Postural Transitions during Activities of Daily Living Could Identify Frailty Status: Application of Wearable Technology to Identify Frailty during Unsupervised Condition

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Keywords

Frailty · Postural transition · Physical activity · Wearable sensor · Cautious sitting · Quick sitting · Walking to sitting · Telehealth

Abstract

Background: Impairment of physical function is a major indicator of frailty. Functional performance tests have been shown to be useful for identification of frailty in older adults. However, these tests are often not translatable into unsupervised and remote monitoring of frailty status at home and/or community settings. **Objective:** In this study, we explored daily postural transition quantified using a chest-worn wearable technology to identify frailty in community-dwelling older adults. **Methods:** Spontaneous daily physical activity was monitored over 24 h in 120 community-dwelling elderly (age: 78 ± 8 years) using an unobtrusive wearable sensor (PAMSys™, BioSensics LLC, Watertown, MA, USA). Participants were classified as non-frail and pre-frail/frail using Fried's criteria. A validated software package was used to identify body postures and postural transition between each

independent postural activity such as sit-to-stand, stand-to-sit, stand-to-walk, and walk-to-stand. The transition from walking to sitting was further classified as quick sitting and cautious sitting based on presence/absence of a standing posture pause between sitting and walking. A general linear model univariate test was used for between-group comparison. Pearson's correlation was used to determine the association between sensor-derived parameters and age. Logistic regression model was used to identify independent predictors of frailty. **Results:** According to Fried's criteria, 63% of participants were pre-frail/frail. The total number of postural transitions, stand-to-walk, and walk-to-stand were, respectively, 25.2, 30.2, and 30.6% lower in the pre-frail/frail group when compared to the non-frail group ($p < 0.05$, Cohen's $d = 0.73$ – 0.79). Furthermore, the ratio of cautious sitting was significantly higher by 6.2% in pre-frail/frail compared to non-frail ($p = 0.025$, Cohen's $d = 0.22$). Total number of postural transitions and the ratio of cautious sitting also showed sig-

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nificant negative and positive correlations with age, respectively ($r = -0.51$ and 0.29 , $p < 0.05$). After applying a logistic regression model, among tested parameters, walk-to-stand (odds ratio [OR] = 0.997 , $p = 0.013$), quick sitting (OR = 1.036 , $p = 0.05$), and age (OR = 1.073 , $p = 0.016$) were recognized as independent variables to identify frailty status. **Conclusions:** This study demonstrated that daily number of specific postural transitions such as walk-to-stand and quick sitting could be used for monitoring frailty status by unsupervised monitoring of daily physical activity. Further study is warranted to explore whether tracking the daily number of specific postural transitions is also sensitive to track change in the status of frailty over time.

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Introduction

The geriatric syndrome of “frailty” is one of the greatest challenges facing our aging population. It is associated with adverse health outcomes, dependency, institutionalization, and mortality [1, 2]. The negative impact of frailty can be reduced by its early detection and providing timely interventions and exercise routines [3, 4]. Impairment in daily physical activities (PA) is a major indicator of frailty [1, 5, 6], and is commonly measured as a phenotype marker of frailty [1]. Most studies have used subjective or semi-objective (i.e., stopwatch) tests, despite limitations including observer bias and nonobjective parameters [7, 8]. Other studies have used laboratory-based motion-tracking systems for frailty diagnostics [7, 8]. These technologies are impractical for routine screening, and are not translatable into home and community settings. Objective instrumented assessments for in-home frailty screening have not been adequately developed or validated.

Recently, advances in wearable technology have provided the opportunity of longitudinal and detailed assessment of daily PA monitoring in unsupervised and natural living environments, such as assisted living centers and individuals' homes [9–12], and, therefore, objective PA assessment in older adults earned more attention. Theou et al. [13] demonstrated that step numbers recorded by an accelerometer had the strongest correlation with frailty and were 75% less in frail compared to non-frail individuals. More recently, Schwenk et al. [14] quantified physical activity more specifically based on duration of lying, sitting, standing, and walking; study results suggested that the percentage of sitting within a 24-h monitoring period was higher in frail compared to non-frail participants.

