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Motor performance and physical activity as predictors of prospective falls in community-dwelling, older adults by frailty level: Application of wearable technology

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Abstract

Background—Few studies of the association between prospective falls and sensor-based measures of motor performance and physical activity have evaluated subgroups of frailty status separately.

Objective—To evaluate wearable sensor-based measures of gait, balance, and physical activity (PA) that are predictive of future falls in community-dwelling older adults.

Methods—The Arizona Frailty Cohort Study in Tucson, Arizona followed community-dwelling adults aged 65 years and over (without baseline cognitive deficit, severe movement disorders, or recent stroke) for falls over six months. Baseline measures included Fried frailty criteria; in-home, and sensor-based gait (normal and fast walk), balance (bipedal eyes open and eyes closed), and spontaneous daily PA over 48 hours, measured using validated wearable technologies.

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Results—Of the 119 participants (36% non-frail, 48% pre-frail, and 16% frail), 48 reported one or more fall (47% of non-frail, 33% of pre-frail, and 47% of frail). Although balance deficit and PA were independent fall predictors in pre-frail and frail groups, they were not sensitive to predict prospective falls in the non-frail group. Even though gait performance deteriorated as frailty increased, gait was not a predictor of prospective falls when participants were stratified based on frailty status. In pre-frail and frail participants combined, center of mass sway (OR= 5.9, 95% CI 2.6 – 13.7), PA mean walking bout duration (OR = 1.1, 95% CI 1.0 – 1.2), PA mean standing bout duration (OR = .94, 95% CI .91 - .99), and a fall in previous 6 months (OR = 7.3, 95% CI 1.5 – 36.4) were independent predictors for prospective falls (AUC: 0.882).

Conclusion—This study suggests that independent predictors of falls are dependent on frailty status. Among sensor-derived parameters, balance deficit, longer typical walking episodes, and shorter typical standing episodes were the most sensitive predictors of prospective falls in the combined pre-frail and frail sample. Gait deficit was not a sensitive fall predictor in the context of frailty status.

Keywords

Frailty; falls; wearable sensors; monitoring; physical function; physical activity; balance; gait

Introduction

Falling is a significant cause of injuries, loss of mobility, institutionalization, and mortality in older adults [1]. In community-dwelling adults, 35%-45% of those over 65 years old report a fall every year, which rises to 50% in those over 80 years old [2]. The high susceptibility to injury in the elderly, for example due to clinical diseases such as osteoporosis or impaired protective reflexes that tend to slow with age, increases the danger of even a relatively mild fall [3]. Furthermore, recovery from fall injury is often delayed in older persons, which leads to deconditioning and further increased fall risk [4]. Many elders who fall experience post-fall syndrome, marked by anxiety, fear of falling, and overcautious walking, which can contribute to further deconditioning, weakness and reduced quality of life [5].

Evaluation of the risk of falling is a necessary step towards the provision of preventive measures for individuals deemed to have a high risk of falling. In addition, systematic screening for fall risk in frail elders would help identify those at ‘high risk of falls’ and in need of specialized geriatric services such as physical rehabilitation. The risk of falling is currently evaluated using questionnaires and short clinical tests of function (e.g., assessments of posture and gait, independence in daily life, cognition, and vision) which have limited precision, and record a single snapshot in time not indicative of activities of daily living. Development of objective and practical tools to track risk of falling in clinic and in home could provide valuable information to reduce fall risk by implementing personalized interventions to address specific motor performance deficit(s). Wearable electro-mechanical sensor technology has provided a new approach for objective measurement of motor performance (including balance and gait) and spontaneous physical activity (PA) under natural conditions [6]. Because wearable sensors are portable and relatively low-cost, they are suitable for real-world fall risk assessment in the complex home and community environments where most falls occur [7,8]. Although wearable technologies have been widely used for assessing risk of falling based on measuring moving ability and motor performance, to date, there has been limited work predicting prospective falls based on monitoring motor performance and daily PA with wearable sensors [9,10]. Other reports on PA and fall risk have used nonlinear frequency analysis to extract quality parameters (gait characteristics) from free living activity data, although not all included prospective fall outcomes [11-13]. Additionally, it is unclear whether the same model for prediction of prospective falls based on motor performance and PA could be generalized within older adults with different frailty status. In other words, the likelihood of falls may depend on activity level and frailty status of older adults, and thus it stands to reason that fall risk based on motor performance and PA should be assessed in the context of frailty status.

The association between PA and falls has been debated in previous literature. Klenk et al. did not observe an association between falls per person-year and average of daily PA among 1,214 community-dwelling older people [14]. Interestingly, they observed the highest rate of falls in less active persons with low walking speed. Considering that speed is an important indicator of frailty, this may suggest that the association between PA and falls would be clarified if results are stratified based on frailty status. Frailty is a geriatric syndrome resulting from age-related cumulative decline across multiple physiologic systems, impaired homeostatic reserve, and reduced capacity to resist stress [15]. Frailty increases vulnerability towards adverse health outcomes including falls, hospitalization, institutionalization, and mortality [15]. A recent systematic review estimated that 10.7% of community-dwelling adults aged 65 and older are frail and 41.6% are pre-frail [16]. The Arizona Frailty Cohort Study was undertaken to identify relevant sensor-based markers of motor performance and PA that are useful for home-based frailty screening [17]. The study employed one of the most commonly accepted operational definitions of frailty syndrome proposed by Fried et al. [15], which is based on weight loss, weakness, exhaustion, slowness, and low energy expenditure. The aim of this report was to evaluate sensor-based measures of gait, balance, and PA that are predictive of prospective falls in a cohort of community-dwelling adults aged 65 and older that is stratified based on frailty status. We hypothesized that sensor-based baseline assessments can predict prospective fall events in older adults, independent of participant characteristics and retrospective fall history.

Methods

Study participants

Reported data were abstracted from the NIH-funded Arizona Frailty Cohort Study, an observational descriptive study of individuals 65 years or older conducted in Tucson, Arizona [17]. Participants were recruited from primary, secondary, and tertiary health care settings, community providers, assisted living facilities, retirement homes, and aging service organizations. Adults aged ≥ 65 years and without gait or mobility disorders (Parkinson's Disease, Multiple Sclerosis, or recent stroke) who reported being able to walk ≥ 9.14 m (30 feet) with or without an assistive device were eligible to be screened for study entry. Exclusion criteria included a Mini-Mental State Examination (MMSE) [18] score ≤ 23, terminal illness, or unwillingness to participate. . Eligible subjects signed a written informed consent form, approved by the University of Arizona institutional review board. In-home assessments were completed between September 2012 and July 2014 by trained clinical research coordinators.

Measures

Participant characteristics—A team of two trained clinical coordinators visited patients within their home or assisted living setting for collecting data, including gait, balance, and daily PA measurement. Measures included self-reported history of falls, use of assistive device (cane or walker), and number of prescriptions. Demographic and health history data (age, sex, race/ethnicity, and daily medication count) were gathered through self-report. Height was taken on-site with a measuring tape between floor and a pen held perpendicularly to a wall at top of participant's head, and weight was measured using a bathroom scale (Ozeri Touch II, Ozeri™, CA, USA) which provided weight, body fat percentage, and muscle percentage. Additionally, participants answered questionnaires to assess tiredness when performing mobility-related tasks on the Mobility-Tiredness Scale (MOB-T) [19], depression using the Center for Epidemiologic Studies Depression Scale (CES-D) [20], and independence as reflected by performance in activities of daily living from the Barthel Activities of Daily Living Index (Barthel ADL) [21]. Individuals were also asked to assess their concerns about falling using the Falls Efficacy Scale-International (FES-I), which poses 16 questions regarding the level of fear of falling across various situations [22]. A Timed Up and Go (TUG) test was administered, in which coordinators measured required time for the participant to rise from a chair, walk three meters, turn around, walk back to the chair, and sit down, at participant's self-selected speed [23].

