Accepted Article

Journal of Frailty, Sarcopenia and Falls

Original Article

Frailty and Physical Activity: A Compositional Isotemporal Substitution Analysis from the All of Us Research Program

Christian W. Schmidt[1], Lisa Cadmus-Bertram[1], Amy Cochran[2], Kristen A. Pickett[1], Sandesh Parajuli[3], Brad C. Astor[2,3]

[1] *Department of Kinesiology, University of Wisconsin-Madison, Madison, Wisconsin, USA;*
[2] *Department of Population Health Sciences, University of Wisconsin School of Medicine and Public Health, Madison, Wisconsin, USA;*
[3] *Division of Nephrology, Department of Medicine, University of Wisconsin School of Medicine and Public Health, Madison, Wisconsin, USA*

Abstract

Objectives: The objective of this study was to quantify the impact of shifting time away from sedentary behavior to physical activity on frailty in older adults. **Methods**: Participants from the All of Us Research Program with Fitbit data were included in the analysis. Fitbit data was used to measure time spent in sleep, sedentary behavior, light-intensity physical activity, and moderate-to-vigorous physical activity. Frailty was assessed using a 33-item frailty index. A compositional isotemporal substitution model was created to assess the estimated effects of substituting 30 minutes of sedentary behavior with an equal amount of time in physical activity on frailty. **Results**: Reductions in frailty index were seen by shifting 30 minutes from sedentary behavior to light activity (-0.003 [95% CI: -0.004, -0.002]) and moderate-to-vigorous activity (-0.016 [-0.017, -0.014]). Lower odds of frailty were also seen from shifting time from sedentary behavior to light activity or moderate-to-vigorous activity. Associations between physical activity and frailty were generally more pronounced in those participants who were frail or pre-frail than in those who were robust. **Conclusions**: Shifting time from sedentary behavior to physical activity is associated with lower odds of frailty, and shifting time to higher intensity activities may have a greater benefit to frailty.

Keywords: Physical activity, Frailty, Isotemporal substitution models, Frailty index, All of Us Research Program

Introduction

Frailty is a syndrome characterized by the loss of homeostasis and increased vulnerability to stressors. The prevalence of frailty increases with age and is more commonly experienced in females[1]. Frail individuals have inferior health outcomes than robust individuals, including lower quality of life, higher rates of hospitalization, increased medical costs, and increased incidence of cardiovascular disease, and mortality, among other negative health outcomes[2–8]. Frailty is dynamic in nature and can change over time, which has made it a target of many interventions seeking to slow or reverse its progression.

Physical activity is associated with improvements in phenotypic attributes of frailty and has shown an ability to combat many of the underlying biological mechanisms of frailty[9]. Lower rates of physical activity and higher amounts of sedentary time are associated with increased frailty, with the majority of frail adults being insufficiently active with regard to the physical activity guidelines[10]. Higher levels of frailty are associated with increasing time spent in sedentary behavior and decreasing amounts of both light intensity physical activity (LPA) and moderate to vigorous physical activity (MVPA)[11].

The authors have no conflict of interest.

Corresponding author: *Christian W. Schmidt, 1300 University Avenue, Room 353, Madison, WI 53706, USA*

E-mail: *cwschmidt@wisc.edu*

Edited by: *Jagadish K. Chhetri*

Accepted *8 November 2025*

Published under Creative Common License CC BY-NC-SA 4.0 (Attribution-Non Commercial-ShareAlike)

Physical activity interventions incorporating both aerobic and muscle-strengthening components improve frailty, physical functioning, and inflammatory biomarkers in the general population and pre-frail or frail individuals[12,13]. Additionally, a longitudinal study that assessed the activity level of individuals over two decades found that those who were consistently active or increased their activity levels over time had a significantly lower risk of becoming frail than those who were consistently inactive[14]. It is important to note that this association may be bidirectional, where lower levels of activity contribute to overall frailty, and being frail further contributes to lower levels of activity and greater sedentary time.

Since behaviors one can engage in are constrained by the finite time available in a day, any activity one engages in must come at the direct cost of another. As such, there is an emerging focus on how behaviors throughout the 24-hour day, and how shifting time from one type of behavior to another, impact health[15]. Several methodologies, including the isotemporal substitution model and the compositional isotemporal substitution model, have been developed to assess the impact of these shifts in behavior times[16,17]. One benefit of the compositional isotemporal substitution over the 'traditional' isotemporal substitution approach is that it allows for the estimation of shifting time from one type of behavior to another, while also accounting for the compositional properties of time-use data[17]. Prior studies have found that shifting time from sedentary behavior to physical activity is associated with improved frailty or lower odds of frailty[18–21]. However, there is some uncertainty regarding what role activity intensity may play. Some studies have found benefits with shifts from sedentary behavior to both LPA and MVPA[18,20,21], while others have only seen improvements associated with higher intensity MVPA[19,22]. Other health benefits, including lower risk of disability, improved physical functioning, and decreased risk of death have been associated with shifting time from sedentary behavior to MVPA, or both LPA and MVPA, respectively[18,20,22].

To date, only one study has examined this relationship of behaviors throughout the 24-hour day with frailty, as assessed using the frailty index, as an outcome[18]. As such, the purpose of this study was to quantify the impact of shifting time away from sedentary behavior to light and moderate to vigorous physical activity on frailty in older adults.

Materials and Methods

All of Us Research Program

This study used data from the All of Us Research Program's Registered Tier Dataset version 8, available to authorized users on the Researcher Workbench[23]. The All of Us Research Program (AoURP) is a longitudinal research study funded by the National Institutes of Health that aims to enroll over one million participants from across the United States with the end goal of improving healthcare for all and to assist in the development of individualized approaches to medicine[23]. Recruitment for AoURP began in May 2018 and as of October 2023 has enrolled over 630,000 participants[24]. This study has emphasized the recruitment of individuals from populations that have been historically understudied in biomedical research. AoURP includes data from a wide range of sources including participant surveys, electronic health records, physical measures, genomics, and digital health data from wearable technology including Fitbit devices. Participant data were included in the analysis if they were over the age of 50, had complete data for >80% of measures included in the frailty index, and had Fitbit data with at least ten hours of non-sleep wear time for 20 out of 28 consecutive days. Participants who were missing data on covariates of interest (age, sex, race, annual household income, body mass index, and current smoking status) were omitted from the analysis. Figure 1 shows a flow chart for included study participants.

