HHS Public Access
Author manuscript
Gerontology. Author manuscript; available in PMC 2018 March 11.

Published in final edited form as:
Gerontology. 2017 ; 63(5): 479–487. doi:10.1159/000460292.

Postural transitions during activities of daily living could identify frailty status – Application of wearable technology to identify frailty during unsupervised condition

Saman Parvaneh[1,2,3], **Jane Mohler**[1,2], **Nima Toosizadeh**[1,2], **Gurtej Singh Grewal**[1], and **Bijan Najafi**[1,2,4]

[1]Interdisciplinary Consortium on Advanced Motion Performance (iCAMP), Department of Surgery, College of Medicine, University of Arizona, Tucson, USA

[2]Arizona Center on Aging, University of Arizona, Tucson, USA

[3]Philips Research North America, Cambridge, USA

[4]Interdisciplinary Consortium on Advanced Motion Performance (iCAMP), Michael E. DeBakey Department of Surgery, Baylor College of Medicine, Houston, Texas, USA

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 hours in 120 community dwelling (age: 78±8 years) using an unobtrusive wearable sensor (PAMSys™, Biosensics LLC). Participants were classified as non-frail and pre-frail/frail using Fried's criteria. A validated software was used to identify body postures and postural transition between each independent postural activities such as sit-to-stand, stand-to-sit, stand-to-walk, and walk-to-stand. 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. General linear model univariate test was used for between groups comparison. Pearson's correlation was used to determine the association between sensor-derived parameters with age. Logistic regression model was used to identify independent predictors of frailty.

Corresponding author: Bijan Najafi, PhD, Interdisciplinary Consortium on Advanced Motion Performance (iCAMP), Michael E. DeBakey Department of Surgery, Baylor College of Medicine, One Baylor Plaza, MS: BCM390, Houston, TX 77030. Phone: +1 (713) 798- 7536, bijan.najafi@bcm.edu. Alternative Corresponding author: Jane Mohler, PhD, Arizona Center on Aging, University of Arizona, Tucson, USA., jmohler@aging.arizona.edu.

Conflict of Interest: 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

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 non-frails (p<0.05, Cohen's d=0.73–0.79). Furthermore, 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 ratio of cautious-sitting also showed significant 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 (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 warrant to explore whether tracking daily number of specific postural transitions are also sensitive to track change in status of frailty over time.

Keywords

Frailty; Postural Transition; Physical Activity; Wearable; Cautious-Sitting; Quick-Sitting; Walking to Sitting; Telehealth

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]. 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 non-objective 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 physical activities monitoring in unsupervised and natural living environments, such as assisted living centers and individual's homes [9–12], and, therefore, objective PA assessment in older adults earned more attention. Theou et al. 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 [13]. More recently, Schwenk et al. quantified physical activity more specifically based on duration of lying, sitting, standing, and walking; study results suggested that sitting percentage within a 24-hour monitoring period was higher in frail compared to non-frail participants [14].

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-frails 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 number of postural transitions during 24-hour monitoring of daily PA for the purposes 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 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 long standing pause) and quick-sitting (transition to sitting from walking without pause or with short standing pause). We hypothesized that in addition to daily number of postural transitions, qualitative data from postural transitions, specifically number of transitions between physically demanded postures (e.g. walk-to-stand, stand-to-walk, walk-to-sit, and sit-to-walk) and 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, Arizona (the Arizona Frailty Cohort sample has 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 meters with or without an assistive device) and cognitive impairment as confirmed by a Mini-Mental State Examination (MMSE) [19] score of 23 or less. Foot pain was evaluated using self-reported visual analog scale (VAS) (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 frailty index [1]. Fried criteria included slowness (walking speed for 4.6 meter distance), weakness (handgrip strength), and self-reported low physical activity, exhaustion, and unintentional weight loss. Individuals with one 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 physical activities were recorded for a period of 48 hour using an unobtrusive shirt-embedded sensor (PAMSys™, Biosensics LLC) where the first 24 hour was used for purpose of this study; the sensor pocket located at the sternum (Error! Reference source not found.). PAMSys system contains a three-axis accelerometer (sampling frequency of 50 Hz) and a built-in memory for recording long-term data. A previously developed and validated software 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 seconds); and 2) cautious-sitting: walking, a standing pause (≥ 5 seconds), and then sitting. The ratio of cautious-sitting was estimated as follows:

$$\mathrm{Ratio\ of\ Cautious{-}sitting,}\ [\%]=\frac{number\ of\ \mathrm{cautious\ sitting\ tranistions}}{number\ of\ \mathrm{cautious\ sitting\ transitions}+number\ of\ quick\ \mathrm{sitting}}\times 100 \quad (1)$$