Frailty assessment—Frailty was assessed using the five components specified in the Fried Frailty Phenotype criteria [15], including self-reported unintentional weight loss of 10 pounds or more in the previous year; weakness, based on grip strength test, stratified by gender and body mass index; slow walking speed, stratified by gender and height; self-reported exhaustion; and low energy expenditure, stratified by gender [24], based on the short version Minnesota Leisure Time Activity questionnaire [25]. Following this algorithm, subjects were categorized as non-frail if they met none of the criteria, pre-frail if they met one or two criteria, and frail if they met three or more criteria. This scale has exhibited high validity and has become a gold standard for classifying frailty in adults over the age of 65 [17].

Prospective falls ascertainment—Prospective fall incidence (falls occurring in the six months after the initial baseline study visit) were recorded and reported by participants. A fall was considered to be an unexpected event in which the participants unintentionally come to rest on the ground, floor, or a lower level [26,27]. Participants were instructed to record all falls prospectively on a provided six-month weekly fall diary log (date, time, activity prior, injury symptoms and need for medical attention), and additionally report all falls by telephone to the study coordination office. A telephone interview after each reported call confirmed details of falls and injuries and resolved any missing data. Fall logs were collected in person at the 6-month follow-up visit. Each participant was dichotomously categorized as a non-faller or a faller (at least one fall during the 6-month follow-up period).

Sensor-derived balance, gait, and PA parameters—Balance and gait trials were performed using a validated wearable technology of five small inertial sensors (tri-axial accelerometer and gyroscope) attached to the shins above ankles, thighs above knees, and lower back close to sacrum (LEGSys™, BioSensics, Cambridge, MA) [28,29]. Balance during quiet standing was measured in two trials of 15 seconds, one with eyes open with no visual target specified, and one with eyes closed. For balance tests, participants were asked to stand silently and erectly with their arms crossed across their chest, and their feet as close together as possible without touching. The balance software (BalanSens™, BioSensics, Cambridge, MA) analysis included sway of hip, ankle, and center of mass (COM) extracted from the sensors attached on the right shin and the lower back [30,31]. The ankle, hip, and COM sways are the product of medial-lateral and anterior-posterior sways for each parameter.

Gait assessment was conducted as participants walked a distance of 4.57 m (15 feet) in their home at a self-selected speed. The gait software (LEGSys™) analysis included gait speed, stride time, stride length, double support (as percentage of stride time), and gait variability (coefficient of variation of stride velocity), based on validated algorithms and data extracted from all five sensors [29,32]. Participants who reported regular daily use of assistive devices (canes or walkers) used their device for the gait assessments.

PA, including posture durations (i.e., sitting, standing, walking, and lying), postural transitions, and locomotion outcomes (i.e., number of walking bouts, steps per day; distribution of steps per walking bout; and cadence)), was monitored over a 48 hour period using a validated triaxial accelerometer wearable technology device (PAMSys™, BioSensics, Cambridge, MA), which was inserted into a tee-shirt with a device pocket located at the sternum. Participants were advised to wear this shirt at all times, except while showering. The device was able to identify postural transitions and movements such as walking, standing, sitting, or lying, which are described in detail elsewhere [32].

Statistical Analysis

To compare demographic and clinical characteristics between fallers to non-fallers, we used Student's t-tests for continuous variables, chi-square tests for categorical variables (Fisher's exact test if any cell had less than five participants), and the Cochran-Armitage (Score) test for ordinal variables. The Mann-Whitney U test was used to compare sensor-based measures of gait, balance and PA between non-fallers and fallers due to non-normal distribution of many of these variables. We compared participant characteristics and wearable sensor-based measures between fallers and non-fallers in a separate column for each frailty category (frail, pre-frail, and non-frail), due to observed significant interactions between frailty category and certain characteristics in predicting faller status. We calculated means, standard deviations (or frequencies of categorical variables), p-values, and Cohen's d effect sizes for the sensor-based parameter differences. We used logistic regression to examine the association between frailty and the risk of being a faller (at least one fall) or a recurrent faller (at least two falls), using two indicator variables of pre-frail and frail, referenced to non-frail.

We used multiple logistic regression to examine the relationship of participant characteristics and wearable sensor-based measures to the risk of falling. Due to significant interactions observed between several sensor-based parameters and frailty status, we constructed separate models for frail/pre-frail combined and for non-frail. Most notably, for COM sway there was a significant interaction (p=.031) indicating that frail/pre-frail had a 5-fold increased risk of falling with every square cm increase in COM sway, whereas non-frail subjects had no increased risk, adjusted for history of fall in previous 6 months. The rationale for combining frail and pre-frail groups was: 1) the frailty sample size by itself lacked sufficient power to detect associations if they existed; 2) effects for a given predictor variable were almost always in the same direction (and when not, the effect size was extremely close to zero); and 3) the interactions observed were strongest and more often statistically significant when evaluated with an indicator of frail/pre-frail combined versus non-frail. However, after regression models were constructed in pre-frail and frail combined, we inspected the final model in pre-frail and frail separately to judge whether combining the subgroups may have biased results.

We first used univariate logistic regression with faller versus non-faller as the dependent variable to test the relationship with candidate variables. Candidate variables were selected if the p-value was less than 0.20 in comparisons between fallers and non-fallers in the pre-frail or frail groups by Mann-Whitney U test or chi-square test. All independent variables in regression were continuous, except fall history in the previous 6 months and use of assistive devices, which were dichotomous. Odds ratios (ORs), 95% confidence intervals, standardized odds ratios (raw coefficient times standard deviation of independent variable) and p-values are reported.

Next, sequential multiple logistic models were constructed by adding blocks of related independent variables for which the p-value was less than 0.20 in univariate logistic regression, as well as retaining any independent significant predictor ($p < 0.05$) from the previous multiple logistic model. When two or more parameters within a block showed collinearity ($r > 0.90$), those with higher univariate p-values were excluded. The sequential models were constructed as follows: Model 1, balance parameters; Model 2, gait parameters; Model 3, PA parameters; and Model 4, subject characteristics. Finally, Model 5 retained all independent significant predictors ($p < 0.05$) from Model 4. For each multiple logistic regression model, we calculated pseudo R^2, a measure of model goodness of fit; area under the curve (AUC) from receiver operating characteristic (ROC) analysis, a measure of model ability to discriminate between fallers and non-fallers; and Akaike information criteria (AIC), a relative measure of model goodness of fit and efficiency allowing comparison of models that are not nested (all terms of the smaller model occur in a larger model). Since AIC comparisons require the same sample across all models, it was derived from models on the subset of 55 participants with no missing block variables. Statistical analysis was performed using Stata version 14.0 (Statacorp, College Station, TX, USA).