Fitbit Data

Physical activity was assessed in the AoURP cohort using a participants' personal Fitbit in a 'Bring your own device' model[25]. Participants were able to choose to link their Fitbit device to their study record and collect physical activity data longitudinally and in real time. Data are made available to researchers in the domains of Activity (as a daily summary), Activity Intraday Steps (assessed at the minute-level), and Heart Rate (at the minute-level and by zone summary). As of October 2023, AoURP has made available Fitbit data for over 59,000 participants[24].

A day of Fitbit data was only considered valid if the AoURP participant had at least ten hours of non-sleep wear time, a minimum of 100 recorded steps, included data on sleep duration, and was within 90 days of the latest survey used in the frailty index. The minimum criteria of requiring at least ten hours of wear time and 100 steps in a valid day has been previously implemented[26]. The first month of valid weartime, where the participant had data for 20 out of 28 consecutive days following the latest survey with data that was included in the Frailty Index, were included in the analysis. This timeframe was selected to better capture true activity patterns and be less susceptible to days or weeks of abnormal activity levels (i.e., vacations, following an acute illness or injury, etc.). Days with erroneous data, or data that may not be indicative of 'normal' activity levels (e.g., days where the combined sleep time and non-sleep wear time accounted for more than 24 hours, days with reported sedentary time or activity time totaling 24 hours in one domain, days with zero reported minutes of sedentary time, and days with more than 50,000 steps) were omitted from the analysis. Additionally, time spent in various activities (sleep, sedentary behavior, light-intensity physical activity, and moderate-to-vigorous physical activity) were winsorized to minimize the effect of

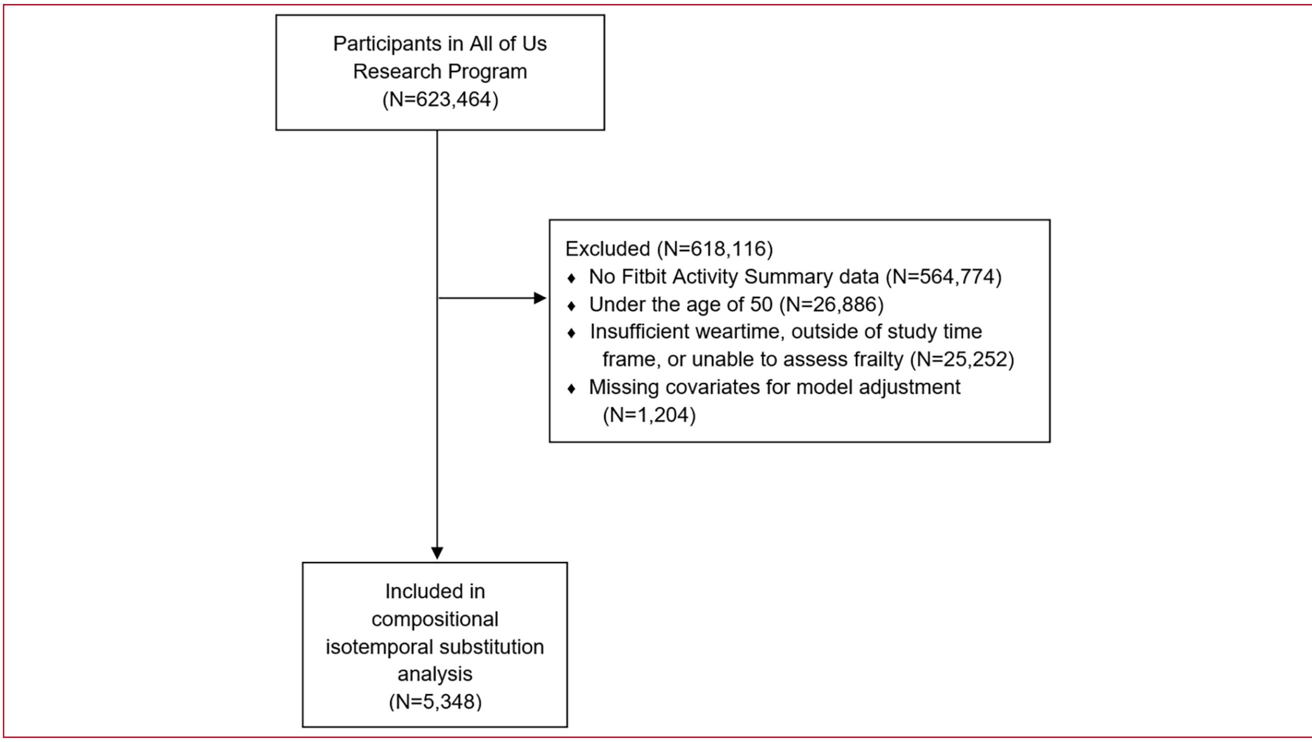

Figure 1. Study inclusion flowchart.