Statistical Analysis

Independent sample *t*-test or chi-square (χ^2) test were used to evaluate between groups differences in demographics and health parameters. Between groups comparisons for postural transitions parameters were done using general linear model (GLM) tests. Post Hoc Sidak adjustment was used to adjust *p*-values based on age, gender, or body mass index (BMI). Between groups 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. Cut-offs 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 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 (IBM, version 24, Chicago, IL), with a significance level of $p < 0.05$.

Results

Data for one frail subject (<1%) was excluded from data analysis based on percentage of walking during 24 hours, as Tukey's outlier labeling method marked it as beyond 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. 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 between frailty groups comparisons for postural transition parameters after adjustment by 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 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 non-frails (Table); medium effect sizes were measured for all these differences (Cohen's d=0.73–0.79). Furthermore, 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). When adjusting the results by age, the total number of transitions, stand-to-walk, and walk-to-stand were still significantly different between groups (Table 3). While 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-Square=0.21).

Significant between-group differences were observed for the same postural transition parameters (i.e., total number of transitions, stand-to-walk, and walk-to-stand) when compared between groups with and without weakness as well as groups with and without slowness Fried's criteria (p<0.001, Table 4). The total daily postural transition number had also 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). Also a moderate effect size was observed for identifying those with low physical activity based on daily postural transitions number but the trend didn't achieve statistical significant level in our sample (d=0.51, p=0.057). This could be explained due to the fact that the number of cases, with 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. Among 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

Daily total number of postural transitions (irrespective of its type) had a negative correlation with age (r=−0.51, p<0.001); suggesting by increasing in age, the amount of daily postural transitions is reducing. 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 increasing in age, reducing the likelihood of having postural transitions including sit-to-stand, quick-sitting, stand-to-walk, and walk-to-stand. Ratio of cautious-sitting also demonstrated a weak but significant positive correlation with age (r=0.29, p=0.002) indicating that by increasing in 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 ratio of cautious-sitting (r= −0.11 to −0.25, p<0.050, Table 2), indicating that by increasing fear of falling, daily number of postural transitions tends to reduce. 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 number of daily postural transitions among older adults could be used as an alternative frailty phenotype. The long-term goal of this study was evaluating 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 transition during long-term unsupervised monitoring of daily physical activities for frailty classification.

Postural transition alterations with age and frailty

The results of this study suggest that lower total number of postural transitions irrespective of its type (i.e., sitting or standing) per day, high ratio of cautious-sitting as well as low number of stand-to-walk and walk-to-stand are sensitive indicators of frailty. Previous study suggested that postural transition is a more reliable measurement of physical activities 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 telehealth monitoring system to remotely track frailty status of older adults at their own home and unsupervised condition. However, cut-off values to identify and track frailty status based on daily postural transition parameters needs 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 which, 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]. Within 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 less, while daily percentage of sitting duration is higher compared to non-frails [14]. Current results suggest that different patterns of daily postural transitions such as walk-to-stand and stand-to-walk are also differ by frailty group. To examine, whether the fewer postural transition is related to lesser 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 physical activities data reported in our previous study [14]. Results suggest a non-significant correlation with daily percentage of 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 lesser daily number of postural transitions could be partially described by higher duration of sitting or lesser daily life activity, which is a natural consequence of frailty.

Sitting strategy alterations with age and frailty

Daily number of cautious-sitting was assessed objectively in the current study, as the transition from walking to sitting with a standing pause before sitting. As hypothesized, 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 due to either longer turning duration or postural adjustment and preparation for sitting. Previous work does suggest longer turning duration in frail compared to non-frail older adults during timed-up-and-go test [26]. Cautious-sitting may be 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].