Results

Demographic and clinical characteristics

The Arizona Frailty Cohort Study included 128 subjects, of which 9 participants dropped out after baseline assessment. All 119 who completed provided prospective fall diaries and telephone confirmation, although by the time of the 6-month visit 5% had lost diaries, which were recreated based on telephone call records and prompting by coordinator. The completed sample included 43 (36%) non-frail, 57 (48%) pre-frail, and 19 (16%) frail participants. Almost 50% of both non-frail (n=20, 47%) and frail (n=9, 47%) participants experienced at least one fall during the 6-month follow-up, but only 33% of pre-frail (n=19) participants did so. The risk of being a faller in follow-up was not significantly associated with being frail (OR 1.00, 95% CI .35 – 3.1, p = .95) or pre-frail (OR = .58, 95% CI .25 – 1.29, p = .18). The number of participants with two or more falls (recurrent faller) was 13 (30%) non-frail, 5 (9%) pre-frail, and 3 (16%) frail. The risk of being a recurrent faller in follow-up was not significantly associated with being frail (OR .43, 95% CI .11 – 1.7, p = .24), but was significantly reduced among the pre-frail group (OR = .32, 95% CI .12 – .90, p = .03). Fear of falling (FES-I) increased significantly with increasing frailty status (20.8 ± 4.2 non-frail, 28.9 ± 10.8 pre-frail, and 41.4 ± 12.8 frail, p < .001 between each category, Bonferroni adjusted).

Table 1 shows participant demographic and clinical characteristics, comparing fallers to non-fallers separately for each frailty category. Age increased across frailty categories, but was not significantly different by faller status within frailty categories. Fallers in the pre-frail group were significantly more likely to have reported a fall in the previous 6 months compared to non-fallers (p=.001), but this commonly reported association was not significant in the non-frail (p=.08) or frail groups (p=.35). Fallers in the pre-frail group were significantly more likely to use an assistive device (cane or walker) compared to non-fallers (p=.02), but the differences were not significant in the non-frail (p=.32) or frail groups (p=.35). However, all of the non-fallers who used assistive devices in the frail group used a walker, which may indicate a different fall risk from a cane. In the frailty group, fallers had a 5.3-point (43%) higher mean depression score that was not statistically significant (p=.09). Notably, the timed up and go performance test did not discriminate between fallers and non-fallers, either as a continuous measure or as a dichotomous measure of ≥ 13.5 seconds. No other significant associations with faller status were observed.

Balance

Table 2 shows wearable sensor-based balance parameters, comparing fallers to non-fallers separately for each frailty category. In the pre-frail group during eyes open trials, we observed significantly larger mean values in fallers for ankle sway (d = .898, p=.007), hip sway (d = .975, p=.02), and COM sway (d = 1.27, p=.01). The same measures in the frail group produced relatively large effect sizes, which were not statistically significant (ankle sway d = .563, hip sway d = .479, COM sway d = .725). Analogous measures in eyes closed trials were not significantly different by faller status.

Gait

Table 3 shows wearable sensor-based gait parameters, comparing fallers to non-fallers separately for each frailty category. In the pre-frail group, fallers had a significantly greater mean double support during gait initiation (d = .604, p=.02); this difference was not statistically significant for double support percent during steady state gait (d = .450, p=.09). No other significant associations between gait parameters and faller status were observed, including several not shown, such as gait cycle time, shin speed, knee range of motion, and trunk sway during walking.

Physical Activity

Table 4 shows wearable sensor-based PA parameters, comparing fallers to non-fallers separately for each frailty category. In the frail group, we observed relatively large effect sizes for walking parameters, indicating larger mean values in fallers: walking time percent (d = 1.08, p=.07), mean walking bout duration (d = 1.16, p=.03), 90th percentile of walking bout duration (d = .960, p=.04), Walking bout duration variability (d = 1.10, p = .05), and steps per 24 hour (d = .991, p = .09). Although few standing and sitting parameter differences by faller status were significant, the pattern of effect sizes suggests that non-fallers in both the pre-frail and frail groups have longer episodes for both standing and sitting and greater episode duration variability for standing, compared to fallers. For example, mean standing bout duration in pre-frail (d = −.452) and frail (d = − .394), as well as mean sitting bout duration in pre-frail (d = −.392) and frail (d = − .977), all showed relatively large negative effect sizes.

Adjusted Model

In the non-frail sample, the only independent, significant predictor of faller status observed was history of a fall in the previous 6 months (OR = 4.8, 95% CI 1.02 – 22.6, p= .047). Table 5 shows the results of sequential multiple logistic regression modeling in the subsample of frail and pre-frail subjects combined. In the frail/pre-frail sample, most variables that were candidates based on results in Tables 2, 3, and 4, had $p < .20$ in univariate logistic regression and were included in subsequent blocks of variables for multiple regression. Excluded due to collinearity were steps per 24 hours (collinear with walking time percent), double support during gait initiation (collinear with double support during steady state), and the 90th percentile bout duration for walking, standing, or sitting (collinear with respective mean duration).

In Model 1 of the balance parameter block, only COM sway was an independent predictor (OR= 4.5, 95% CI 1.7 - 12.0, p=0.003). In Model 2, the addition of the only candidate gait parameter, double support percent, yielded similar estimates for COM sway (OR= 3.8, 95% CI 1.9 - 7.8, $p < 0.001$). Model 3 introduced a block of candidate PA parameters; mean walking bout duration and mean standing bout duration were both significant predictors, indicating an increased risk of falling with increasing walking episode duration and a decreased risk of falling with increasing standing episode duration. In Model 3, the association with COM sway was strengthened considerably, indicating possible confounding by PA. Model 4 shows that fall history in previous 6 months is a strong predictor of future falls, but its inclusion did not alter the estimates of other independent predictors substantially. The use of assistive devices had a large OR point estimate, but an extremely wide confidence interval indicating uncertainty in this estimate (p=0.20).

Finally, Model 5 demonstrates that exclusion of the non-significant covariates from Model 4, particularly use of assistive devices, made very little change to the estimates of other independent predictors. Furthermore, Model 5 in frail and pre-frail separately produced estimated ORs similar or stronger (though not always statistically significant) to Model 5 in pre-frail combined for COM sway (OR 8.8, p <.001 pre-frail; OR 13.9, p = .10 frail), mean walking bout duration (OR 1.1, p = .02 pre-frail; OR 1.5, p = .01 frail), mean standing bout duration (OR .95, p = .03 pre-frail; OR .77, p = .07 frail). In Model 5 for frail only, an OR for fall history in previous 6 months could not be estimated because it predicted prospective falls perfectly.

For Model 5 in pre-frail and frail combined, the standardized OR for continuous parameters were $OR_S = 4.6$ COM sway, $OR_S = 3.4$ mean walking bout duration, $OR_S = 0.4$ mean standing bout duration and $OR_S = 2.7$ for fall history in previous 6 months, indicating that the relative importance of the sensor-based parameters is COM sway > walking bout duration > fall history > standing bout duration. Inspection of the pseudo R^2 across models shows better prediction of the outcome with each addition of independent predictors, rising to .478 in Model 4. The AUC increased markedly from .705 in Model 1 to .907 in Model 4, indicating that Model 4 is highly accurate in discriminating between fallers and non-fallers. A lower AIC indicates better quality in terms of goodness of fit, or the presence of fewer covariates without loss of fit. The AIC decrease between Model 1 and Model 4 indicates increasing model quality, in terms of goodness of fit without superfluous covariates that do not contribute to fit. For Model 5, all three indicators are slightly less optimal, suggesting that the more parsimonious model does not improve predictive value or goodness of fit.

Discussion

This study examined the most sensitive sensor-derived PA, gait, and balance parameters for prediction of prospective falls during a 6-month follow-up period in community dwelling elders stratified based on frailty status. A strength of the study was conducting measures in the home and community settings, which allowed for inclusion of nearly homebound participants who are often excluded in clinic-based studies. The results suggest that performance-based tests such as gait trials and TUG are insensitive predictors of future falls in particular among frail and pre-frail older adults, whereas certain balance and PA parameters related to walking and standing may be useful fall risk predictors in populations with indicators of frailty.