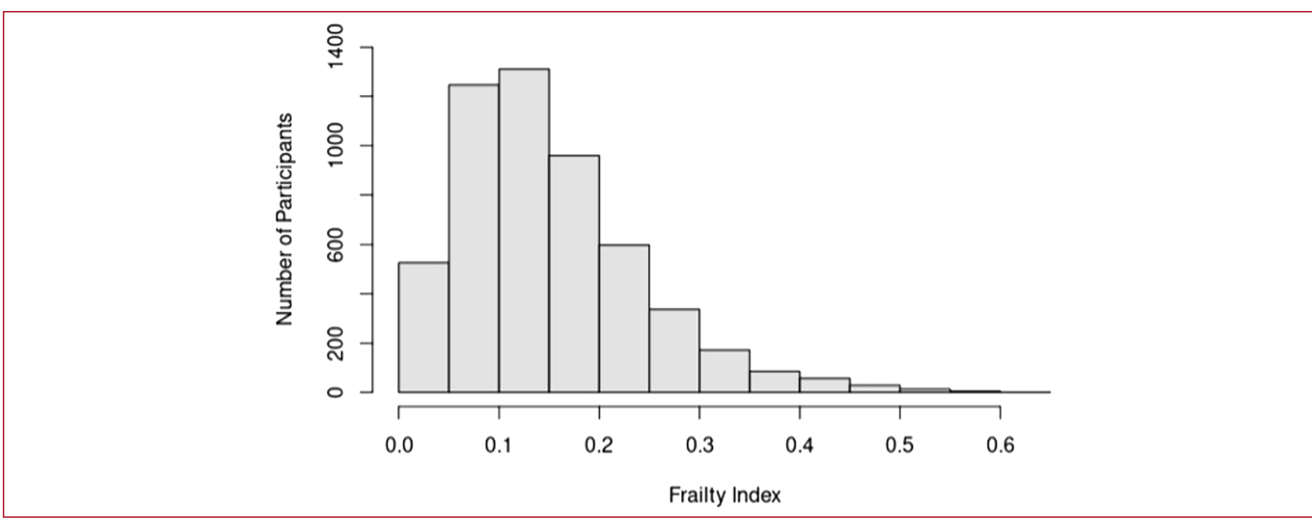

Figure 2. Distribution of frailty index for the overall AoURP cohort.

outliers, where reported times were capped at the 5th and 95th percentiles.

Frailty

Frailty was assessed using a 33-item frailty index (FI) developed for the All of Us Research Program by Wong et al.[27]. The FI quantifies frailty as an accumulation of deficits associated with aging[28], and offers many benefits including its ability to be assessed in ambulatory and non-ambulatory patients, its adaptability across studies, and having greater sensitivity to discriminate frailty severity than the frailty phenotype[29,30]. The index used in this study assesses 33 deficits across the domains of cognitive functioning, self-reported history of comorbid conditions, general health status, geriatric syndromes, mental health, physical functioning, and sensory impairment[27]. A detailed description of the deficits included in the frailty index can be found in Table 2. Participants who were missing data for more than 20% of the FI deficits were excluded from the study. Severity of frailty was stratified using established cutoffs, where FI ≤ 0.10 was considered to be robust, 0.10 < FI ≤ 0.20 as vulnerable or pre-frail, and a score > 0.20 as frail[31]. A clinically meaningful change in frailty has been estimated to be a change of at least 0.03 in FI[32].

Statistical Analysis

Descriptive data are presented as mean ± standard deviation or median (interquartile range) for continuous variables, and discrete variables are reported as count and percentages. To align with the AoURP data and statistics dissemination policy, cells with counts of less than 20 are reported as <20 and the number missing that data will be reported only as the nearest rounded percentage to obscure the exact count. Compositional isotemporal substitution models were created to examine the effect of shifting time between the domains of sleep, sedentary behavior, LPA, and MVPA on FI. Additionally, logistic regression models were created examining the effect of shifting times between behaviors on the odds of frailty. The creation of the models and analysis utilized R packages *compositions* and *robCompositions*. Models were adjusted for participant age, sex, white/non-white race, annual household income, body mass index, and current smoking status. Additionally, since it is plausible that the benefits of shifting time from sedentary time to activity may have differing benefits for those who are frail or pre-frail, we also conducted analyses stratified by frailty severity. All analyses were performed in the All of Us Researcher Workbench using R version 4.4.0 (Vienna, Austria).

Results

A total of 5,348 participants were included in the analysis. Participants had a median age of 65[59,71] years and 1900 (35.5%) were male. The majority of participants (88.8%) were white and 46.1% had an annual household income of over $100,000. A detailed breakdown of the study population can be found in Table 1. The median FI in the cohort was 0.133 (0.086, 0.198). 1774 (33.2%) of the participants were robust, 2272 (42.5%) were pre-frail, and 1302 (24.3%) were frail. Figure 2 shows the distribution of the FI in the population. The most reported deficits in the FI were arthritis (42.7%), hypertension (40.4%), depression (29.0%), and cancer (28.8%). The breakdown of the proportion of the cohort with each deficit is included in Table 2 and Table 3 includes information regarding the time spent in various behaviors with regards to frailty severity.

Variable	N=5348
Age, median (IQR)	65 (59, 71)
Male sex, n (%)	1900 (35.5)
Race, n (%)	
Asian	117 (2.2)
Black or African American	290 (5.4)
White	4749 (88.8)
Other	27 (0.5)
More than one population	165 (3.1)
Hispanic Ethnicity, n (%)	105 (2.0)
Smoking Status, n (%)	
Never	3209 (60)
Former	1972 (36.9)
Current	167 (3.1)
Annual household income, n (%)	
Less than $10,000	84 (1.6)
$10-25,000	289 (5.4)
$25-35,000	299 (5.6)
$35-50,000	479 (9.0)
$50-75,000	844 (15.8)
$75-100,000	887 (16.6)
$100-150,000	1194 (22.3)
$150-200,000	565 (10.6)
More than $200,000	707 (13.2)
BMI, median (IQR)	28.0 (24.6, 32.3)
Frailty Index, median (IQR)	0.133 (0.086, 0.198)
Frailty Status, n (%)	
Robust	1774 (33.2)
Pre-frail	2272 (42.5)
Frail	1302 (24.3)

Table 1. Participant characteristics.

Table 2. Description of deficits included in the frailty index.