However, while ratio of cautious-sitting is a significant predictor of frailty status it has poor effect size to identify components 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 components of Fried's criteria. This suggests that assessing daily number of different types of postural transitions could be useful in identifying different components 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 status or foot problems may contribute to increasing the likelihood of caution sitting. Our results also suggest that fear of falling may contribute in increasing the likelihood of caution sitting, but its impact compared to frailty status may be less significant.

Rather than balancing problem (or maybe in response to poor balance), kinematic analyses of older adults and frail individuals suggest that conservative movement is a mechanism they often employ to prevent fall; we are unable to state whether this is intentional or due to deconditioning, instability and/or and weakness. Similar to what was observed within the current study, Weiss et al., demonstrated that older adult fallers perform walking, sit-to-stand, and stand-to-sit tasks more cautiously, as measured by lower range and jerk (i.e., acceleration amplitude) of trunk motion, to increase the stability and reduce the risk of falling [36]. 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 fall risk 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 effective use of interventions as well as preventive strategies in non-frail and pre-frail groups to prevent frailty [38]. Further, within the current study, no direct measure of lower-extremity muscle strength is available. As we found associations between less postural transition and 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-sitting and its association with frailty, weakness and intention. Also, it would be interesting to capture other potential confounder 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 hours activities of daily living and data were captured in subjects' natural living environments (e.g., assisted living centers and individual's 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 than 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 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 or outcomes researches to screen potential benefit of frailty intervention programs; however, a longitudinal setup is required to assess power of physical activity monitoring over longer period for studying frailty status progress. Lastly, the observed relationship between less number of postural transitions and weakness, in agreement with previous work [32], suggest that customized balance and strength training exercise routines might be beneficial for re-conditioning and slowing the progression of frailty [42,43].

Acknowledgments

The project described was supported in part by Award Number 2R42AG032748 from the National Institute on Aging. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institute of Aging or the National Institutes of Health. The clinical trial was registered with ClinicalTrials.gov, identifier NCT01880229. We thank Marilyn Gilbert and the coordination team for helping with data collection.

References

1. Fried LP, Tangen CM, Walston J, Newman AB, Hirsch C, Gottdiener J, Seeman T, Tracy R, Kop WJ, Burke G. Frailty in older adults evidence for a phenotype. The Journals of Gerontology Series A: Biological Sciences and Medical Sciences. 2001; 56:M146–M157.
2. Santos-Eggimann B, Cuénoud P, Spagnoli J, Junod J. Prevalence of frailty in middle-aged and older community-dwelling europeans living in 10 countries. The Journals of Gerontology Series A: Biological Sciences and Medical Sciences. 2009; 64:675–681.
3. Fairhall N, Langron C, Sherrington C, Lord SR, Kurrle SE, Lockwood K, Monaghan N, Aggar C, Gill L, Cameron ID. Treating frailty-a practical guide. BMC medicine. 2011; 9:1. [PubMed: 21219637]
4. Liu CK, Fielding RA. Exercise as an intervention for frailty. Clinics in geriatric medicine. 2011; 27:101–110. [PubMed: 21093726]
5. Fugate Woods N, LaCroix AZ, Gray SL, Aragaki A, Cochrane BB, Brunner RL, Masaki K, Murray A, Newman AB. Frailty: Emergence and consequences in women aged 65 and older in the women's health initiative observational study. Journal of the American Geriatrics Society. 2005; 53:1321–1330. [PubMed: 16078957]

