New methods to monitor stair ascents using a wearable pendant device reveal how behavior, fear, and frailty influence falls in octogenarians

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New methods to monitor stair ascents using a wearable pendant device reveals how behavior, fear, and frailty influence falls in octogenarians

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***Abstract*—*Goals:* To investigate if stair negotiation by older people during activities of daily life (ADL) can be accurately identified using a freely worn pendant device. To investigate how usual stair ascent performances during ADL relate to clinical assessments and prospective falls. *Methods:* ADL were recorded for thirty minutes by fifty-two community-dwelling older people (83 ± 4 years) using a small pendant device. Classification accuracy was assessed using annotated video and 4-fold cross validation. Correlations between sensor-derived stair ascent features (comprising intensity, variability, and stability) and a battery of clinical tests (comprising physiological, psychological, health, and follow-up falls) were investigated. *Results:* Accurate identification of stair events (99.8%, Kappa 0.92) was possible in both 'frail' and 'athletic' participants by scaling the barometer threshold to stair cadences. Cautious double stepping strategy could be identified remotely. Stair ascent performance was correlated with ascent strategy (r = -0.67), age (r = -0.44), concern about falling (r = -0.43), fall risk scores (r = -0.41), processing speed (r = -0.38), and contrast sensitivity (r = 0.32). Follow-up falls were correlated with ascent stability (r = -0.35). *Conclusions:* Remote analysis of stair ascents is feasible. In our healthy older people, outcomes appeared more related to mental rather than physiological factors. The ascent strategies we observed in some older people may have reflected an appropriate behavioral response to increased concerns about falling. *Significance:* Given acceptance of wearable devices is increasing; reduced functional performance and altered strategies for undertaking ADL could soon be routinely tracked to augment health care.**

***Index Terms*—Accelerometers, accident, activity, aged, avoidance, behavior, climb, classification, concern, daily life, device, falls, fear, gait, healthy, identification, monitoring, older, people, pendant, processing speed, remote, response, risk, sensor, stairs, strategy, variability, walking, wearable.**

I. INTRODUCTION

Stairs present a material, physiological, and psychological obstacle that becomes more significant with aging [1]. Inability to undertake this task is a strong predictor of nursing home admission [2]. Older people are more likely to trip over obstacles and show greater behavioral adaptions to stairs [3, 4]. Trips on stairs are compounded by greater fall height and account for over 10% of fatal fall accidents [5].

In laboratory settings, reduced stair performances are associated with motor impairment, pain, fear of falling, poor vision, and reduced strength [1, 2, 6-12]. However, little is known about how stair performances measured during laboratory sessions correspond to assessments during activities of daily living (ADL) [13].

For example; compared with level walking assessed in a laboratory, older people walk with significantly lower cadences, reduced intensity, and greater variability during ADL [14]. Assessments during ADL may provide new insights into usual stair ascent performance and how behavioral strategies used to negotiate stairs (handrail use, double stepping, or avoidance) are influenced by increased age, fear, frailty, and fall risk in older people.

Recent advances in wearable devices have made remote monitoring of many daily activities possible [15-22], but accuracy may be sensitive to precise placement [23]. Wearable devices have been used to identify stair ascents and descents in younger people and/or tightly controlled environments [24-26]. However, accurate stair event classification in frail older people during ADL remains a challenge [27]. Activity recognition algorithms often rely on barometric measurement of height change, which contains noise [28].

Furthermore, in ADL, frail people may use the handrail, double step (both feet touch each step), or rest on the landing when climbing stairs. Ascents may therefore be too slow to register [29], which may be problematic for algorithms developed in tightly controlled settings.

The current paper presents new methods of identifying and characterizing stair ascent performances during ADL in older people using a freely worn pendant sensor. Our aims were to: 1) Determine device thresholds that best discriminate stair negotiation from walking; 2) Determine the accuracy of the developed algorithms in detecting stair negotiation during ADL; and 3) Investigate how stair ascent performances during ADL are associated with clinical assessments and prospectively measured falls.