With the exception of balance measures and history of falls, none of the demographic, questionnaires, or performance-based tests (i.e., gait trials, TUG test) discriminated between future fallers and non-fallers. When categorizing older adults based on frailty status, we did not observe an association between fall risk and gait velocity or gait measures other than double support percent, which was not a significant predictor in adjusted models. Previous studies have described increased fall risk associated with slower gait speed, swing, double-support percent, swing time variability, and stride length variability [33,34]. However, these studies did not stratify or adjust for frailty status to the best of our knowledge, and often excluded frail, home-bound, older adults. Although there are reports of TUG as a significant predictor of fall risk [35], a recent systematic review concluded that performance-based tests such as TUG had poor to moderate accuracy for predicting future falls, especially in higher functioning older people [36].

Our results suggest that among frail and pre-frail older adults, balance and PA parameters are predictive of fall risk, but gait parameters are not. The findings indicate that COM sway, mean walking bout duration, and mean standing bout duration, are sensor-based measures that could enhance the accuracy of fall risk assessment in frail elders. We found that increased COM sway (each cm^2) was associated with a roughly 4 to 6-fold increased odds of a fall over 6 months, increased mean walking bout duration (each second) with a 10% increased odds, and increased mean standing bout duration (each second) with a 6% decreased odds, adjusted for history of a fall in the previous 6 months. Of particular interest is the finding that increased PA (as measured by bout duration) was associated with greater occurrence of falls, which we observed in the frail group (unadjusted and adjusted results) and the pre-frail group (adjusted results), consistent with the possibility that frail and pre-frail elders who do not avoid PA may experience more falls. None of the sensor-derived parameters were sensitive to predict prospective falls in non-frail group, which may indicate that falls in non-frail people are not dependent on motor performance and functional status.

We did not observe an increased risk of falling with increasing frailty category, which is inconsistent with numerous previous reports [37,38]. One explanation could be that the non-frail participants in our study were unusually active, had a lower fear of falling, took more risks or were less cautious, and experienced a higher rate of falls than typically observed in non-frail samples. For example, in the Study of Osteoporotic Fractures (SOF), only 8% of non-frail women (mean age 75, same as our non-frail sample) reported two or more falls over a year, compared to 30% in our study over 6 months [37]. Another contributing explanation could be that the frail participants exercised greater caution, which could have been heighted by a Hawthorne effect of participating in a study whose goals included surveillance of falls. Such caution may have a greater preventive effect in pre-frail participants, because many frail persons have reached a level of weakness and mobility deficit where a high fall risk is difficult to mitigate. Finally, fall rates in the frail group of our study may have been reduced by the exclusion of those with an MMSE score of 23 or lower, movement disorders such as Parkinson's or Multiple Sclerosis, or recent stroke. These exclusions were made to assure that subjects could complete the body worn sensor assessments, but also removed more complicated and higher risk subjects.

Limitations and future research

There are several limitations to consider in the interpretation of these findings. First, our sample size included 57 pre-frail and 19 frail participants. Power to detect differences between fallers and non-fallers in participant characteristics and sensor-based measures may have been limited in the frail group and, as a result, we combined pre-frail and frail for multiple logistic regression predicting a prospective faller Although this combination was supported by a pattern of effect sizes for faller status that were comparable or in the same direction between pre-frail and frail, there were more exceptions to this pattern among PA parameters than gait or balance parameters. However, the final adjusted model in frail and pre-frail separately were comparable to and corroborated the model with frail and pre-frail combined. Second, our sample was predominantly women; although we did not observe a difference in fall risk by sex, our model parameter estimates may have limited generalizability to a population with a more balanced sex composition. Third, the study exclusions for cognitive impairment, movement disorders, and stroke may limit generalizability of our findings to populations without these comorbidities. Fourth, we recruited participants using a convenience sample technique designed to oversample frail and pre-frail community-dwelling elders. Therefore, the sample may not adequately represent the general population of community-dwelling older adults, and the effects we estimated should be validated in a larger probability sample.

Fifth, we used the most widely adopted Fried frailty criteria, which has been associated with numerous poor outcomes. However, there is to date no clear consensus regarding the definition of frailty [39]. It is possible that a broader frailty concept including cognitive, psychological, or social components (such as the LASA frailty instrument [38]) or a continuous measure (such as the Rockwood Index [40]), could have altered the moderating effect we observed for frailty. A sixth potential limitation is the 48-hour PA assessment period, which may not cover day-to-day variability. Given that PA in older adults is less variable and high day-today reliability of PA assessment has been reported for older adults (>60 years) [41], we believe that 48-hour monitoring in our study was most likely sufficient to document habitual PA. Seventh, we reported gait parameters that are most commonly reported and associated with falls in previous studies [33,42,43]. However, there are some other gait parameters (e.g., fractal gait analysis or Local Dynamic Stability) that require nonlinear analysis on large sample of gait data. Due to limitations of our experimental setup, we were not able to perform a long distance walking test and our data were not sufficiently large for nonlinear gait analysis. Additional frequency-based gait (quality) parameters can be extracted from free living activity data using nonlinear frequency analysis, which we plan to assess in future analyses. Finally, about five percent of subjects who recreated their fall diaries at the follow-up visit may have been prone to recall bias. We would expect that in our cohort of cognitively intact subjects, all serious falls requiring medical intervention would have been reported, whereas minor falls may have been underreported in the small number of participants requiring assistance to fill out diaries.

We included assistive device users (canes and walkers) who used their regular devices during gait trials, which may have minimized the detection of gait deficits [44]. Gait in older adults who use a walking assistive device is more irregular and unstable than gait in independently mobile older adults. Assistive device users have better gait when using their device than when walking without it. Gait performances significantly improve when assessed with walking aids, both for canes (increased stride time and length, decreased cadence and stride length variability) and walkers (increased gait speed and stride length, decreased base of support and double support) [45]. The need for assistive devices is an indicator of conditions that increase fall risk, as replicated in our results, but their use generally mitigates fall risk. We believe that gait assessment with assistive device most closely characterizes the nature of participants' gait during the time of falls ascertainment.

Conclusions

Importantly, we found that the association between motor performance and risk of falling is dependent on frailty status. While, prospective falls in non-frail older adults are not dependent on motor performance, balance deficits and inability of ample walking and ample standing are strong predictors of prospective falls in pre-frail and frail older adults. Surprisingly, while gait is deteriorated by increasing frailty status, it is not a predictor of falls when older adults are categorized based on frailty status. Our findings highlight the potential value of wearable sensor technology as a practical tool for assessing of fall risk in home setting even among frail older adults with limited mobility ability. Using these variables in a future index, and validating this index in a larger cohort could provide a useful fall prediction tool in particular among pre-frail and frail older adults.

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Sponsor's Role

The sponsor had no role in the design or conduct of this study; collection, management, analysis, or interpretation of the data; or preparation, review, or approval of the manuscript.