Beyond duration of physical activity mentioned above, postural transitions, including rising from or sitting down on a chair are basic motor tasks that each individual, regardless of physical condition, is obliged to perform several times during a day. Assessing postural transitions is especially important in older adults, since they may change the execution of these motor tasks due to lack of strength or to increase their safety, in particularly older frail adults [15]. Previous studies demonstrated differences among frail and non-frail older adults in required time and trunk motion for performing postural transitions within supervised clinical settings [16, 17], as well as long-term PA monitoring [14]. However, to the best of our knowledge, no research has objectively examined the number of postural transitions during 24-h monitoring of daily PA for the purpose of frailty identification using motion sensor data. Furthermore, previous work limited the definition of postural transition to simple transfer from sit to stand or vice versa, whereas measuring additional parameters such as cautious sitting (with significant standing pause before sitting) is possible, when studying motor performance in older adults, and may add important new information.

The purpose of the current observational study was to monitor and assess daily postural transition differences by frailty level, in community-dwelling older adults. We have expanded the definition of postural transition to include not only the transition between sitting and standing (i.e., sit-to-stand and stand-to-sit), but also the transition between sitting/standing and walking (i.e., stand-to-walk, walk-to-stand, sit-to-walk, and walk-to-sit). Furthermore, we classified walk-to-sit into cautious sitting (transition to sitting from walking with a long standing pause) and quick sitting (transition to sitting from walking without a pause or with a short standing pause). We hypothesized that in addition to the daily number of postural transitions, qualitative data from postural transitions, specifically number of transitions between physically demanding postures (e.g., walk-to-stand, stand-to-walk, walk-to-sit, and sit-to-walk) and the number of cautious sitting and/or quick sitting would distinguish non-frail from pre-frail/frail elders.

Methods

Participants

Reported data were extracted from the NIH-funded Arizona Frailty Cohort Study (ClinicalTrials.gov, identifier NCT01880229), an observational descriptive study of individuals 65 years or older performed in Tucson, AZ (the Arizona Frailty Cohort sample has

Fig. 1. Shirt-embedded sensor (PAMSys™; BioSensics LLC) for daily physical activity monitoring. The sensor is placed on the inside of a comfortable washable and breathable t-shirt (PAM-Shirt™). Illustration shows the sensor on the outside of the shirt.

been previously well described) [14]. A sample of 120 cognitively intact community-dwelling older adults (aged 65 years and older) without gait or mobility disorders were recruited from primary, secondary, and tertiary health-care settings, community providers, assisted living facilities, retirement homes, and aging service organizations. The University of Arizona Institutional Review Board approved the study, and written informed consent according to the principles expressed in the Declaration of Helsinki [18] was obtained from all subjects before participation. Exclusion criteria included being non-ambulatory (unable to walk a distance of 20 m with or without an assistive device) and cognitive impairment as confirmed by a Mini-Mental State Examination [19] score of 23 or less. Foot pain was evaluated using the self-reported visual analogue scale (0–10 scale). Fear of falling was assessed using the validated 16-item Fall Efficacy Scale-International (FES-I) [20].

Frailty Assessment

Participants were classified as non-frail and pre-frail/frail using the validated Fried's frailty index [1]. Fried's criteria included slowness (walking speed for a 4.6-m distance), weakness (handgrip strength), and self-reported low physical activity, exhaustion, and unintentional weight loss. Individuals with 1 or more positive frailty criteria were considered pre-frail/frail, and those with none of the above criteria were considered non-frail.

Sensor-Derived Monitoring of Daily Physical Activity

Spontaneous daily PA were recorded for a period of 48 h using an unobtrusive shirt-embedded sensor (PAMSys™, BioSensics LLC, Watertown, MA, USA), where the first 24 h was used for the purpose of this study; the sensor pocket was located at the sternum (Fig. 1). The PAMSys system contains a 3-axis accelerometer (sampling frequency of 50 Hz) and a built-in memory for recording long-term data. A previously developed and validated computer program was used to identify body postures, including lying, sitting, standing, and walking [9, 21, 22]. High sensitivity and specificity of 87–99 and 87–99.7% have been reported for PAMSys for identification of body postures in older adults [9, 21, 22]. Details regarding posture detection algorithms are described in our previous publications [9, 21, 22].