Domain and Deficit	Answer choices and values	N (%) N = 5348
Cognitive Function		
Difficulty Concentrating	Yes=1, No=0	286 (5.3)
Dementia	Yes=1, No=0	<20
Morbidities or health conditions		
Cancer	Yes=1, No=0	1540 (28.8)
Hypertension	Yes=1, No=0	2163 (40.4)
Peripheral Vascular Disease	Yes=1, No=0	83 (1.6)
Stroke and/or Transient Ischemic Attack	Yes=1, No=0	242 (4.5)
Atrial Fibrillation or Atrial Flutter	Yes=1, No=0	401 (7.5)
Heart Failure	Yes=1, No=0	109 (2.0)
Coronary artery disease and/or Heart Attack	Yes=1, No=0	401 (7.5)
Diabetes	Yes=1, No=0	595 (11.1)
Kidney	Yes=1, No=0	183 (3.4)
Asthma	Yes=1, No=0	992 (18.5)
Chronic Lung Disease	Yes=1, No=0	257 (4.8)
Physical Function		
Transportation	Yes=1, No=0	156 (2.9)
Difficulty Bathing	Yes=1, No=0	81 (1.5)
Difficulty with Errands Alone	Yes=1, No=0	161 (3.0)
Difficulty with Walking or Climbing Stairs	Yes=1, No=0	436 (8.2)
Average Pain (7 day) Median (IQR)	Worst pain imaginable=1 to No pain=0 (increments of 0.1)	0.2 (0.1, 0.3)
Ability to do everyday activities	Not At All=1, A Little=0.75, Moderately=0.50 Mostly=0.25, Completely= 0	<20, >130, 335 (6.3), 784 (14.7), 4061 (75.9)
Geriatric syndromes		
Fractured Bone	Yes=1, No=0	661 (12.4)
Osteoporosis	Yes=1, No=0	570 (10.7)
Arthritis (OA/RA/other)	Yes=1, No=0	2282 (42.7)
Health Status		
General Health	Poor=1, Fair=0.75, Good=0.50, Very Good=0.25, Excellent=0	64 (1.2) 558 (10.4) 1627 (30.4) 2306 (43.1) 767 (14.3)
General Social health	Poor=1, Fair=0.75, Good=0.50, Very Good=0.25, Excellent=0	56 (1.0) 312 (5.8) 881 (16.5) 2161 (40.4) 1921 (35.9)
Health Literacy (Help with health materials and Confidence with medical forms)	Always/Not At All=1, Often/A Little Bit=0.75, Sometimes/Somewhat=0.50, Occasionally/ Quite a Bit=0.25, Never/Extremely=0	30 (0.6) 54 (1.0) 220 (4.1) 1163 (21.7) 3839 (71.8)

Table 2. *(Cont. from previous page).*

Domain and Deficit	Answer choices and values	N (%) N = 5348
General social satisfaction	Poor=1, Fair=0.75, Good=0.50, Very Good=0.25, Excellent=0	135 (2.5) 504 (9.4) 1323 (24.7) 2194 (41.0) 1168 (21.8)
Average Fatigue (7 day)	Very Severe=1, Severe=0.75, Moderate=0.50, Mild=0.25, None=0	25 (0.5) 206 (3.9) 1096 (20.5) 2629 (49.2) 1377 (25.7)
Mental Health		
Anxiety	Yes=1, No=0	857 (16.0)
Depression	Yes=1, No=0	1552 (29.0)
Average emotional problems (7 day)	Always=1, Often=0.75, Sometimes=0.50, Rarely=0.25, Never=0,	44 (0.8) 354 (6.6) 1341 (25.1) 2080 (38.9) 1514 (28.3)
General Mental Health	Poor=1, Fair=0.75, Good=0.50, Very Good=0.25, Excellent=0	57 (1.1) 350 (6.5) 1111 (20.8) 2328 (43.5) 1291 (24.1)
Sensory deficit		
Hearing Impairment	Yes=1, No=0	436 (8.2)
Blindness	Yes=1, No=0	90 (1.7)

	Full Cohort N=5348	Robust N=1774	Pre-Frail N=2272	Frail N=1302	Non-Robust† N=3574
Total Wear Time	1352 ± 40	1351 ± 39	1353 ± 39	1353 ± 41	1353 ± 40
Sleep Time	400 ± 51	404 ± 47	401 ± 50	392 ± 59	398 ± 54
Sedentary Behavior	701 ± 98	675 ± 93	700 ± 94	739 ± 99	714 ± 98
LPA	211 ± 62	223 ± 58	211 ± 62	195 ± 66	205 ± 64
MVPA	38 ± 31	48 ± 32	38 ± 30	25 ± 26	34 ± 29

† The Non-Robust group is a combination of the pre-frail and frail groups.

Table 3. Description of time spent in various activities and physical activity intensities.

The compositional isotemporal substitution model demonstrated that shifting time from sedentary behavior to physical activity was associated with reductions in FI (Table 4). A shift of 30 minutes of sedentary behavior to LPA was associated with an FI reduction of 0.003 [-0.004, -0.002]. Additionally, reductions in FI were seen from shifting time from sedentary behavior (-0.016 [-0.017, -0.014]), sleep (-0.013 [-0.015, -0.011]), and LPA (-0.013 [-0.015, -0.010]) to MVPA. A replacement of 311 minutes of sedentary time with LPA, or 79 minutes with MVPA, was

Overall Cohort			
30 Minutes From...	30-Minutes of Additional Time		
	Sleep	LPA	MVPA
Sedentary Behavior	-0.003 [-0.004, -0.002] *	-0.003 [-0.004, -0.002] *	-0.016 [-0.017, -0.014] *
Sleep	---	0.000 [-0.001, 0.001]	-0.013 [-0.015, -0.011] *
LPA	---	---	-0.013 [-0.015, -0.010] *
Robust			
30 Minutes From...	30-Minutes of Additional Time		
	Sleep	LPA	MVPA
Sedentary Behavior	0.000 [0.000, 0.001]	0.000 [0.000, 0.001]	-0.001 [-0.002, -0.001] *
Sleep	---	0.000 [-0.001, 0.001]	-0.002 [-0.003, -0.001] *
LPA	---	---	-0.002 [-0.003, 0.000] *
Pre-Frail			
30 Minutes From...	30-Minutes of Additional Time		
	Sleep	LPA	MVPA
Sedentary Behavior	0.000 [-0.001, 0.000]	0.000 [-0.001, 0.000]	-0.003 [-0.004, -0.002] *
Sleep	---	0.000 [-0.001, 0.001]	-0.002 [-0.004, -0.001] *
LPA	---	---	-0.003 [-0.004, -0.001] *
Frail			
30 Minutes From...	30-Minutes of Additional Time		
	Sleep	LPA	MVPA
Sedentary Behavior	-0.001 [-0.002, 0.001]	-0.002 [-0.004, -0.001] *	-0.012 [-0.016, -0.009] *
Sleep	---	-0.001 [-0.003, 0.001]	-0.011 [-0.015, -0.007] *
LPA	---	---	-0.010 [-0.014, -0.005] *
Non-Robust †			
30 Minutes From...	30-Minutes of Additional Time		
	Sleep	LPA	MVPA
Sedentary Behavior	-0.002 [-0.004, -0.001] *	-0.002 [-0.004, -0.001] *	-0.014 [-0.016, -0.012] *
Sleep	---	0.000 [-0.001, 0.002]	-0.012 [-0.014, -0.010] *
LPA	---	---	-0.012 [-0.014, -0.009] *