References

1. Tinetti ME, Williams CS. Falls, injuries due to falls, and the risk of admission to a nursing home. The New England journal of medicine. 1997; 337:1279–1284. [PubMed: 9345078]
2. American Geriatrics Society BGS, and American Academy of Orthopedic surgeons Guideline for the prevention of falls in older persons. American geriatrics society, british geriatrics society, and american academy of orthopaedic surgeons panel on falls prevention. Journal of the American Geriatrics Society. 2001; 49:664–672. [PubMed: 11380764]
3. Rubenstein LZ. Falls in older people: Epidemiology, risk factors and strategies for prevention. Age and ageing. 2006; 35(Suppl 2):ii37–ii41. [PubMed: 16926202]
4. Horan MA, Clague JE. Injury in the aging: Recovery and rehabilitation. British medical bulletin. 1999; 55:895–909. [PubMed: 10746338]
5. Bloch F, Blandin M, Ranerison R, Claessens YE, Rigaud AS, Kemoun G. Anxiety after a fall in elderly subjects and subsequent risk of developing post traumatic stress disorder at two months. A pilot study. The journal of nutrition, health & aging. 2014; 18:303–306.
6. 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]
7. Lord SR, Menz HB, Sherrington C. Home environment risk factors for falls in older people and the efficacy of home modifications. Age and ageing. 2006; 35(Suppl 2):ii55–ii59. [PubMed: 16926207]
8. Weiss A, Brozgol M, Dorfman M, Herman T, Shema S, Giladi N, Hausdorff JM. Does the evaluation of gait quality during daily life provide insight into fall risk? A novel approach using 3-day accelerometer recordings. Neurorehabilitation and neural repair. 2013; 27:742–752. [PubMed: 23774124]
9. Shany T, Redmond SJ, Marschollek M, Lovell NH. Assessing fall risk using wearable sensors: A practical discussion. A review of the practicalities and challenges associated with the use of wearable sensors for quantification of fall risk in older people. Zeitschrift fur Gerontologie und Geriatrie. 2012; 45:694–706. [PubMed: 23184295]
10. Howcroft J, Kofman J, Lemaire ED. Review of fall risk assessment in geriatric populations using inertial sensors. Journal of neuroengineering and rehabilitation. 2013; 10:91. [PubMed: 23927446]

11. Rispens SM, van Schooten KS, Pijnappels M, Daffertshofer A, Beek PJ, van Dieen JH. Do extreme values of daily-life gait characteristics provide more information about fall risk than median values? JMIR research protocols. 2015; 4:e4. [PubMed: 25560937]
12. Weiss A, Herman T, Giladi N, Hausdorff JM. Objective assessment of fall risk in parkinson's disease using a body-fixed sensor worn for 3 days. PloS one. 2014; 9:e96675. [PubMed: 24801889]
13. Ihlen EA, Weiss A, Helbostad JL, Hausdorff JM. The discriminant value of phase-dependent local dynamic stability of daily life walking in older adult community-dwelling fallers and nonfallers. BioMed research international. 2015; 2015:402596. [PubMed: 26491669]
14. Klenk J, Kerse N, Rapp K, Nikolaus T, Becker C, Rothenbacher D, Peter R, Denkinger MD. Physical activity and different concepts of fall risk estimation in older people--results of the actife-ulm study. PloS one. 2015; 10:e0129098. [PubMed: 26058056]
15. 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.
16. Collard RM, Boter H, Schoevers RA, Oude Voshaar RC. Prevalence of frailty in community-dwelling older persons: A systematic review. Journal of the American Geriatrics Society. 2012; 60:1487–1492. [PubMed: 22881367]
17. 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. 2015; 61:258–267. [PubMed: 25547185]
18. 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]
19. Fieo RA, Mortensen EL, Rantanen T, Avlund K. Improving a measure of mobility-related fatigue (the mobility-tiredness scale) by establishing item intensity. Journal of the American Geriatrics Society. 2013; 61:429–433. [PubMed: 23452001]
20. Orme JG, Reis J, Herz EJ. Factorial and discriminant validity of the center for epidemiological studies depression (ces-d) scale. Journal of clinical psychology. 1986; 42:28–33. [PubMed: 3950011]
21. Mahoney FI, Barthel DW. Functional evaluation: The barthel index. Md State Med J. 1965; 14:61–65.
22. Yardley L, Beyer N, Hauer K, Kempen G, Piot-Ziegler C, Todd C. Development and initial validation of the falls efficacy scale-international (fes-i). Age and ageing. 2005; 34:614–619. [PubMed: 16267188]
23. Podsiadlo D, Richardson S. The timed “up & go”: A test of basic functional mobility for frail elderly persons. Journal of the American Geriatrics Society. 1991; 39:142–148. [PubMed: 1991946]
24. Bandeen-Roche K, Xue QL, Ferrucci L, Walston J, Guralnik JM, Chaves P, Zeger SL, Fried LP. Phenotype of frailty: Characterization in the women's health and aging studies. Journals of Gerontology Series a-Biological Sciences and Medical Sciences. 2006; 61:262–266.
25. Taylor HL, Jacobs DR Jr. Schucker B, Knudsen J, Leon AS, Debacker G. A questionnaire for the assessment of leisure time physical activities. Journal of chronic diseases. 1978; 31:741–755. [PubMed: 748370]
26. Lamb SE, Jorstad-Stein EC, Hauer K, Becker C. Development of a common outcome data set for fall injury prevention trials: The prevention of falls network europe consensus. Journal of the American Geriatrics Society. 2005; 53:1618–1622. [PubMed: 16137297]
27. Campbell AJ, Robertson MC, Gardner MM, Norton RN, Tilyard MW, Buchner DM. Randomised controlled trial of a general practice programme of home based exercise to prevent falls in elderly women. BMJ (Clinical research ed). 1997; 315:1065–1069.
28. Najafi B, Horn D, Marclay S, Crews RT, Wu S, Wrobel JS. Assessing postural control and postural control strategy in diabetes patients using innovative and wearable technology. Journal of diabetes science and technology. 2010; 4:780–791. [PubMed: 20663438]