In addition to previously developed software for detecting body postures, additional software algorithm was developed to identify and count the number of postural transitions including sit-to-stand, sit-to-walk, stand-to-sit, stand-to-walk, walk-to-sit, and walk-to-stand using posture data and their corresponding time stamps. The developed code also identifies transitions from walking to sitting posture, including: (1) quick sitting: walk-to-sit without any long-standing pause (<5 s); and (2) cautious sitting: walking, a standing pause (≥5 s), and then sitting. The ratio of cautious sitting was estimated as follows:

Ratio of cautious sitting (%)

$$= \frac{\text{number of cautious sitting transitions}}{\text{number of cautious sitting transitions} + \text{number of quick sitting}} \times 100. \quad (1)$$

Statistical Analysis

The independent-sample *t* test or χ^2 test was used to evaluate between-group differences in demographics and health parameters. Between-group comparisons for postural transitions parameters were done using general linear model tests. Post hoc Sidak adjustment was used to adjust *p* values based on age, gender, or body mass index (BMI). Between-group difference effect size was assessed using Cohen's *d*. Cohen's *d* values of 0.2, 0.5, and 0.8 were considered as small, medium, and large effect size, respectively [23]. Pearson's correlation was used to determine the association between sensor-derived parameters with continuous variables including age, FES-I, and foot pain scores. Cutoffs of 0.01–0.19: very weak, 0.20–0.39: weak, 0.40–0.59: moderate, 0.60–0.79: strong, and 0.80–1.00: very strong were selected for correlations [24]. Independent predictors of frailty among participants' demographics and sensor-derived parameters were determined using the logistic regression model (forward conditional model) assuming frailty status as independent variable. Age, BMI, gender, and sensor-derived postural transition variables were used as independent variables. The odds ratio (OR) for the significant predictors was estimated. All the analyses were performed using SPSS version 24 (IBM, Chicago, IL, USA), with a significance level of *p* < 0.050.

Results

Data for 1 frail subject (<1%) were excluded from data analysis based on percentage of walking during 24 h, as Tukey's outlier labeling method marked it as beyond

Table 1. Demographic and health information of participants expressed as mean $\pm$ standard deviation or percentage across non-frail and pre-frail/frail groups categorized using the Fried index

Characteristic	Non-frail	Pre-frail/frail	<i>p</i> value
Participants, <i>n</i> (%)	43 (36.2)	76 (63.8)	–
Male, <i>n</i> (%)	7 (16.3)	18 (23.7)	0.341
Age, years	74.23 $\pm$ 6.15	80.70 $\pm$ 8.68	<0.001
Weight, kg	66.17 $\pm$ 15.95	76.50 $\pm$ 18.35	0.002
Height, cm	161.73 $\pm$ 6.95	161.52 $\pm$ 9.38	0.90
BMI	25.25 $\pm$ 5.77	29.33 $\pm$ 6.63	0.001
MMSE score	29.16 $\pm$ 1.15	28.67 $\pm$ 1.57	0.075
Fear of falling (7–49 scale ^a)	19.58 $\pm$ 6.34	28.84 $\pm$ 10.94	<0.001
Foot pain (0–10 scale ^b)	0.61 $\pm$ 1.01	1.20 $\pm$ 2.08	0.040

Values in bold indicate statistical significance ($p < 0.05$). MMSE, Mini-Mental State Examination. ^a Short Fall Efficacy Scale-International (FES-I). ^b Visual analogue scale between 0 and 10.