*† The Non-Robust group is a combination of the pre-frail and frail groups. Results noted with a * are statistically significant at p<0.05.*

Table 4. Estimates from the compositional isotemporal substitution models, showing the resulting change in frailty index from a shift in time spent in behaviors.

associated with a clinically meaningful change in frailty. Shifting 30-minutes from sedentary behavior to sleep (-0.003 [-0.004, -0.002]) was also associated with a small reduction in FI.

Associations between physical activity and frailty were generally more pronounced in those participants who were frail or pre-frail than in those who were robust. Non-robust participants saw an associated reduction in FI when 30 minutes was shifted from sedentary time to LPA (-0.002 [-0.004, -0.001]). Additionally, in this subgroup, shifts from sedentary behavior (-0.014 [-0.016, -0.012]), sleep (-0.012 [-0.014, -0.010]), and LPA (-0.012 [-0.014, -0.009]) to MVPA were all associated with decreased frailty. Shifting time from sedentary behavior to sleep was associated with a reduction in frailty among non-robust participants. Robust participants only saw reductions in FI associated with MVPA, but the overall differences were small. Shifting 30 minutes from sedentary time (-0.001

[-0.002, -0.001]), sleep (-0.002 [0.003, -0.001]), and LPA (-0.002 [-0.003, 0.000]) to MVPA were associated with reductions in FI.

A 30-minute shift from sedentary behavior to LPA was associated with lower odds of frailty (OR: 0.942 [0.931, 0.954]). Additionally, a 30-minute shift to of time from sedentary behavior (0.701 [0.687, 0.715]), sleep (OR 0.765 [0.747, 0.784]), or LPA (0.745 [0.725, 0.766]) to MVPA was associated with lower odds of frailty.

Discussion

Our study used compositional isotemporal substitution to estimate the effect of shifting time spent in various behaviors to either LPA or MVPA on the frailty index. Overall, frail individuals spent a greater amount of time in sedentary behavior and lower amounts of time engaging in physical activity, which is consistent with other studies[10,11,33]. Our results show that shifting time from sedentary behavior to LPA; or from either sleep, sedentary behavior, or LPA to MVPA behaviors is associated with lower FI scores. Shifting time from sedentary time to MVPA was associated with a greater reduction in FI than a shift to LPA. Finally, we found that these same shifts were associated with a lower odds of frailty among older adults. These results are consistent with other studies that have used the isotemporal substitution approach[18–21].

A study by Godin et al.[18] found that a replacement of one hour of sedentary time with an equivalent amount of LPA was associated with a 0.02 [-0.02, -0.01] reduction of FI, and replacing that time with MVPA was associated with a 0.04 [-0.06, -0.03] reduction. Furthermore, replacing sedentary time with 113 minutes of LPA, or 41 minutes of MVPA, was associated with a clinically meaningful change in frailty. These results contrast somewhat with the results of our study. Despite finding that shifting 30-minutes a day from sedentary behavior to either LPA and MVPA, or shifting an equivalent time from sleep to MVPA, were associated with a reduction in FI; clinically relevant changes were only seen after replacing 311 minutes of sedentary time with LPA, or 79 minutes of MVPA. Additionally, analyses stratified by frailty severity showed pre-frail or frail individuals had a greater benefit of shifting time spent in behaviors. Other studies examining the effect of time-use on frailty have found that shifting 30-minutes of activity from sedentary behavior to MVPA has been associated with less frailty, as assessed using the Fried phenotype and frailty trait scale, as well as better physical functioning in community dwelling older adults[19,20]. There may also be benefits of lower-intensity physical activity on frailty. Nagai et. al found that shifting 30-minutes of sedentary time for LPA was associated with a 14% lower odds of frailty (OR: 0.86 [0.80–0.92]), but there was not a significant difference for a similar shift to MVPA[21]. Whereas our study found an approximate 6% decrease in odds with a shift to LPA and a 30% lower odds with a shift to MVPA. The differences between these estimates are likely impacted by the differences in baseline compositions of behaviors across the levels of frailty severity in each study. Participants in our study spent much less time in LPA and MVPA and more time in sedentary behavior and had a much higher prevalence of frailty.

There are mixed opinions on the health benefits of LPA, which have been largely understudied. Our study found that shifting time from sedentary behavior to either LPA or MVPA was associated with lower FI, but the effect was higher when shifting the time to MVPA. This supports findings from the English Longitudinal Study of Aging that LPA may be insufficient to slow the progression of frailty among non-frail adults and that vigorous intensity physical activity has the greatest impact on improving frailty progression[34]. Additionally, moderate intensity physical activity showed benefit in frailty trajectories among those over the age of 65[34]. The finding that higher-intensity activity is beneficial for improving health has been well-established. However, light intensity physical activity may still be beneficial for individuals, and time spent in LPA has been associated with better balance, flexibility, and lower limb muscle strength[19,21,35]. More importantly, it may present an achievable means of incorporating more activity into the day of older frail individuals, or those with comorbidities or other health conditions, who may be unable to safely reach higher intensities of physical activity.