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II. Methods

Fifty-two community-dwelling older adults (83 ± 4 years, Table 1) recruited from the Sydney Memory and Ageing Study [30] participated in a thirty minute free-living experiment where they were asked to perform a number of activities (such as stair climbing) that they might complete in their home environment [13, 29]. Participants wore a small pendant device during the experiment which recorded data from a tri-axial accelerometer and barometer, whilst a video camera recorded their movements to validate the accuracy of the activity classifications derived from the sensors. Participants also underwent a battery of physiological, psychological, and health-related measures. Falls were recorded prospectively over the following twelve months.

TABLE I
Participant's characteristics, Median, Interquartile Range

N=52	Median	IQR
Demographics		
Age (y)	82	6
Height (cm)	168.7	13.85
Weight (Kg)	68.8	20.85
Gender (M:F)	31:21	N/A
Health		
Co-morbidities	4	2
Psychology Health		
Concern about Falls (FES-I)	21	7.5
Depression (PHQ-9)	1	4.5
Anxiety (GAD-7)	1	2
Processing Speed		
Hand Reaction Time (ms)	224.05	42.2
Physiology Capacity		
Leg Strength (Kg)	26.74	13.9
Contrast Sensitivity (MET)	21	1
Sway on Foam (mm^2)	986	749
Proprioception (cm)	1.7	2
Falls Risk Score (PPA)	0.85	1.07

A. Free-living stair climbing protocol

The free-living experiment was performed at Neuroscience Research Australia, Sydney, Australia, in a semi-controlled environment in which participants had to navigate through corridors frequented by other members of the facility. Participants were free to decline any activity and were unaware of special emphasis on stair negotiation. During one of the walking bouts, participants ascended a 3.35 meter staircase with 19 steps with a landing after 9 steps (see Fig. 1, panel A). Afterwards they continued walking to another room, carried out various other postural transitions, which included a rest period, and then descended the same staircase. The protocol included negotiating six steps that connected two wings of the building that were not annotated as stairs because they were not considered to be long enough to complete a meaningful analysis of stair ascent variability or stair ascent stability.

B. The pendant device

The Senior Mobility Monitor (SMM) research prototype (Philips Research Europe, Eindhoven, Netherlands) is a small pendant (39.5 x 12 x 63.5 mm) containing a tri-axial accelerometer and a barometer. The accelerometer sampling frequency was 50 Hz and its range was ± 8 g. The barometer had a sampling frequency of 25 Hz and an operating pressure range of 10 to 1200 hPa. The lanyard was adjusted to a self-selected length and the device freely worn over or underneath clothing.

C. Clinical assessments

Demographics of age, height, weight, and gender were recorded. Physiological performance was assessed using the Physiological Profile Assessment (PPA) [31]. The PPA is a battery of five sensorimotor tests comprising: (i) Visual contrast sensitivity, using the Melbourne Edge Test (MET); (ii) Proprioception; (iii) Quadriceps strength while seated; (iv) Hand reaction time, using a button press in response to a light stimulus; and (v) Postural sway on foam with eyes open. Weighted contributions were then used to calculate a physiological fall risk score [31], which has demonstrated ability to identify older people who fall (higher scores indicate greater fall risk).

Health was assessed by documenting the number co-morbidities (0-9) from nine domains [32] comprising: cardiovascular; respiratory; musculoskeletal; endocrine; urogenital; cancer; neurological; mental health; and eye diseases. Falls over the following 12 months were monitored using self-reported falls calendars and monthly phone calls. Psychological health was assessed using the Patient Health Questionnaire (PHQ-9) - a 9-item questionnaire for screening of depression in which a higher score (range 0-14) indicates more depressive symptoms [33]. Concern about falling during ADL was assessed using the Falls Efficacy Scale International (FES-I). A higher score (16-64) indicates more concern about falling [34]. Anxiety was assessed using the Generalized Anxiety Disorder (GAD-7) questionnaire [35].