Table 2. Between-group comparisons adjusted for BMI and gender with no adjustment for age

Parameter	Non-frail (<i>n</i> = 43)	Pre-frail/ frail (<i>n</i> = 76)	Effect size	<i>p</i> value ^a	Correlation with age	Correlation with FES-I ^b	Correlation with foot pain ^c
Total number of transitions, <i>n</i>	1,174 $\pm$ 468	878 $\pm$ 333	0.73	0.001	$r = -0.51$ $p < \mathbf{0.001}$	$r = -0.24$ $p < \mathbf{0.001}$	$r = -0.09$ $p = 0.321$
Sit-to-stand, <i>n</i>	85 $\pm$ 45	83 $\pm$ 40	0.07	0.789	$r = -0.19$ $p = \mathbf{0.040}$	$r = -0.11$ $p = \mathbf{0.009}$	$r = -0.04$ $p = 0.679$
Sit-to-walk, <i>n</i>	23 $\pm$ 11	23 $\pm$ 9	0.04	0.941	$r = -0.18$ $p = \mathbf{0.044}$	$r = 0.03$ $p = 0.769$	$r = -0.01$ $p = 0.981$
Stand-to-sit, <i>n</i>	64 $\pm$ 37	66 $\pm$ 34	0.06	0.288	$r = -0.05$ $p = 0.554$	$r = -0.03$ $p = 0.703$	$r = -0.01$ $p = 0.972$
Stand-to-walk, <i>n</i>	475 $\pm$ 208	332 $\pm$ 148	0.79	<0.001	$r = -0.53$ $p < \mathbf{0.001}$	$r = -0.25$ $p = \mathbf{0.007}$	$r = -0.10$ $p = 0.266$
Quick sitting, <i>n</i>	45 $\pm$ 16	40 $\pm$ 15	0.29	0.097	$r = -0.49$ $p < \mathbf{0.001}$	$r = -0.190$ $p = \mathbf{0.039}$	$r = -0.09$ $p = 0.315$
Walk-to-stand, <i>n</i>	453 $\pm$ 202	314 $\pm$ 141	0.79	<0.001	$r = -0.51$ $p < \mathbf{0.001}$	$r = -0.24$ $p = \mathbf{0.010}$	$r = -0.10$ $p = 0.286$
Ratio of cautious sitting, %	47 $\pm$ 14	49 $\pm$ 12	0.22	0.025	$r = 0.29$ $p = \mathbf{0.002}$	$r = 0.147$ $p = 0.111$	$r = 0.12$ $p = 0.185$

Correlations between sensor-derived parameters and age, fear of falling, and foot pain are reported. Values in bold indicate significant difference ($p < 0.05$). ^a Adjustment for multiple comparisons: Sidak. ^b Short Fall Efficacy Scale-International (FES-I; fear of falling) ^c Visual analogue scale between 0 and 10.

physiological range [25]. Using Fried's frailty criteria, 43 of participants were classified as non-frail (36%), and 76 were categorized as pre-frail/frail (64%). Demographic and clinical characteristics of participants are listed in Table 1. In general, pre-frail/frail participants were older and demonstrated greater fear of fall and foot pain scores ($p < 0.050$).

Association between Sensor-Derived Postural Transitions and Frailty Status

Table 2 summarizes comparisons of postural transition parameters between frailty groups after adjustment for BMI and gender. Results showed that the total number of transitions, stand-to-walk, and walk-to-stand, and the ratio of cautious sitting were all significantly different

Table 3. Between-group comparisons with adjustment for age

Parameter	Non-frail (<i>n</i> = 43)	Pre-frail/ frail (<i>n</i> = 76)	<i>p</i> value ^a
Total transitions, <i>n</i>	1,174±468	878±333	0.032
Sit-to-stand, <i>n</i>	85±45	83±40	85±40
Sit-to-walk, <i>n</i>	23±11	23±9	0.664
Stand-to-sit, <i>n</i>	64±37	66±34	0.568
Stand-to-walk, <i>n</i>	475±208	332±148	0.011
Quick sitting, <i>n</i>	45±16	40±15	0.570
Walk-to-stand, <i>n</i>	453±202	314±141	0.011
Ratio of cautious sitting, %	47±14	49±12	0.363

Values in bold indicate statistical significance ($p < 0.05$).
^a Adjustment for multiple comparisons: Sidak.