29. Najafi B, Helbostad JL, Moe-Nilssen R, Zijlstra W, Aminian K. Does walking strategy in older people change as a function of walking distance? Gait & posture. 2009; 29:261–266. [PubMed: 18952435]
30. Najafi B, Lee-Eng J, Wrobel JS, Goebel R. Estimation of center of mass trajectory using wearable sensors during golf swing. Journal of sports science & medicine. 2015; 14:354–363. [PubMed: 25983585]
31. Toosizadeh N, Lei H, Schwenk M, Sherman SJ, Sternberg E, Mohler J, Najafi B. Does integrative medicine enhance balance in aging adults? Proof of concept for the benefit of electroacupuncture therapy in parkinson's disease. Gerontology. 2015; 61:3–14. [PubMed: 25341431]
32. Toosizadeh N, Mohler J, Lei H, Parvaneh S, Sherman S, Najafi B. Motor performance assessment in parkinson's disease: Association between objective in-clinic, objective in-home, and subjective/semi-objective measures. PloS one. 2015; 10:e0124763. [PubMed: 25909898]
33. Verghese J, Holtzer R, Lipton RB, Wang C. Quantitative gait markers and incident fall risk in older adults. The journals of gerontology Series A, Biological sciences and medical sciences. 2009; 64:896–901.
34. Beauchet O, Annweiler C, Allali G, Berrut G, Herrmann FR, Dubost V. Recurrent falls and dual task-related decrease in walking speed: Is there a relationship? Journal of the American Geriatrics Society. 2008; 56:1265–1269. [PubMed: 18510582]
35. Greene BR, Doheny EP, Walsh C, Cunningham C, Crosby L, Kenny RA. Evaluation of falls risk in community-dwelling older adults using body-worn sensors. Gerontology. 2012; 58:472–480. [PubMed: 22571883]
36. Schoene D, Wu SM, Mikolaizak AS, Menant JC, Smith ST, Delbaere K, Lord SR. Discriminative ability and predictive validity of the timed up and go test in identifying older people who fall: Systematic review and meta-analysis. Journal of the American Geriatrics Society. 2013; 61:202–208. [PubMed: 23350947]
37. Ensrud KE, Ewing SK, Taylor BC, Fink HA, Stone KL, Cauley JA, Tracy JK, Hochberg MC, Rodondi N, Cawthon PM. Frailty and risk of falls, fracture, and mortality in older women: The study of osteoporotic fractures. The journals of gerontology Series A, Biological sciences and medical sciences. 2007; 62:744–751.
38. de Vries OJ, Peeters GM, Lips P, Deeg DJ. Does frailty predict increased risk of falls and fractures? A prospective population-based study. Osteoporosis international : a journal established as result of cooperation between the European Foundation for Osteoporosis and the National Osteoporosis Foundation of the USA. 2013; 24:2397–2403.
39. Rodriguez-Manas L, Feart C, Mann G, Vina J, Chatterji S, Chodzko-Zajko W, Gonzalez-Colaco Harmand M, Bergman H, Carcaillon L, Nicholson C, Scuteri A, Sinclair A, Pelaez M, Van der Cammen T, Beland F, Bickenbach J, Delamarche P, Ferrucci L, Fried LP, Gutierrez-Robledo LM, Rockwood K, Rodriguez Artalejo F, Serviddio G, Vega E. Searching for an operational definition of frailty: A delphi method based consensus statement: The frailty operative definition-consensus conference project. The journals of gerontology Series A, Biological sciences and medical sciences. 2013; 68:62–67.
40. Rockwood K, Mitnitski A. Frailty in relation to the accumulation of deficits. The journals of gerontology Series A, Biological sciences and medical sciences. 2007; 62:722–727.
41. Rowe DA, Kemble CD, Robinson TS, Mahar MT. Daily walking in older adults: Day-to-day variability and criterion-referenced validity of total daily step counts. Journal of physical activity & health. 2007; 4:434–446. [PubMed: 18209234]
42. Guimaraes RM, Isaacs B. Characteristics of the gait in old people who fall. International rehabilitation medicine. 1980; 2:177–180. [PubMed: 7239777]
43. Bridenbaugh SA, Kressig RW. Laboratory review: The role of gait analysis in seniors' mobility and fall prevention. Gerontology. 2011; 57:256–264. [PubMed: 20980732]
44. Schwenk M, Schmidt M, Pfisterer M, Oster P, Hauer K. Rollator use adversely impacts on assessment of gait and mobility during geriatric rehabilitation. Journal of rehabilitation medicine. 2011; 43:424–429. [PubMed: 21448557]

45. Hardi I, Bridenbaugh SA, Gschwind YJ, Kressig RW. The effect of three different types of walking aids on spatio-temporal gait parameters in community-dwelling older adults. Aging clinical and experimental research. 2014; 26:221–228. [PubMed: 24619887]

Table 1

Participant characteristics by incident faller status

	Non-frail			Pre-frail			Frail		
	Faller (n=20)	**Non-faller (n=23)**	**P-Value**	**Faller (n=19)**	**Non-faller (n=38)**	**P-Value**	**Faller (n=9)**	**Non-faller (n=10)**	**P-Value**
Age, mean±SD	74.4 ± 6.6	74.7 ± 6.7	0.882	79.4 ± 8.8	79.7 ± 8.5	0.896	80.9 ± 9.8	86.6 ± 5.9	0.137
Sex (female), n (%)	17 (85.0)	19 (82.6)	1.00	15 (79.0)	28 (73.7)	0.754	9 (100.0)	7 (70.0)	0.211
Race/ethnicity, n (%)			0.852			0.668			0.851
Non-Hispanic White	16 (80.0)	16 (69.6)		16 (84.2)	28 (73.7)		7 (77.8)	6 (60.0)	
Hispanic	0 (0)	1 (4.4)		0 (0)	3 (7.9)		1 (11.1)	1 (10.0)	
Black	0 (0)	0 (0)		0 (0)	0 (0)		1 (11.1)	1 (10.0)	
Other/refused	4 (20.0)	6 (26.1)		3 (15.8)	7 (18.4)		0 (0)	2 (20.0)	
Fall history previous 6 months[1], n (%)	9 (47.4)	3 (15.8)	0.079	14 (82.4)	11 (31.4)	0.001	6 (66.7)	3 (37.5)	0.350
Fear of falling (FES-I), mean±SD	20.8 ± 4.0	20.9 ± 4.5	0.958	32.2 ± 11.9	27.3 ± 9.9	0.106	42.8 ± 9.6	40.1 ± 15.5	0.661
Body Mass Index, n (%)			0.359[3]			0.793[3]			0.468[3]
< 25	9 (45.0)	14 (60.9)		5 (26.3)	12 (31.6)		2 (22.2)	2 (20.0)	
25 - 29.9	7 (35.0)	5 (21.7)		7 (36.8)	7 (18.4)		2 (22.2)	6 (60.0)	
30 - 34.9	3 (15.0)	4 (17.4)		4 (21.1)	13 (34.2)		3 (33.3)	0 (0)	
≥ 35	1 (5.0)	0 (0)		3 (15.8)	6 (15.8)		2 (22.2)	2 (20.0)	
Fat, percent body composition, mean±SD	21.9 ± 8.1	20.3 ± 6.4	0.469	25.7 ± 10.7	27.6 ± 8.8	0.469	32.0 ± 12.2	27.5 ± 10.8	0.428
Muscle, percent body composition, mean±SD	34.0 ± 4.1	34.2 ± 3.1	0.860	34.0 ± 5.1	31.9 ± 3.8	0.099	32.6 ± 4.8	32.7 ± 3.4	0.951
Timed up and go (TUG), sec, mean±SD	9.8 ± 2.8	9.3 ± 1.0	0.439	13.0 ± 3.7	14.0 ± 5.2	0.454	21.7 ± 8.8	22.3 ± 13.1	0.911
Timed up and go (TUG) ≥ 13.5 sec, n (%)	2 (10.0)	0 (0)	0.210	6 (31.6)	16 (43.2)	0.397	7 (77.8)	5 (62.5)	0.620
CES-Depression Scale, mean±SD	5.7 ± 4.3	7.5 ± 6.7	0.293	5.0 ± 5.9	7.9 ± 6.9	0.120	17.6 ± 7.0	12.3 ± 5.8	0.091
Barthel ADL Index, mean±SD	97.0 ± 4.7	98.0 ± 4.7	0.450	95.0 ± 7.1	96.2 ± 5.9	0.512	86.7 ± 6.6	88.0 ± 12.7	0.782

	Non-frail			Pre-frail			Frail		
	Faller (n=20)	**Non-faller (n=23)**	**P-Value**	**Faller (n=19)**	**Non-faller (n=38)**	**P-Value**	**Faller (n=9)**	**Non-faller (n=10)**	**P-Value**
Mobility-Tiredness Scale, mean±SD	5.5 ± 1.1	5.7 ± .57	0.445	4.6 ± 1.5	4.6 ± 1.7	1.00	2.1 ± 1.5	3.1 ± 2.0	0.243
3 or more prescriptions[2], n (%)	11 (57.9)	10 (50.0)	0.621	11 (68.8)	19 (52.8)	0.282	8 (88.9)	7 (87.5)	1.00
Use of assistive device, n (%)	3 (15.0)	1 (4.4)	0.323	12 (63.2)	12 (31.6)	0.023	5 (55.6)	8 (80.0)	0.350