Canada was the first country to release guidelines for adults regarding movement behaviors in the context of the 24-hour day[36]. In addition to their guidelines regarding sleep, sedentary, and movement behaviors, they recommended that sedentary behavior be replaced with additional physical activity, and that replacing LPA with MVPA may provide greater health benefits. This finding is consistent with our study, where we found that although shifting time to LPA from sedentary behavior was associated with small reductions in FI, the largest differences were associated with shifts to MVPA. However, there remains uncertainty on the best way to shift time spent on behaviors and how to break up sedentary time. It has been established that any physical activity throughout the day provides health benefits, regardless of whether it is a part of intentional bouts of exercise[37,38]. As such, exercise snacks, brief intermittent bouts of activity spread throughout the day, have emerged as a convenient way to incorporate more activity into one's day[39]. Exercise snacks are beneficial in improving measures of frailty, including lower extremity strength and balance, among pre-frail older adults[40,41].

It is plausible that part of our findings may be attributed to the misclassification of time spent in light versus higher intensity activity. Estimates of time spent in sedentary behavior and total sleep time are reliable using Fitbit devices, while MVPA in free living settings is often underestimated by up to 30-50%[42–47]. Additionally, there are mixed results for the accuracy of Fitbit monitors on heart rate variability. Heart rate variability has also been found to be underestimated by Fitbit devices in free-living settings, and the accuracy may be diminished when performing MVPA when compared to sedentary time or LPA[44,48]. Additionally, it has been proposed that special populations, including older adults or those with functional limitations, should have activity assessed using different cutpoints than the general population[49,50]. Differences in gait, the use of walking assists, or even differences in baseline relative fitness levels could lead to differences in relative intensity and energy expenditure despite devices measuring the same absolute amount of work. Due to the proprietary nature of the algorithms utilized by Fitbit devices in assessing physical activity intensities, we are unable to determine if time may have been misclassified, which could also influence our results.

Our study is strengthened both by the large sample size of free-living adults and the inclusion of one month of real-world behavioral activity data. This extended length of time allows for the analysis to be more representative of normal activity behaviors and less prone to fluctuations in behaviors in a shorter period. The use of a frailty index is also a strength of this study as this approach has been shown to better distinguish frailty severity[51]. However, it also has limitations. It has been noted that Fitbit devices lack the precision and accuracy of research-grade accelerometry, however, they outperform many other commercially available devices[52]. Additionally, the "bring your own device" model of collecting physical activity data in AoURP results in a largely self-selected sample of participants who already owned a Fitbit and also consented to share their data. As a result, our population is more homogeneous than the overall AoURP cohort, consisting of a majority of participants who are white and female, which affects the generalizability of our results. There have been efforts to expand this population to include more historically understudied populations by providing Fitbit devices to those who do not own one, such as in the WEAR study[53]. An additional limitation is the cross-sectional nature of the analysis. As such, there remains the possibility of reverse causality where frailty status plays a role in the amount of physical activity one engages in and vice versa.

In conclusion, our study suggests that shifting time from sedentary behavior to physical activity is associated with lower levels, and lower odds, of frailty, and that shifting time to MVPA may have a greater benefit to frailty than LPA. Further work is still needed to identify optimal time use compositions to minimize frailty in older adults. Additionally, further work is needed to identify interventions that may be useful to shift behaviors and increase the amount of activity this population engages in.

Ethics Approval

All data collection and experimental protocols for the NIH All of Us Research Program were approved by the NIH All of Us Institutional Review Board (https://allofus.nih.gov/about/who-we-are/institutional-review-board-irb-of-all-of-us). This study used only secondary, de-identified data from that program. The University of Wisconsin–Madison Health Sciences Institutional Review Board determined that this analysis does not constitute human subjects research and is exempt from IRB review.

Consent to participate

Informed consent was obtained by the NIH All of Us Research Program from all participants at the time of enrollment. No additional consent was required for this secondary analysis of de-identified data.

Authors' contributions

Christian W. Schmidt: conceptualization, formal analysis, methodology, writing – original draft, writing – review and editing. Lisa Cadmus-Bertram, Amy Cochran, Kristen A. Pickett, Sandesh Parajuli: methodology, interpretation, writing – review and editing. Brad C. Astor: conceptualization, supervision, interpretation, writing – review and editing. All authors read and approved the final version of the manuscript.

Acknowledgements

We gratefully acknowledge the All of Us participants for their contributions, without whom this research would not have been possible. We also thank the National Institutes of Health's All of Us Research Program for making available the participant data examined in this study.

References

1. O'Caoimh R, Sezgin D, O'Donovan MR, Molloy DW, Clegg A, Rockwood K, et al. Prevalence of frailty in 62 countries across the world: a systematic review and meta-analysis of population-level studies. Age Ageing. 2021 Jan 8;50(1):96–104.
2. Crocker TF, Brown L, Clegg A, Farley K, Franklin M, Simpkins S, et al. Quality of life is substantially worse for community-dwelling older people living with frailty: systematic review and meta-analysis. Qual Life Res Int J Qual Life Asp Treat Care Rehabil. 2019 Aug;28(8):2041–56.
3. Kojima G. Increased healthcare costs associated with frailty among community-dwelling older people: A systematic review and meta-analysis. Arch Gerontol Geriatr. 2019;84:103898.
4. Damluji AA, Chung SE, Xue QL, Hasan RK, Moscucci M, Forman DE, et al. Frailty and cardiovascular outcomes in the National Health and Aging Trends Study. Eur Heart J. 2021 Oct 1;42(37):3856–65.
5. He D, Wang Z, Li J, Yu K, He Y, He X, et al. Changes in frailty and incident cardiovascular disease in three prospective cohorts. Eur Heart J. 2024 Mar 27;45(12):1058–68.
6. Hanlon P, Nicholl BI, Jani BD, Lee D, McQueenie R, Mair FS. Frailty and pre-frailty in middle-aged and older adults and its association with multimorbidity and mortality: a prospective analysis of 493 737 UK Biobank participants. Lancet Public Health. 2018 July;3(7):e323–32.
7. Kojima G, Iliffe S, Walters K. Frailty index as a predictor of mortality: a systematic review and meta-analysis. Age Ageing. 2018 Mar