between non-frail and pre-frail/frail ($p < 0.05$). The total number of transitions, stand-to-walk, and walk-to-stand were, respectively, 25.2, 30.2, and 30.6% less in the pre-frail/frail group compared to the non-frail group (Table 2); medium effect sizes were measured for all these differences (Cohen's $d = 0.73$ – 0.79). Furthermore, the ratio of cautious sitting was significantly higher by 6.2% in the pre-frail/frail compared to the non-frail group ($p = 0.025$, Cohen's $d = 0.22$). When adjusting the results for age, the total number of transitions, stand-to-walk, and walk-to-stand were still significantly different between the groups (Table 3). The ratio of cautious sitting became insignificant after adjustment by age. After applying a logistic regression model, among tested parameters, walk-to-stand (OR = 0.997 $p = 0.013$), quick sitting (OR = 1.036, $p = 0.05$), and age (OR = 1.073, $p = 0.016$) were recognized as independent variables to identify frailty status ($p = 0.000$, Cox & Snell $R^2 = 0.21$).

Significant differences were observed in the same postural transition parameters (i.e., total number of transitions, stand-to-walk, and walk-to-stand) between the groups with and without weakness as well as groups with and without slowness Fried's phenotypes ($p < 0.001$, Table 4). The total daily postural transition number also had moderate to large effect sizes to separate those with slowness ($d = 0.76$, $p < 0.001$) and those with weakness ($d = 0.80$, $p < 0.001$). A moderate effect size was observed for identifying those with low physical activity based on the daily postural transition number, but the trend did not achieve statistical significance in our sample ($d = 0.51$, $p = 0.057$). This could be explained by the fact that the number of cases with a positive low physical activity phenotype ($n = 18$) is much less than the number of cases with

positive weakness ($n = 33$) and slowness ($n = 52$) phenotypes. As for the type of postural transition, stand-to-walk had the highest effect sizes for identifying those with slowness and weakness ($d = 0.81$ – 0.84 , $p < 0.001$).

Association between Sensor-Derived Postural Transitions and Age

The daily total number of postural transitions (irrespective of its type) had a negative correlation with age ($r = -0.51$, $p < 0.001$), suggesting that the amount of daily postural transitions is decreasing with increasing age. All studied postural transitions except stand-to-sit, had significant but weak-to-moderate negative correlations with age ($r = -0.19$ to -0.53 , $p < 0.050$), indicating that the likelihood of having postural transitions including sit-to-stand, quick sitting, stand-to-walk, and walk-to-stand decreases with increasing age. The ratio of cautious sitting also demonstrated a weak but significant positive correlation with age ($r = 0.29$, $p = 0.002$), indicating that with increasing age the likelihood of having more cautions sitting per day is increasing.

Association between Sensor-Derived Postural Transitions, Fear of Falling, and Foot Pain

Fear of falling was weakly associated with almost all types of postural transitions, except for sit-to-walk, stand-to-sit, and the ratio of cautious sitting ($r = -0.11$ to -0.25 , $p < 0.050$, Table 2), indicating that with increasing fear of falling, the daily number of postural transitions tends to decrease. None of extracted parameters was significantly correlated with the foot pain score in our sample (Table 2).

Discussion

The goal of this observational research was to examine whether monitoring the number of daily postural transitions among older adults could be used as an alternative frailty phenotype. The long-term goal of this study was to evaluate whether monitoring postural transition behavior could be used as a sensitive physical biomarker to identify and track frailty status during non-supervised condition and for telehealth and remote monitoring applications. Although previous studies highlighted the differences in transition from standing to sitting, and sitting to standing, between frailty groups within the supervised condition [16, 26, 27], to the best of our knowledge, this is the first study that objectively examined the "number" of different postural transitions during long-term unsupervised monitoring of daily PA for frailty classification.

