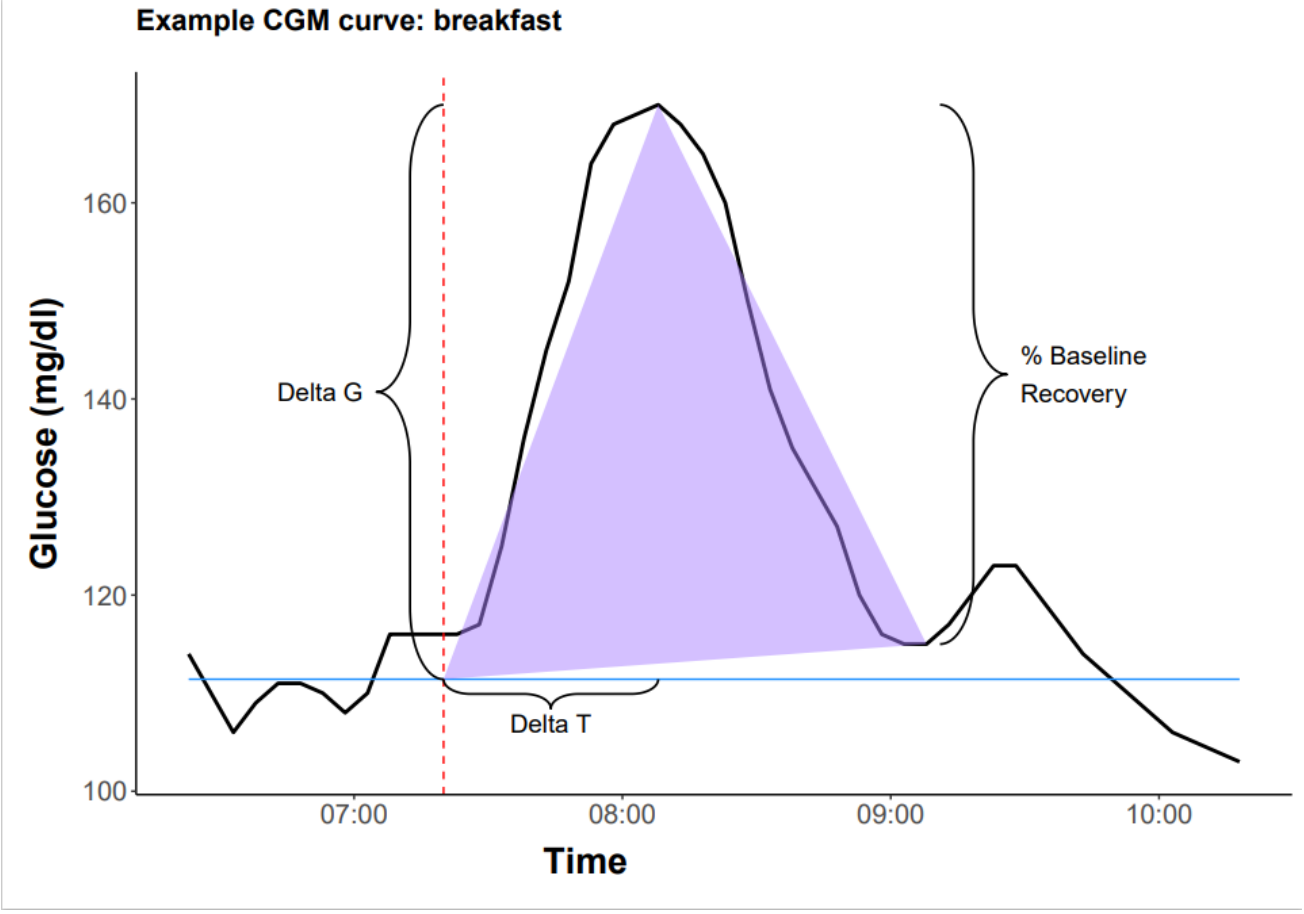
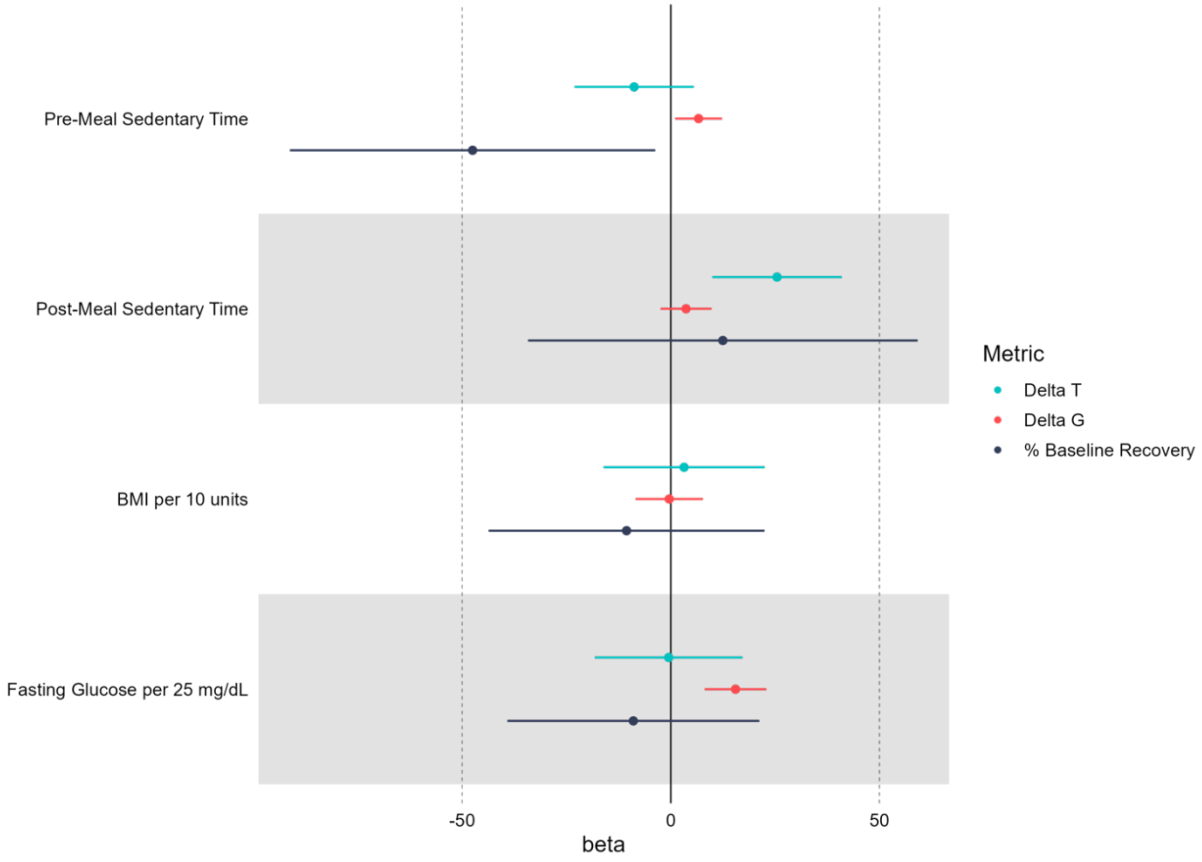


Figure 3: Forest plot of linear mixed models

Results of linear mixed models summarized in a forest plot. Each horizontal line shows the 95% confidence interval for the corresponding metric/response pair. Lines that do not pass through or touch the central vertical line represent significant effects.



Tables and Footnotes

Table 1: Descriptive Characteristics (mean (SD)) of Study Sample (n = 15)

Age (y)	68.1 (5.4)
Gender (n) Female Male	 12 3
BMI (kg/m^2)	32.1 (4.5)
Fasting glucose (mg/dL)	96.0 (12.2)
Number of meals per subject	37.2 (6.8)

Table 2: Linear Mixed Model results

	ΔG (mg/dL)		ΔT (min)		% Baseline Recovery	
	p-value	coefficient	p-value	coefficient	p-value	coefficient
Pre-Meal Sedentary Time	**0.021***	**6.7**	0.246	-8.8	**0.026***	**-47.5**
Post-Meal Sedentary Time	0.238	3.7	**0.001***	**25.5**	0.877	12.5
BMI	0.904	-0.04	0.718	0.32	0.669	-1.1
Fasting Glucose	**< 0.001**	**0.62**	0.954	-0.02	0.475	-0.4

Boldface indicates statistical significance (*$p < 0.05$)