D. Wavelet decision tree classification of stair negotiation

Similar to previous gait analysis over level ground [14], corrections were applied to compensate for changes in device orientation. Discrete wavelet decomposition used a Daubechies 'db5' wavelet. Heel-strikes were identified by peaks in detail levels 4 and 5 of the global vertical acceleration (Fig. 1) greater than 0.5 ms^{-2} during stable orientation.

In the new methods described here, stair negotiation is further separated from flat walking by pressure changes that are negatively correlated to height. We use an adaptive threshold for rate of pressure change (scaled to the stair cadence) in order to accommodate both 'athletic' people with greater movement intensity (Fig. 1B) and 'frail' people or people who may present more cautious behavior on stairs (Fig. 1D). Algorithm training is described in the next section; the final decision tree thresholds are described below:

1. Periods of stable device orientation were found when the low frequency content (details 6 & 7) of the acceleration was below a 2.2 ms^{-2} threshold developed for level walking [14].
2. Heel-strikes were identified by peaks in details 4 and 5

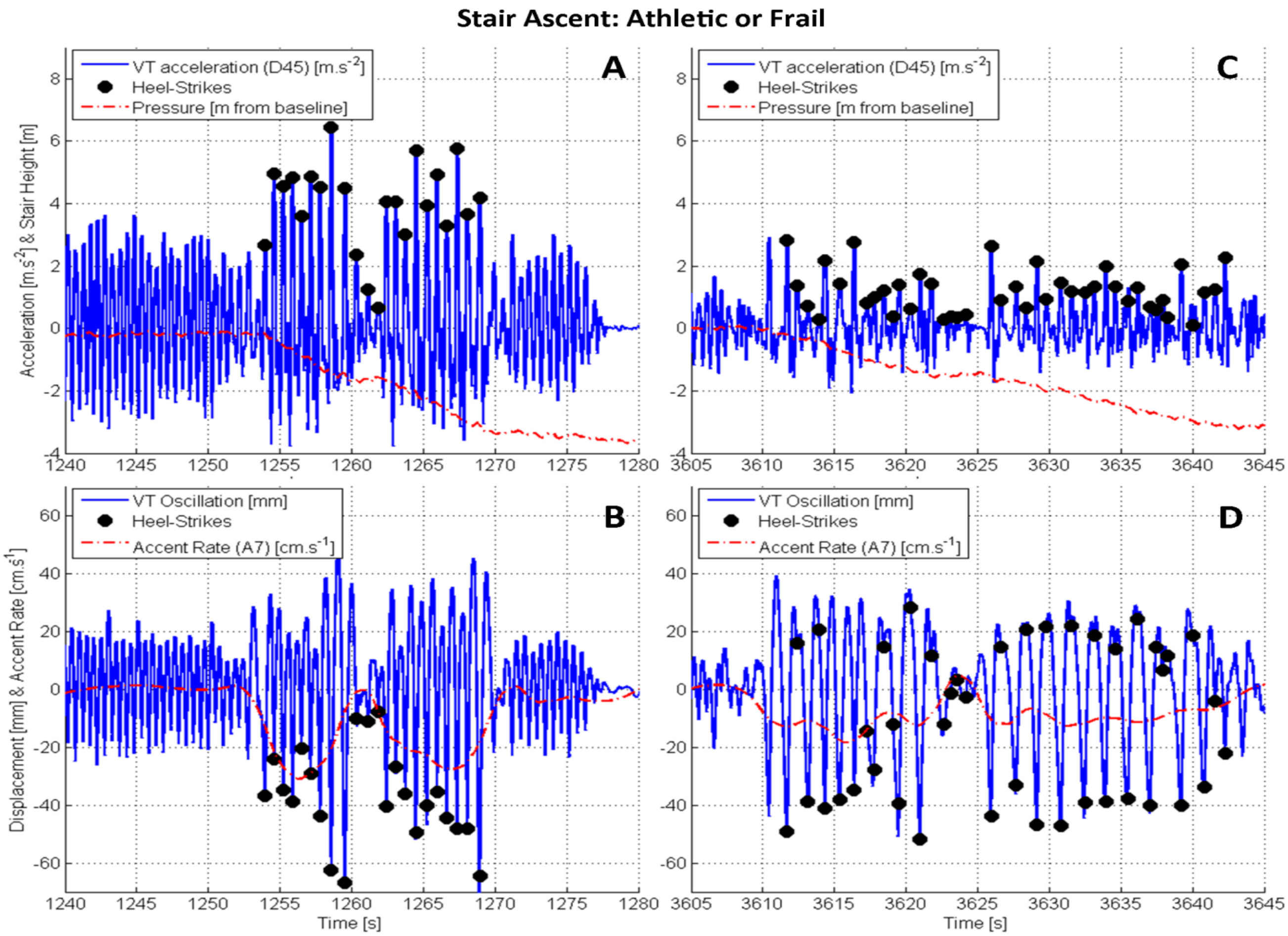

Fig. 1. Shows how periods of stair climbing were identified and difference between normal and double stepping strategies for athletic and frail. A – Acceleration peaks for an athletic participant. Dashed line shows the pressure change associated with stair climbing in meters of air. B – Vertical oscillations for the athletic participant with one heel strike (circle) per oscillation. Dashed line shows the rate of pressure change in cms^{-1} which is negatively correlated to height change. C – Acceleration peaks for a frail participant who presents reduced amplitude and more irregular peaks. D – Vertical oscillations for the frail participant with two heel strikes per oscillation indicating a double stepping ascent strategy. Dashed line show a reduced rate of ascent for the frail.

(≈2Hz & 1Hz pseudo frequencies) using a $0.5ms^{-2}$ threshold developed for level walking [14].

3. Stair cadence was calculated using 10 step moving average window. To exclude counting multiple steps on each stair peaks greater than twice the heel-strike threshold were used. Based on previous work [29] in older people, the minimum stair cadence for threshold scaling was fixed at 50 stairs/min.