[1] missing fall history in 5 non-frail, 5 pre-frail, 2 frail

[2] missing prescriptions in 4 non-frail, 4 pre-frail, 2 frail

[3] Score test for trend

Table 2

Balance parameters by incident faller status, stratified by frailty status

		Non-frail			Pre-frail			Frail		
		Faller (n=20)	**Non-faller (n=23)**	**Effect size[1] (P-Value[2])**	**Faller (n=19)**	**Non-faller (n=38)**	**Effect size[1] (P-Value[2])**	**Faller (n=9)**	**Non-faller (n=10)**	**Effect size[1] (P-Value[2])**
Eyes Open	Ankle sway, deg^2	3.5 ± 3.0	3.3 ± 3.4	.065 (0.232)	7.2 ± 5.3	3.6 ± 3.1	.898 (0.007)	8.0 ± 10.8	3.7 ± 2.3	.563 (0.564)
	Hip sway, deg^2	4.8 ± 3.4	3.9 ± 4.3	.203 (0.092)	8.6 ± 6.8	4.1 ± 3.0	.975 (0.021)	9.4 ± 14.1	4.6 ± 4.0	.479 (0.923)
	Hip sway-ankle sway ratio	1.5 ± .65	1.9 ± .86	−.134 (0.057)	1.3 ± 1.00	1.4 ± .72	−.067 (0.506)	1.1 ± .86	1.3 ± .75	.142 (0.564)
	Center of mass, cm^2	.77 ± .66	.69 ± .65	.130 (0.168)	1.6 ± 1.2	.66 ± .38	1.27 (0.010)	1.2 ± .89	.68 ± .44	.725 (0.386)
	Center of mass, medial-lateral, cm	.62 ± .32	.56 ± .32	.203 (0.500)	.86 ± .44	.59 ± .33	.724 (0.021)	.70 ± .38	.53 ± .30	.505 (0.248)
	Center of mass, anterior-posterior, cm	1.2 ± .54	1.1 ± .68	.177 (0.214)	1.6 ± .73	1.2 ± .44	.838 (0.058)	1.6 ± .79	1.5 ± .58	.161 (0.736)
Eyes Closed	Ankle sway, deg^2	7.1 ± 5.6	5.2 ± 3.6	.392 (0.307)	12.9 ± 14.2	8.1 ± 5.9	.519 (0.566)	13.4 ± 19.0	14.9 ± 20.1	−.076 (0.923)
	Hip sway, deg^2	6.6 ± 2.9	5.5 ± 3.8	.312 (0.223)	16.8 ± 20.6	10.1 ± 9.0	.485 (0.409)	16.7 ± 23.1	8.7 ± 2.5	.455 (0.630)
	Hip sway-ankle sway ratio	1.4 ± .94	1.3 ± .72	.134 (0.922)	1.5 ± .86	1.4 ± .92	.105 (0.591)	1.5 ± .72	1.1 ± .82	.446 (0.083)
	Center of mass, cm^2	1.4 ± .96	1.0 ± .15	.438 (0.268)	3.2 ± 3.4	1.7 ± 1.2	.694 (0.247)	2.5 ± 2.3	2.2 ± 2.5	.131 (0.847)
	Center of mass, medial-lateral, cm	.82 ± .36	.70 ± .37	.337 (0.233)	1.2 ± .92	.89 ± .49	.390 (0.435)	1.1 ± .61	.83 ± .40	.444 (0.564)
	Center of mass, anterior-posterior, cm	1.6 ± .63	1.4 ± .75	.307 (0.214)	2.3 ± 1.4	1.8 ± .80	.480 (0.294)	2.0 ± .85	2.1 ± 1.4	−.195 (0.847)

[1] Cohen's d

[2] Mann-Whitney U test

Table 3

Gait parameters by incident faller status, stratified by frailty status

		Non-frail			Pre-frail			Frail		
		Faller (n=20)	**Non-faller (n=23)**	**Effect size[1] (P-Value[2])**	**Faller (n=19)**	**Non-faller (n=38)**	**Effect size[1] (P-Value[2])**	**Faller (n=9)**	**Non-faller (n=10)**	**Effect size[1] (P-Value[2])**
Steady-state	Speed, m/s	1.18 ± .18	1.17 ± .14	.079 (0.592)	.93 ± .26	.98 ± .19	−.254 (0.527)	.68 ± .27	.75 ± .47	−.195 (0.930)
	Stride time, s	1.09 ± .09	1.08 ± .10	.109 (0.567)	1.23 ± .22	1.17 ± .16	.366 (0.254)	1.30 ± .19	1.29 ± .22	.049 (0.810)
	Stride length, m	1.26 ± .14	1.24 ± .09	.194 (0.119)	1.09 ± .20	1.12 ± .15	−.154 (0.640)	.84 ± .25	.88 ± .36	−.121 (0.895)
	Double support, %	22.9 ± 4.4	21.4 ± 3.9	.370 (0.330)	28.4 ± 5.6	25.9 ± 5.8	.450 (0.088)	32.5 ± 6.4	30.5 ± 9.8	.245 (0.402)
	CV of speed, %	4.2 ± 2.8	4.2 ± 3.2	−.007 (0.968)	5.4 ± 4.6	5.0 ± 3.6	.113 (0.992)	6.6 ± 5.4	5.0 ± 2.3	.374 (0.491)
Initiation	Speed, m/s	1.18 ± .18	1.18 ± .14	.046 (0.634)	.92 ± .26	.98 ± .20	−.234 (0.556)	.67 ± .27	.76 ± .49	−.232 (0.923)
	Stride time, s	1.10 ± .09	1.09 ± .11	.074 (0.480)	1.25 ± .22	1.18 ± .15	.394 (0.332)	1.31 ± .20	1.32 ± .24	−.008 (0.772)
	Stride length, m	1.26 ± .15	1.25 ± .08	.134 (0.150)	1.09 ± .20	1.12 ± .16	−.145 (0.651)	.84 ± .25	.90 ± .40	−.178 (0.847)
	Double support, %	23.2 ± 4.3	21.8 ± 3.6	.348 (0.301)	30.0 ± 5.2	26.6 ± 5.9	.604 (0.019)	33.4 ± 6.7	32.8 ± 12.6	.055 (0.773)
	CV of speed, %	4.1 ± 2.8	3.4 ± 1.5	.328 (0.751)	5.5 ± 4.5	5.4 ± 4.0	.018 (0.967)	6.0 ± 2.7	7.5 ± 7.2	−.289 (0.791)

CV: coefficient of variation = mean / standard deviation

[1] Cohen's d

[2] Mann-Whitney U test

Table 4

Physical activity parameters (48 hour) by incident faller status, stratified by frailty status