1;47(2):193–200.
8. Chong E, Ho E, Baldevarona-Llego J, Chan M, Wu L, Tay L, et al. Frailty in Hospitalized Older Adults: Comparing Different Frailty Measures in Predicting Short- and Long-term Patient Outcomes. J Am Med Dir Assoc. 2018 May;19(5):450-457.e3.
9. Angulo J, El Assar M, Álvarez-Bustos A, Rodríguez-Mañas L. Physical activity and exercise: Strategies to manage frailty. Redox Biol. 2020 Mar 20;35:101513.
10. Blodgett J, Theou O, Kirkland S, Andreou P, Rockwood K. The association between sedentary behaviour, moderate–vigorous physical activity and frailty in NHANES cohorts. Maturitas. 2015 Feb 1;80(2):187–91.
11. Kehler DS, Theou O. The impact of physical activity and sedentary behaviors on frailty levels. Mech Ageing Dev. 2019 June;180:29–41.
12. Baltasar-Fernandez I, Soto-Paniagua H, Alcazar J, Uceta Espinosa MI, Alegre LM, Gracía-García FJ, et al. Long-Term Effects of a 6-Week Power-Based Resistance Training and Fast Walking Interval Training Program on Physical Function, Muscle Power, Disability, and Frailty in Pre-Frail and Frail Older Adults. Gerontology. 2024;70(7):701–14.
13. Sadjapong U, Yodkeeree S, Sungkarat S, Siviroj P. Multicomponent Exercise Program Reduces Frailty and Inflammatory Biomarkers and Improves Physical Performance in Community-Dwelling Older Adults: A Randomized Controlled Trial. Int J Environ Res Public Health. 2020 May 26;17(11):3760.
14. Lin YK, Chen CY, Cheung DST, Montayre J, Lee CY, Ho MH. The relationship between physical activity trajectories and frailty: a 20-year prospective cohort among community-dwelling older people. BMC Geriatr. 2022 Nov 16;22(1):867.
15. Miatke A, Olds T, Maher C, Fraysse F, Mellow ML, Smith AE, et al. The association between reallocations of time and health using compositional data analysis: a systematic scoping review with an interactive data exploration interface. Int J Behav Nutr Phys Act. 2023 Oct 19;20(1):127.
16. Mekary RA, Willett WC, Hu FB, Ding EL. Isotemporal Substitution Paradigm for Physical Activity Epidemiology and Weight Change. Am J Epidemiol. 2009 Aug 15;170(4):519–27.
17. Dumuid D, Pedišić Ž, Stanford TE, Martín-Fernández JA, Hron K, Maher CA, et al. The compositional isotemporal substitution model: A method for estimating changes in a health outcome for reallocation of time between sleep, physical activity and sedentary behaviour. Stat Methods Med Res. 2019 Mar;28(3):846–57.
18. Godin J, Blodgett JM, Rockwood K, Theou O. Replacing Sedentary Time with Light or Moderate-Vigorous Physical Activity Across Levels of Frailty. J Aging Phys Act. 2020 Jan 1;28(1):18–23.
19. Mañas A, Del Pozo-Cruz B, Guadalupe-Grau A, Marín-Puyalto J, Alfaro-Acha A, Rodríguez-Mañas L, et al. Reallocating Accelerometer-Assessed Sedentary Time to Light or Moderate- to Vigorous-Intensity Physical Activity Reduces Frailty Levels in Older Adults: An Isotemporal Substitution Approach in the TSHA Study. J Am Med Dir Assoc. 2018 Feb;19(2):185.e1-185.e6.
20. Higueras-Fresnillo S, de la Cámara MÁ, Cabanas-Sánchez V, Martínez-Gómez D. Associations of Frailty and Physical Function with a Daily Activities Measured by a Pattern-Recognition Activity Monitor: An Isotemporal Substitution Analysis in the IMPACT65+ Study. J Nutr Health Aging. 2020;24(1):55–62.
21. Nagai K, Tamaki K, Kusunoki H, Wada Y, Tsuji S, Ito M, et al. Isotemporal substitution of sedentary time with physical activity and its associations with frailty status. Clin Interv Aging. 2018;13:1831–6.
22. Chiba I, Lee S, Bae S, Makino K, Shinkai Y, Katayama O, et al. Isotemporal Substitution of Sedentary Behavior With Moderate to Vigorous Physical Activity Is Associated With Lower Risk of Disability: A Prospective Longitudinal Cohort Study. Phys Ther. 2022 May 1;102(5):pzac002.
23. Ginsburg GS, Denny JC, Schully SD. Data-driven science and diversity in the All of Us Research Program. Sci Transl Med. 2023 Dec 13;15(726):eade9214.
24. Researcher Workbench – All of Us Research Hub [Internet]. [cited 2025 Mar 26]. Available from: https://www.researchallofus.org/data-tools/workbench/
25. Master H, Kouame A, Marginean K, Basford M, Harris P, Holko M. How Fitbit data are being made available to registered researchers in All of Us Research Program. Pac Symp Biocomput Pac Symp Biocomput. 2023;28:19–30.
26. Master H, Annis J, Huang S, Beckman JA, Ratsimbazafy F, Marginean K, et al. Association of step counts over time with the risk of chronic disease in the All of Us Research Program. Nat Med. 2022 Nov;28(11):2301–8.
27. Wong CN, Wilczek MP, Smith LH, Bosse JD, Richard EL, Cavanaugh R, et al. Frailty Among Sexual and Gender Minority Older Adults: The All of Us Database. J Gerontol A Biol Sci Med Sci. 2023 Nov;78(11):2111.
28. Mitnitski AB, Mogilner AJ, Rockwood K. Accumulation of Deficits as a Proxy Measure of Aging. Sci World J. NaN/NaN/NaN;1:323–36.
29. Blodgett J, Theou O, Kirkland S, Andreou P, Rockwood K. Frailty in NHANES: Comparing the frailty index and phenotype. Arch Gerontol Geriatr. 2015;60(3):464–70.
30. Cesari M, Gambassi G, van Kan GA, Vellas B. The frailty phenotype and the frailty index: different instruments for different purposes. Age Ageing. 2014 Jan;43(1):10–2.
31. Hoover M, Rotermann M, Sanmartin C, Bernier J. Validation of an index to estimate the prevalence of frailty among community-dwelling seniors. Health Rep. 2013;24(9):10–7.
32. Theou O, van der Valk AM, Godin J, Andrew MK, McElhaney JE, McNeil SA, et al. Exploring Clinically Meaningful Changes for the Frailty Index in a Longitudinal Cohort of Hospitalized Older Patients. J Gerontol A Biol Sci Med Sci. 2020 Sept 25;75(10):1928–34.
33. Mayo A, O'Brien MW, Godin J, Kehler DS, Kimmerly DS, Theou O. Can an active lifestyle offset the relationship that poor lifestyle behaviours have on frailty? Arch Gerontol Geriatr. 2024 Dec;127:105556.
34. Rogers NT, Marshall A, Roberts CH, Demakakos P, Steptoe A, Scholes S. Physical activity and trajectories of frailty among older adults: Evidence from the English Longitudinal Study of Ageing. PloS One. 2017;12(2):e0170878.
35. Tse ACY, Wong TWL, Lee PH. Effect of Low-intensity Exercise on Physical and Cognitive Health in Older Adults: a Systematic Review. Sports Med - Open. 2015;1(1):37.
36. Ross R, Chaput JP, Giangregorio LM, Janssen I, Saunders TJ, Kho ME, et al. Canadian 24-Hour Movement Guidelines for Adults aged 18-64 years and Adults aged 65 years or older: an integration of physical activity, sedentary behaviour, and sleep. Appl Physiol Nutr Metab Physiol Appl Nutr Metab. 2020 Oct;45(10 (Suppl. 2)):S57–102.
37. Saint-Maurice PF, Troiano RP, Matthews CE, Kraus WE. Moderate-to-Vigorous Physical Activity and All-Cause Mortality: Do Bouts Matter? J Am Heart Assoc Cardiovasc Cerebrovasc Dis. 2018 Mar 22;7(6):e007678.
38. Piercy KL, Troiano RP, Ballard RM, Carlson SA, Fulton JE, Galuska DA, et al. The Physical Activity Guidelines for Americans. JAMA. 2018 Nov 20;320(19):2020–8.
39. Jones MD, Clifford BK, Stamatakis E, Gibbs MT. Exercise Snacks and