6. Rothman MD, Leo-Summers L, Gill TM. Prognostic significance of potential frailty criteria. Journal of the American Geriatrics Society. 2008; 56:2211–2216. [PubMed: 19093920]
7. Schwenk M, Howe C, Saleh A, Mohler J, Grewal G, Armstrong D, Najafi B. Frailty and technology: A systematic review of gait analysis in those with frailty. Gerontology. 2014; 60:79–89. [PubMed: 23949441]
8. Mohler MJ, Fain MJ, Wertheimer AM, Najafi B, Nikolich-Zugich J. The frailty syndrome: Clinical measurements and basic underpinnings in humans and animals. Exp Gerontol. 2014; 54:6–13. [PubMed: 24503059]
9. Najafi B, Aminian K, Paraschiv-Ionescu A, Loew F, Bula CJ, Robert P. Ambulatory system for human motion analysis using a kinematic sensor: Monitoring of daily physical activity in the elderly. Biomedical Engineering, IEEE Transactions on. 2003; 50:711–723.
10. Schwenk M, Hauer K, Zieschang T, Englert S, Mohler J, Najafi B. Sensor-derived physical activity parameters can predict future falls in people with dementia. Gerontology. 2013; 60:483–492.
11. Mohler MJ, Wendel CS, Taylor-Piliae RE, Toosizadeh N, Najafi B. Motor performance and physical activity as predictors of prospective falls in community-dwelling older adults by frailty level: Application of wearable technology. Gerontology. 2016; 62:654–664. [PubMed: 27160666]
12. Armstrong DG, Najafi B, Shahinpoor M. Potential applications of smart multifunctional wearable materials to gerontology. Gerontology. 2017
13. Theou O, Jakobi JM, Vandervoort AA, Jones GR. A comparison of physical activity (pa) assessment tools across levels of frailty. Archives of gerontology and geriatrics. 2012; 54:e307–e314. [PubMed: 22209454]
14. Schwenk M, Mohler J, Wendel C, D'Huyvetter K, Fain M, Taylor-Piliae R, Najafi B. Wearable sensor-based in-home assessment of gait, balance, and physical activity for discrimination of frailty status: Baseline results of the arizona frailty cohort study. Gerontology. 2014
15. Ganea, R., Paraschiv-Ionescu, A., Salarian, A., Bula, C., Martin, E., Rochat, S., Hoskovec, C., Piot-Ziegler, C. Kinematics and dynamic complexity of postural transitions in frail elderly subjects: Engineering in Medicine and Biology Society. 2007 EMBS 2007 29th Annual International Conference of the IEEE; 2007. p. 6117-6120.
16. Galán-Mercant A, Cuesta-Vargas AI. Differences in trunk accelerometry between frail and non-frail elderly persons in functional tasks. BMC research notes. 2014; 7:100. [PubMed: 24559490]
17. Greene BR, Doheny EP, Kenny RA, Caulfield B. Classification of frailty and falls history using a combination of sensor-based mobility assessments. Physiological measurement. 2014; 35:2053. [PubMed: 25237821]
18. Association WM. World medical association declaration of helsinki: Ethical principles for medical research involving human subjects. Jama. 2013; 310:2191–2194. [PubMed: 24141714]
19. Folstein MF, Folstein SE, McHugh PR. "Mini-mental state": A practical method for grading the cognitive state of patients for the clinician. Journal of psychiatric research. 1975; 12:189–198. [PubMed: 1202204]
20. Kempen GI, Yardley L, Van Haastregt JC, Zijlstra GR, Beyer N, Hauer K, Todd C. The short fes-i: A shortened version of the falls efficacy scale-international to assess fear of falling. Age and ageing. 2008; 37:45–50. [PubMed: 18032400]
21. Najafi B, Aminian K, Loew F, Blanc Y, Robert PA. Measurement of stand-sit and sit-stand transitions using a miniature gyroscope and its application in fall risk evaluation in the elderly. Biomedical Engineering, IEEE Transactions on. 2002; 49:843–851.
22. Najafi B, Armstrong DG, Mohler J. Novel wearable technology for assessing spontaneous daily physical activity and risk of falling in older adults with diabetes. Journal of diabetes science and technology. 2013; 7:1147–1160. [PubMed: 24124940]
23. Cohen, J. Statistical power analysis for the behavioral sciences. Routledge Academic; 2013.
24. Lawrence I, Lin K. A concordance correlation coefficient to evaluate reproducibility. Biometrics. 1989:255–268. [PubMed: 2720055]
25. Tukey, JW. Exploratory data analysis. 1977.
26. Galán-Mercant A, Cuesta-Vargas AI. Differences in trunk accelerometry between frail and nonfrail elderly persons in sit-to-stand and stand-to-sit transitions based on a mobile inertial sensor. JMIR mhealth and uhealth. 2013; 1:e21. [PubMed: 25098977]