Table 4. Comparison of sensor-derived postural transitions between different Fried's phenotypes (slowness, weakness, low physical activity, exhaustion, and weight loss)

	Total transitions, <i>n</i>	Sit-to-stand, <i>n</i>	Sit-to-walk, <i>n</i>	Stand-to-sit, <i>n</i>	Stand-to-walk, <i>n</i>	Quick sitting, <i>n</i>	Walk-to-stand, <i>n</i>	Ratio of cautious sitting, %
<i>Slowness</i>								
No (<i>n</i> = 67)	1,111±421	86±44	23±10	66±38	444±187	44±15	423±182	47±14
Yes (<i>n</i> = 52)	823±339	81±38	22±9	65±31	306±151	39±16	289±142	50±11
<i>p</i> value (<i>d</i>)	<i>p</i> < 0.001 (0.76)	<i>p</i> = 0.485 (0.13)	<i>p</i> = 0.419 (0.15)	<i>p</i> = 0.873 (0.03)	<i>p</i> < 0.001 (0.81)	<i>p</i> = 0.046 (0.37)	<i>p</i> < 0.001 (0.82)	<i>p</i> = 0.214 (0.23)
<i>Weakness</i>								
No (<i>n</i> = 86)	1,066±420	86±44	23±9	65±37	422±188	44±16	401±181	47±13
Yes (<i>n</i> = 33)	773±302	77±33	22±10	64±29	284±135	35±13	270±131	52±11
<i>p</i> value (<i>d</i>)	<i>p</i> < 0.001 (0.80)	<i>p</i> = 0.251 (0.22)	<i>p</i> = 0.381 (0.18)	<i>p</i> = 0.849 (0.04)	<i>p</i> < 0.001 (0.84)	<i>p</i> = 0.004 (0.62)	<i>p</i> < 0.001 (0.82)	<i>p</i> = 0.084 (0.37)
<i>Low physical activity</i>								
No (<i>n</i> = 101)	1,015±412	86±43	23±9	67±37	396±186	42±15	377±180	48±13
Yes (<i>n</i> = 18)	815±372	72±32	22±11	55±21	313±162	39±21	296±152	49±11
<i>p</i> value (<i>d</i>)	<i>p</i> = 0.057 (0.51)	<i>p</i> = 0.198 (0.36)	<i>p</i> = 0.580 (0.13)	<i>p</i> = 0.065 (0.39)	<i>p</i> = 0.079 (0.47)	<i>p</i> = 0.504 (0.19)	<i>p</i> = 0.076 (0.48)	<i>p</i> = 0.943 (0.02)
<i>Exhaustion</i>								
No (<i>n</i> = 93)	1,018±420	85±42	23±10	66±35	398±188	42±16	379±181	49±13
Yes (<i>n</i> = 26)	867±360	80±41	23±11	63±37	330±166	40±16	313±160	48±12
<i>p</i> value (<i>d</i>)	<i>p</i> = 0.097 (0.39)	<i>p</i> = 0.606 (0.12)	<i>p</i> = 0.841 (0.04)	<i>p</i> = 0.718 (0.08)	<i>p</i> = 0.097 (0.38)	<i>p</i> = 0.510 (0.15)	<i>p</i> = 0.094 (0.39)	<i>p</i> = 0.892 (0.03)
<i>Weight loss</i>								
No (<i>n</i> = 111)	981±414	84±42	23±10	66±36	381±186	41±16	362±179	49±13
Yes (<i>n</i> = 8)	1,048±392	86±35	22±8	59±21	421±179	49±15	394±170	45±11
<i>p</i> value (<i>d</i>)	<i>p</i> = 0.651 (0.17)	<i>p</i> = 0.885 (0.06)	<i>p</i> = 0.716 (0.14)	<i>p</i> = 0.612 (0.22)	<i>p</i> = 0.552 (0.22)	<i>p</i> = 0.195 (0.48)	<i>p</i> = 0.629 (0.18)	<i>p</i> = 0.495 (0.27)

The highest effect size is highlighted in italics, when the difference achieved statistical significance. The values in bold highlight statistical significance. *d*, Cohen's effect size *d*.