		Non-frail			Pre-frail			Frail		
		Faller (n=20)	**Non-faller (n=23)**	**Effect size^1 (P-Value^2)**	**Faller (n=19)**	**Non-faller (n=38)**	**Effect size^1 (P-Value^2)**	**Faller (n=9)**	**Non-faller (n=10)**	**Effect size^1 (P-Value^2)**
Walking	Walking during 48 h, %	6.9 ± 3.2	7.7 ± 3.2	−.254 (0.543)	5.4 ± 1.8	5.3 ± 2.6	.035 (0.518)	5.2 ± 3.1	2.4 ± 2.0	1.08 (0.072)
	Mean walking bout duration, s	39.3 ± 16.1	42.9 ± 16.8	−.218 (0.551)	39.6 ± 15.9	39.0 ± 12.3	.040 (0.530)	45.4 ± 12.4	30.2 ± 13.7	1.16 (0.034)
	Walking bout duration, 90th percentile, s	70.6 ± 28.9	78.0 ± 27.3	−.263 (0.368)	84.0 ± 36.4	78.8 ± 28.5	.164 (0.804)	97.0 ± 39.5	61.8 ± 34.1	.960 (0.041)
	Walking bout duration variability, s	89.1 ± 76.3	87.9 ± 80.4	.015 (0.715)	56.3 ± 37.6	59.6 ± 44.1	−.078 (0.684)	49.2 ± 20.2	28.4 ± 17.6	1.10 (0.050)
	Steps per 24 h, n	5969 ± 3730	6147 ± 2671	−.056 (0.644)	3790 ± 1589	3981 ± 2488	−.086 (0.697)	3644 ± 2568	1625 ± 1407	.991 (0.086)
Standing	Standing during 48 h, %	17.3 ± 4.8	17.1 ± 4.9	.167 (0.798)	14.2 ± 5.2	13.9 ± 4.2	.076 (0.763)	13.6 ± 4.3	10.8 ± 5.2	.590 (0.165)
	Mean standing bout duration, s	65.2 ± 26.7	59.9 ± 17.6	.235 (0.361)	56.0 ± 12.9	63.6 ± 18.7	−.452 (0.124)	66.2 ± 10.4	73.0 ± 21.3	−.394 (0.514)
	Standing bout duration, 90th percentile, s	155.8 ± 68.5	143.2 ± 38.5	.230 (0.450)	129.5 ± 26.7	147.6 ± 38.2	−.522 (0.055)	157.0 ± 32.0	164.9 ± 51.7	−.180 (0.744)
	Standing bout duration variability, s	99.0 ± 43.6	94.6 ± 47.1	.098 (0.635)	82.6 ± 34.8	100.8 ± 58.3	−.353 (0.154)	89.2 ± 13.2	110.4 ± 67.5	−.424 (0.744)
Sitting	Sitting during 48 h, %	35.1 ± 7.7	33.9 ± 10.1	.133 (0.961)	41.5 ± 11.5	38.6 ± 10.3	.269 (0.371)	41.1 ± 6.5	45.2 ± 16.6	−.319 (0.568)
	Mean sitting bout duration, s	210.9 ± 81.4	224.6 ± 108.4	−.142 (0.697)	254.0 ± 93.3	310.1 ± 162.7	−.392 (0.344)	298.8 ± 57.6	429.4 ± 175.4	−.977 (0.041)
	Sitting bout duration, 90th percentile, s	545.1 ± 224.0	625.7 ± 350.5	−.270 (0.511)	613.8 ± 312.9	876.0 ± 546.1	−.546 (0.046)	776 ± 195	1148 ± 601	−.815 (0.121)
	Sitting bout duration variability, s	512.6 ± 214.9	473.4 ± 175.0	.202 (0.422)	628.2 ± 216.8	629.8 ± 280.1	−.006 (0.804)	594 ± 141	910 ± 494	−.849 (0.050)
Lying	Lying during 48 h, %	40.1 ± 8.1	41.3 ± 9.2	−.136 (0.836)	38.9 ± 12.5	42.2 ± 9.7	−.309 (0.184)	40.1 ± 9.2	41.6 ± 18.3	−.100 (0.624)
	Mean lying bout duration, s	1930 ± 860	1941 ± 864	−.012 (0.865)	2778 ± 1366	2734 ± 1587	.029 (0.490)	2289 ± 598	3239 ± 1873	−.668 (0.414)
	Lying bout duration, 90th percentile, s	5392 ± 2979	5993 ± 2926	−.203 (0.450)	8438 ± 5221	7800 ± 5549	.117 (0.468)	6718 ± 1777	8665 ± 4463	−.561 (0.462)

		Non-frail			Pre-frail			Frail		
		Faller (n=20)	**Non-faller (n=23)**	**Effect size[1] (P-Value[2])**	**Faller (n=19)**	**Non-faller (n=38)**	**Effect size[1] (P-Value[2])**	**Faller (n=9)**	**Non-faller (n=10)**	**Effect size[1] (P-Value[2])**
	Lying bout duration variability, s	3572 ± 1483	3445 ± 1652	.081 (0.679)	3856 ± 1828	4289 ± 3200	−.154 (0.697)	2982 ± 958	3813 ± 1780	−.572 (0.289)
	Postural transitions per 24 h, n	163.7 ± 50.1	152.2 ± 47.8	.236 (0.450)	158.2 ± 57.1	126.8 ± 41.1	.668 (0.063)	124.5 ± 23.4	106.2 ± 44.8	.505 (0.191)

[1] Cohen's d

[2] Mann-Whitney U test

Table 5

Multiple logistic regression models predicting having any incident fall in frail and pre-frail subjects combined

Variable	Univariate OR (95% CI)	Model 1 Balance block OR (95% CI) N = 67	Model 2 Gait block OR (95% CI) N = 62	Model 3 PA block OR (95% CI) N = 65	Model 4 Other block OR (95% CI) N = 60	Model 5 Parsimonious OR (95% CI) N = 60
Center of mass EO, cm^2	4.4 (2.2 – 9.1)[1]	4.5 (1.7 - 12.0)[2]	3.8 (1.9 - 7.8)[1]	5.8 (2.5 – 13.3)[1]	6.2 (2.1 - 18.9)[1]	5.9 (2.6 – 13.7)[1]
Ankle sway EO, deg^2	1.2 (1.0 – 1.5)[3]	1.0 (.85 – 1.2)				
Hip sway EO, deg^2	1.2 (1.0 -1.3)[2]	.99 (.86 – 1.1)				
Double support, steady state, %	1.1 (.98 – 1.2)[5]		1.0 (.94 – 1.2)			
Walking during 48 h, %	1.1 (.91 – 1.3)					
Mean walking bout duration, s	1.0 (.99 – 1.1)[5]			1.1 (1.0 – 1.1)[2]	1.1 (1.0 – 1.2)[2]	1.1 (1.0 – 1.2)[2]
Walking bout duration variability, s	1.0 (.99 – 1.0)					
Mean standing bout duration, s	.97 (.95 – 1.0)[4]			.94 (.90 - .99)[3]	.91 (.84 - .98)[2]	.94 (.91 - .99)[2]
Mean sitting bout duration, s	.99 (.99 – 1.0)[3]			.99 (.98 – 1.0)		
Sitting bout duration variability, s	.99 (.99 – 1.0)					
Postural transitions per 24 h, n	1.0 (1.0 – 1.0)[3]			1.0 (.99 – 1.0)		
Age, years	.98 (.93 - 1.0)					
Fall history previous 6 months, (Y/N)	6.9 (2.2 – 21.2)[1]				6.7 (1.3 – 34.7)[3]	7.3 (1.5 – 36.4)[3]
Use of assistive device (Y/N)	2.2 (.83 – 5.6)[5]				5.1 (.42 – 60.6)[5]	
Fear of falling (FES-I) score	1.0 (.99 – 1.1)[4]				1.0 (.92 – 1.1)[5]	
Muscle, percent body composition, %	1.1 (.97 – 1.2)[5]				1.1 (.93 – 1.4)[5]	
CES-Depression Scale	1.0 (.94 -1.1)					
Model pseudo R^2		.186	.189	.327	.478	.427
Model AUC		.705	.738	.842	.907	.882
Model AIC		68.7	66.6	63.1	54.4	54.8

EO=eyes open. AUC = area under curve. AIC = Akaike information criteria (from models on subset of 55 subjects with no missing variables)

[1] p < .001

[2] $p < .01$

[3] $p < .05$

[4] $p < .10$

[5] $p < .20$