27. Ganea R, Paraschiv-Ionescu A, Büla C, Rochat S, Aminian K. Multi-parametric evaluation of sit-to-stand and stand-to-sit transitions in elderly people. Medical engineering & physics. 2011; 33:1086–1093. [PubMed: 21601505]
28. De Bruin ED, Najafi B, Murer K, Uebelhart D, Aminian K. Quantification of everyday motor function in a geriatric population. Journal of rehabilitation research and development. 2007; 44:417. [PubMed: 18247238]
29. Lord SR, Murray SM, Chapman K, Munro B, Tiedemann A. Sit-to-stand performance depends on sensation, speed, balance, and psychological status in addition to strength in older people. The Journals of Gerontology Series A: Biological Sciences and Medical Sciences. 2002; 57:M539–M543.
30. Bohannon RW. Sit-to-stand test for measuring performance of lower extremity muscles. Perceptual and motor skills. 1995; 80:163–166. [PubMed: 7624188]
31. Jones CJ, Rikli RE, Beam WC. A 30-s chair-stand test as a measure of lower body strength in community-residing older adults. Research quarterly for exercise and sport. 1999; 70:113–119. [PubMed: 10380242]
32. Peterson MJ, Giuliani C, Morey MC, Pieper CF, Evenson KR, Mercer V, Cohen HJ, Visser M, Brach JS, Kritchevsky SB. Physical activity as a preventative factor for frailty: The health, aging, and body composition study. The Journals of Gerontology Series A: Biological Sciences and Medical Sciences. 2009; 64:61–68.
33. Brown M, Sinacore DR, Binder EF, Kohrt WM. Physical and performance measures for the identification of mild to moderate frailty. The Journals of Gerontology Series A: Biological Sciences and Medical Sciences. 2000; 55:M350–M355.
34. Davis DH, Rockwood MR, Mitnitski AB, Rockwood K. Impairments in mobility and balance in relation to frailty. Archives of gerontology and geriatrics. 2011; 53:79–83. [PubMed: 20678816]
35. Toosizadeh N, Mohler J, Wendel C, Najafi B. Influences of frailty syndrome on open-loop and closed-loop postural control strategy. Gerontology. 2014
36. Weiss A, Herman T, Plotnik M, Brozgol M, Giladi N, Hausdorff J. An instrumented timed up and go: The added value of an accelerometer for identifying fall risk in idiopathic fallers. Physiological measurement. 2011; 32:2003. [PubMed: 22094550]
37. Hahn ME, Chou L-S. Age-related reduction in sagittal plane center of mass motion during obstacle crossing. Journal of biomechanics. 2004; 37:837–844. [PubMed: 15111071]
38. Apóstolo J, Cooke R, Bobrowicz-Campos E, Santana S, Marcucci M, Cano A, Vollenbroek M, Holland C. Effectiveness of the interventions in preventing the progression of pre-frailty and frailty in older adults: A systematic review protocol. JBI database of systematic reviews and implementation reports. 2016; 14:4–19.
39. Toosizadeh N, Mohler J, Lei H, Parvaneh S, Sherman S, Najafi B. Motor performance assessment in parkinson's disease: Association between objective inclinic, objective in-home, and subjective/semi-objective measures. PloS one. 2015; 10:e0124763. [PubMed: 25909898]
40. Lamoth CJ, van Deudekom FJ, van Campen JP, Appels BA, de Vries OJ, Pijnappels M. Gait stability and variability measures show effects of impaired cognition and dual tasking in frail people. Journal of neuroengineering and rehabilitation. 2011; 8:1. [PubMed: 21226898]
41. van Iersel MB, Munneke M, Esselink RA, Benraad CE, Rikkert MGO. Gait velocity and the timed-up-and-go test were sensitive to changes in mobility in frail elderly patients. Journal of clinical epidemiology. 2008; 61:186–191. [PubMed: 18177792]
42. Schwenk M, Grewal G, Holloway D, Muchna A, Garland L, Najafi B. Interactive sensor-based balance training in older cancer patients with chemotherapy-induced peripheral neuropathy: A randomized controlled trial. Gerontology. 2015
43. Schwenk M, Grewal GS, Honarvar B, Schwenk S, Mohler J, Khalsa DS, Najafi B. Interactive balance training integrating sensor-based visual feedback of movement performance: A pilot study in older adults. Journal of neuroengineering and rehabilitation. 2014; 11:1. [PubMed: 24393611]

Figure 1.