Postural Transition Alterations with Age and Frailty

The results of this study suggest that a lower total number of postural transitions irrespective of their type (i.e., sitting or standing) per day, a high ratio of cautious sitting and a low number of stand-to-walk and walk-to-stand are sensitive indicators of frailty. A previous study suggested that postural transition is a more reliable measurement of PA in older adults and is least influenced by environmental conditions unlike total number of steps and duration of walking [28]. Thus, characterization of postural transition as an alternative frailty phenotype is highly valuable and could open new avenues to design a telehealth monitoring system to remotely track the frailty status of older adults at their own home and in the unsupervised condition. However, the cutoff values to identify and track frailty status based on daily postural

transition parameters need to be addressed in a larger longitudinal study.

The observed fewer postural transitions among pre-frail/frail individuals may be related to compromised postural transition performance, as well as sedentary behavior among frail people, in general. Several factors including strength of lower-extremity muscles, impaired sensation and balance, visual impairments, or even psychological factors such as anxiety can influence sit-to-stand and stand-to-sit performance; among them, lack of lower-extremity strength has been reported as the strongest predictor of poor performance for this motor task [29]. Therefore, the sit-to-stand test has been used as a measure of lower-extremity strength in older adults [30, 31]. In addition to muscle weakness, studies have suggested that lack of physical activity may lead to frailty and,

conversely, frailty may lead to further physical inactivity, creating a vicious cycle of deconditioning and increased risk [1, 32]. In our previous work, spontaneous daily physical activity was monitored using an accelerometry-based wearable sensor, and we demonstrated that among pre-frail and frail participants, the daily number of steps and daily percentage of walking duration are lower, while the daily percentage of sitting duration is higher compared to non-frail participants [14]. Current results suggest that different patterns of daily postural transitions such as walk-to-stand and stand-to-walk also differ by frailty group. To examine whether the fewer postural transitions are related to less daily life activities, we have retrospectively estimated the correlation between the number of daily postural transitions and percentage of sedentary postures including percentage of lying and sitting postures using the PA data reported in our previous study [14]. Results suggest a non-significant correlation with daily percentage of the lying posture ($r = -0.15$, $p = 0.116$) and a weak but significant negative correlation with daily percentage of sitting ($r = -0.38$, $p < 0.001$). This suggests that a lower daily number of postural transitions could partially be related to a higher duration of sitting or less daily life activity, which is a natural consequence of frailty.

Sitting Strategy Alterations with Age and Frailty

The daily number of cautious sitting was objectively assessed in the current study as the transition from walking to sitting with a standing pause before sitting. As hypothesized, the ratio of cautious sitting was significantly higher in the pre-frail/frail group compared to the non-frail group. The longer standing pause measured among pre-frail/frail participants may be because of either longer turning duration or duration needed for postural adjustment and preparation for sitting. Previous work suggests longer turning duration in frail compared to non-frail older adults during the timed up-and-go test [26]. Cautious sitting may be also related to poor balance, impaired local muscle balance control, and higher dependency on central somatosensory feedback, which have all been observed in frail individuals [33–35].

While the ratio of cautious sitting is a significant predictor of frailty status, it has a poor effect size to identify different phenotypes of Fried's criteria. On the other hand, other postural transition types such as stand-to-walk, and walk-to-stand, as well as total number of postural transition irrespective of type, have moderate-to-large effect sizes to identify those with weakness and slowness phenotypes. This suggests that assessing the daily

number of different types of postural transitions could be useful in identifying different phenotypes of physical frailty (i.e., slowness, weakness, low activity).

Interestingly, foot pain was not a predictor of cautious sitting, indicating that frailty status irrespective of pain intensity or foot problems may contribute to increasing the likelihood of cautious sitting. Our results also suggest that fear of falling may contribute in increasing the likelihood of cautious sitting, but its impact compared to frailty status may be less significant.

Rather than a balance problem (or maybe in response to poor balance), kinematic analysis of older frail individuals suggests that conservative postural transition is a mechanism they often employ to prevent fall; we are unable to state whether this is an intentional strategy to prevent falls or it is because of deconditioning, instability and/or weakness. Similar to what was observed within the current study, Weiss et al. [36] demonstrated that older adult fallers perform walking, sit-to-stand, and stand-to-sit tasks more cautiously, as measured by a lower range and jerk (i.e., acceleration amplitude) of trunk motion, to increase the stability and reduce the risk of falling. Cautious motion has also been observed among older adults compared to healthy young control for obstacle crossing; older adults minimize the distance between center of pressure and center of mass to reduce the burden on lower extremity joints and minimize the risk of fall during obstacle crossing [37]. Overall, results from the current study suggest that similar to supervised experiments, older frail adults move more cautiously in unsupervised environment of their home.