Other Forms of Intermittent Physical Activity for Improving Health in Adults and Older Adults: A Scoping Review of Epidemiological, Experimental and Qualitative Studies. Sports Med. 2024 Apr 1;54(4):813–35.
40. Western MJ, Welsh T, Keen K, Bishop V, Perkin OJ. Exercise snacking to improve physical function in pre-frail older adult memory clinic patients: a 28-day pilot study. BMC Geriatr. 2023 Aug 4;23(1):471.
41. Liang IJ, Perkin OJ, Williams S, McGuigan PM, Thompson D, Western MJ. The Efficacy of 12-Week Progressive Home-Based Strength and Tai-Chi Exercise Snacking in Older Adults: A Mixed-Method Exploratory Randomised Control Trial. J Frailty Aging. 2024;13(4):572–81.
42. Redenius N, Kim Y, Byun W. Concurrent validity of the Fitbit for assessing sedentary behavior and moderate-to-vigorous physical activity. BMC Med Res Methodol. 2019 Feb 7;19(1):29.
43. Liang Z, Chapa Martell MA. Validity of Consumer Activity Wristbands and Wearable EEG for Measuring Overall Sleep Parameters and Sleep Structure in Free-Living Conditions. J Healthc Inform Res. 2018 Apr 20;2(1–2):152–78.
44. Bai Y, Tompkins C, Gell N, Dione D, Zhang T, Byun W. Comprehensive comparison of Apple Watch and Fitbit monitors in a free-living setting. PloS One. 2021;16(5):e0251975.
45. Degroote L, De Bourdeaudhuij I, Verloigne M, Poppe L, Crombez G. The Accuracy of Smart Devices for Measuring Physical Activity in Daily Life: Validation Study. JMIR MHealth UHealth. 2018 Dec 13;6(12):e10972.
46. Gomersall SR, Ng N, Burton NW, Pavey TG, Gilson ND, Brown WJ. Estimating Physical Activity and Sedentary Behavior in a Free-Living Context: A Pragmatic Comparison of Consumer-Based Activity Trackers and ActiGraph Accelerometry. J Med Internet Res. 2016 Sept 7;18(9):e239.
47. Collins JE, Yang HY, Trentadue TP, Gong Y, Losina E. Validation of the Fitbit Charge 2 compared to the ActiGraph GT3X+ in older adults with knee osteoarthritis in free-living conditions. PLoS ONE. 2019 Jan 30;14(1):e0211231.
48. Fuller D, Colwell E, Low J, Orychock K, Tobin MA, Simango B, et al. Reliability and Validity of Commercially Available Wearable Devices for Measuring Steps, Energy Expenditure, and Heart Rate: Systematic Review. JMIR MHealth UHealth. 2020 Sept 8;8(9):e18694.
49. Strath SJ, Pfeiffer KA, Whitt-Glover MC. Accelerometer Use with Children, Older Adults, and Adults with Functional Limitations. Med Sci Sports Exerc. 2012 Jan;44(1S):S77.
50. Gorman E, Hanson HM, Yang PH, Khan KM, Liu-Ambrose T, Ashe MC. Accelerometry analysis of physical activity and sedentary behavior in older adults: a systematic review and data analysis. Eur Rev Aging Phys Act. 2014 Apr 1;11(1):35–49.
51. Clegg A, Young J, Iliffe S, Rikkert MO, Rockwood K. Frailty in elderly people. Lancet Lond Engl. 2013 Mar 2;381(9868):752–62.
52. Brooke SM, An HS, Kang SK, Noble JM, Berg KE, Lee JM. Concurrent Validity of Wearable Activity Trackers Under Free-Living Conditions. J Strength Cond Res. 2017 Apr;31(4):1097–106.
53. WEAR | Join All of Us [Internet]. [cited 2024 Nov 1]. Available from: https://www.joinallofus.org/wear-study