Shirt-embedded sensor (PAMSys™, Biosensics LLC, MA, USA) for daily physical activity monitoring. Sensor is placed on the inside of comfortable washable and breathable t-shirt (PAMShirt™). Illustration shows the sensor on the outside of the shirt.

Table 1

Demographic and health information of participant expressed in mean±standard deviation or percentage across non-frail and pre-frail/frail groups categorized using the Fried index. The asterisk symbol indicates a significant difference with *p*-value less than 0.05.

Characteristic	**Non-frail**	**Pre-frail/Frail**	***p*-value**
Participants, n	43 (36.2%)	76 (63.8%)	-
Male, n	7 (16.3%)	18 (23.7%)	0.341
Age, years	**74.23±6.15**	**80.70±8.68**	**<0.001**
Weight, kg	**66.17±15.95**	**76.50±18.35**	**0.002**
Height, cm	161.73±6.95	161.52±9.38	0.90
BMI, kg/m^2	**25.25±5.77**	**29.33±6.63**	**0.001**
MMSE score[1]	29.16±1.15	28.67±1.57	0.075
Fear of falling (7–49 scale[2])	**19.58±6.34**	**28.84±10.94**	**<0.001**
Foot Pain (0–10 Scale[3])	**0.61±1.01**	**1.20±2.08**	**0.040**

[1] Mini–mental state examination (MMSE)

[2] Short fall efficacy scale international (FES-I)

[3] Visual analog scale between 0 and 10

Bolded values indicate statistical significant of $p<0.050$

Table 2

Between groups comparisons adjusted by BMI and Gender with no adjustment with age. Correlations between sensor-derived parameters with age, FES-I (fear of falling), and foot pain are reported. The asterisk symbol indicates a significant difference with *p*-value less than 0.05.

Parameter	Non-frail (n=43)	Pre-frail/Frail (n=76)	Effect Size	*p*-value †	Correlation with age (r) *p*-value	Correlation with FES-I[1] (r) *p*-value	Correlation with foot pain[2] (r) *p*-value
Total number of transitions, [n]	**1174±468**	**878±333**	**0.73**	**0.001***	r=−0.51 **p<0.001***	*r=−0.24* ***p<0.001****	*r=−0.09 p=0.321*
Sit-to-stand, [n]	85±45	83±40	0.07	0.789	r=−0.19 **p=0.040***	*r=−0.11* ***p=0.009****	*r=−0.04 p=0.679*
Sit-to-walk, [n]	23±11	23±9	0.04	0.941	r=−0.18 **p=0.044***	*r=0.03 p=0.769*	*r=−0.01 p=0.981*
Stand-to-sit, [n]	64±37	66±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, [n]	**475±208**	**332±148**	**0.79**	**<0.001***	r=−0.53 **p<0.001***	*r=−0.25* ***p=0.007****	*r=−0.10 p=0.266*
Quick-sitting, [n]	45±16	40±15	0.29	0.097	r=−0.49 **p<0.001***	*r=−0.190* ***p=0.039****	*r=−0.09 p=0.315*
Walk-to-stand, [n]	**453±202**	**314±141**	**0.79**	**<0.001***	r=−0.51 **p<0.001***	*r=−0.24* ***p=0.010****	*r=−0.10 p=0.286*
Ratio of cautious-sitting, [%]	**47±14**	**49±12**	**0.22**	**0.025***	r=0.29 **p=0.002***	*r=0.147 p=0.111*	*r=0.12 p=0.185*

[1] Short fall efficacy scale international (FES-I)

[2] Visual analog scale between 0 and 10

† Adjustment for multiple comparisons: Sidak.

Bolded values indicate statistical significant of $p<0.050$

Table 3

Between groups comparisons with adjustment by age.