Limitations and Future Direction

The small number of frail participants ($n = 18$) is a limitation of this study; pre-frail and frail groups were combined to increase the statistical power. Further, in this investigation the association between frailty and sensor-derived daily PA parameters was studied using a cross-sectional study design. As such, results from the current study, although promising, should be confirmed in a larger sample size within a prospective study design. This is of interest for the effective use of interventions as well as preventive strategies in the non-frail and pre-frail groups to prevent frailty [38]. In the current study, no direct measure of lower-extremity muscle strength is available. As we found associations between less postural transition and a higher daily ratio of cautious sitting with weakness, it would be interesting to study muscle strength and activation during walking to sitting transition to better understand the underlying mechanism of cautious sit-

ting and its association with frailty, weakness, and intention. Also, it would be interesting to capture other potential confounders such as contextual events (e.g., chatting and manipulating an object) through self-report questionnaires or using additional sensors (e.g., microphone) that can contribute to a pause before sitting.

In a recent study, we have demonstrated that motor performance (e.g., duration of sit-to-stand, gait speed, etc.) assessed in clinic (supervised assessment) has significant agreement with motor performance assessed in home (unsupervised assessment) among healthy older adults. But this association is diminished for patients suffering from Parkinson's disease [39]. Thus, it would be interesting to explore whether the association between supervised motor assessment and unsupervised motor assessment could be different based on frailty level. If this hypothesis is confirmed, it may suggest that unsupervised assessment may provide supplementary information compared to in-clinic assessment for those who are suffering from frailty.

Summary of Findings and Clinical Implications

Measures such as gait speed and gait variability within clinical settings are the most common approach to objectively assess frailty [16, 17, 26, 40, 41]. However, they required supervised assessment in a dedicated environment. To our best of knowledge, this is the first study that proposed quantification of daily postural transitions as alternative frailty phenotypes. These parameters were measured using a practical wearable sensor during 24-h activities of daily living, and data were captured in subjects' natural living environments (e.g., assisted living centers and individuals' homes).

Current results suggest that monitoring daily physical activity, specifically quantification of postural transitions using inertial wearable sensor may provide an objective and practical tool for assessing frailty during unsupervised condition in an in-home or assisted living setting. Furthermore, the transition to activity-demanding postures such as daily walk-to-stand and quick sitting postural transitions are independent predictors of frailty and could provide additional insight, other than the traditional definition of postural transition such as sit-to-stand and stand-to-sit.

Although the proposed daily activity-derived frailty phenotypes may not be as accurate as supervised phenotype tests, such as the Fried's index, it has the advantage of capturing frailty status under unsupervised condition and in-home remote assessment, and therefore reduces the burden of testing (e.g., traveling to a clinic for frailty

assessment). Also, using in-home assessment is beneficial to target homebound elderly adults, who are often excluded from clinical studies. The daily physical activity monitoring may be useful for "screening" the frailty status progress when assessing the potential benefit of frailty intervention programs; however, a longitudinal setup is required to assess the power of physical activity monitoring over a longer period for studying frailty status progress. Lastly, the observed relationship between a lower number of postural transitions and weakness, in agreement with previous work [32], suggests that customized balance and strength training exercise routines might be beneficial for re-conditioning and slowing the progression of frailty [42, 43].

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Disclosure Statement

A patent pending has been filed, which includes part of algorithms described in this study for assessing frailty status using physical activity monitoring (US Patent App. 14/671,980). The patent is owned by the University of Arizona, and Saman Parvaneh, Jane Mohler, and Bijan Najafi are listed as co-inventors on this patent pending. No other conflict of interest was reported by other authors.

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