Parameter	**Non-frail (n=43)**	**Pre-frail/Frail (n=76)**	***p*-value†**
Total number of transitions, [n]	**1174±468**	**878±333**	**0.032**
Sit-to-stand, [n]	85±45	83±40	85±40
Sit-to-walk, [n]	23±11	23±9	0.664
Stand-to-sit, [n]	64±37	66±34	0.568
Stand-to-walk, [n]	**475±208**	**332±148**	**0.011**
Quick-sitting, [n]	45±16	40±15	0.570
Walk-to-stand, [n]	**453±202**	**314±141**	**0.011**
Ratio of cautious-sitting, [%]	**47±14**	**49±12**	0.363

†: Adjustment for multiple comparisons: Sidak.

Bolded values indicate statistical significant of $p<0.050$

Table 4

Comparison between different Fried's phenotypes (slowness, weakness, low physical activity, exhaustion, and weight loss). The highest effect size is highlighted by gray color, when the difference was achieved statistical significant level. The bolded values highlight statistical significant.

		Total number of transitions, [n]	Sit-to-stand, [n]	Sit-to-walk, [n]	Stand-to-sit, [n]	Stand-to-walk, [n]	Quick-sitting, [n]	Walk-to-stand, [n]	Ratio of cautious-sitting, [%]
Slowness	No (n=67)	1111±421	86±44	23±10	66±38	444±187	44±15	423±182	47±14
	Yes (n=52)	823±339	81±38	22±9	65±31	306±151	39±16	289±142	50±11
	***p*-value (*d*)**	***p*<0.001 (*d*= 0.76)**	*p* =0.485 (*d*= 0.13)	*p* =0.419 (*d*= 0.15)	*p* =0.873 (*d*= 0.03)	***p* <0.001 (*d* = 0.81)**	***p* =0.046 (*d* = 0.37)**	***p* <0.001 (*d* = 0.82)**	*p*=0.214 (*d* = 0.23)
Weakness	No (n=86)	1066±420	86±44	23±9	65±37	422±188	44±16	401±181	47±13
	Yes (n=33)	773±302	77±33	22±10	64±29	284±135	35±13	270±131	52±11
	p-value (*d*)	***p* <0.001 (*d* = 0.80)**	*p* =0.251 (*d* = 0.22)	*p*=0.381 (*d* = 0.18)	*p*=0.849 (*d*= 0.04)	***p* <0.001 (*d*= 0.84)**	***p* =0.004 (*d*= 0.62)**	***p* <0.001 (*d*= 0.82)**	*p*=0.084 (*d*= 0.37)
Low Physical	No (n=101)	1015±412	86±43	23±9	67±37	396±186	42±15	377±180	48±13
	Yes (n=18)	815±372	72±32	22±11	55±21	313±162	39±21	296±152	49±11
	p-value (d)	*p =0.057* (*d*= 0.51)	*p =0.198* (*d*= 0.36)	*p =0.580* (*d*= 0.13)	*p =0.065* (*d*= 0.39)	*p =0.079* (*d*= 0.47)	*p =0.504* (*d*= 0.19)	***p*** *=0.076* (*d*= 0.48)	*p =0.943* (*d*= 0.02)
Exhaustion	No (n=93)	1018±420	85±42	23±10	66±35	398±188	42±16	379±181	49±13
	Yes (n=26)	867±360	80±41	23±11	63±37	330±166	40±16	313±160	48±12
	p-value (*d*)	*p =0.097* (*d*= 0.39)	*p =0.606* (*d*= 0.12)	*p =0.841* (*d*= 0.04)	*p =0.718* (*d*= 0.08)	*p =0.097* (*d*= 0.38)	*p =0.510* (*d*= 0.15)	*p =0.094* (*d*= 0.39)	*p = 0.892* (*d*= 0.03)
Weight Loss	No (n=111)	981±414	84±42	23±10	66±36	381±186	41±16	362±179	49±13
	Yes (n=8)	1048±392	86±35	22±8	59±21	421±179	49±15	394±170	45±11
	p-value (*d*)	*p =0.651* (*d*= 0.17)	*p =0.885* (*d*= 0.06)	*p =0.716* (*d*= 0.14)	*p =0.612* (*d*= 0.22)	*p =0.552* (*d*= 0.22)	*p =0.195* (*d*= 0.48)	*p =0.629* (*d*= 0.18)	*p =0.495* (*d*= 0.27)

d: Cohen's effect size *d*