4. The threshold rate of pressure change for stair negotiation ($\pm 3Pas^{-1}$) was scaled by multiplying by the stair cadence (calculated in point 3) and then dividing by the expected median cadence over flat ground (100 stairs/min) [14]. The scaled thresholds for stair climbing ranged from $\pm 1.5Pas^{-1}$ or approximately $12.5cms^{-1}$ for the 'frail' (Fig. 1D) to $\pm 3Pas^{-1}$ or $25cms^{-1}$ for the 'athletic' (Fig. 1B). Scaling was used because the group was heterogeneous with both fast and slow stair climbers (Fig. 1). Once the scaled pressure threshold was exceeded, stair boundaries were defined by crossings at one quarter the scaled threshold.
5. Partial stair events comprising a height change and walking (three or more consecutive heel-strikes) were identified.
6. To accommodate the stair landing and/or pauses by frail people, partial stair events were joined if any gaps associated with traversing the landing were shorter than 6 seconds.
7. Stair events were kept if the total step count exceeded 17.

E. Grid Search and 4-fold cross validation

Participants were randomly split into four groups and 4-fold cross validation conducted. For each fold, thresholds for nodes 4, 6, and 7 of the decision tree above were trained in 75% of the data and performance calculated with the remaining 25% "hold out" data. Training and validation were repeated four times and therefore all 48 participants were used once in one of the hold out groups. Results from the four hold out groups were combined and the median and range are reported.

During training, grid searches were used to determine the number of steps (5 to 20 steps), the rate of pressure change (1 to 5 Pas^{-1}), and the duration to traverse the landing (0 to 10 s) that best classified stairs (Fig. 2). Thresholds for ascents were made identical to thresholds for descents except the barometer threshold was inverted. Agreement between stair events detected by the algorithm and stair events annotated in the video recordings was calculated using Cohen's Kappa [36], which accounts for the bias caused by stair negotiation comprising only a fraction of the total test duration.

We also calculated accuracy, defined as the percentage of all activities (stairs or not stairs) correctly classified, false positive errors (percentage of not stairs incorrectly identified as stairs) and sensitivity (percentage of stairs correct).

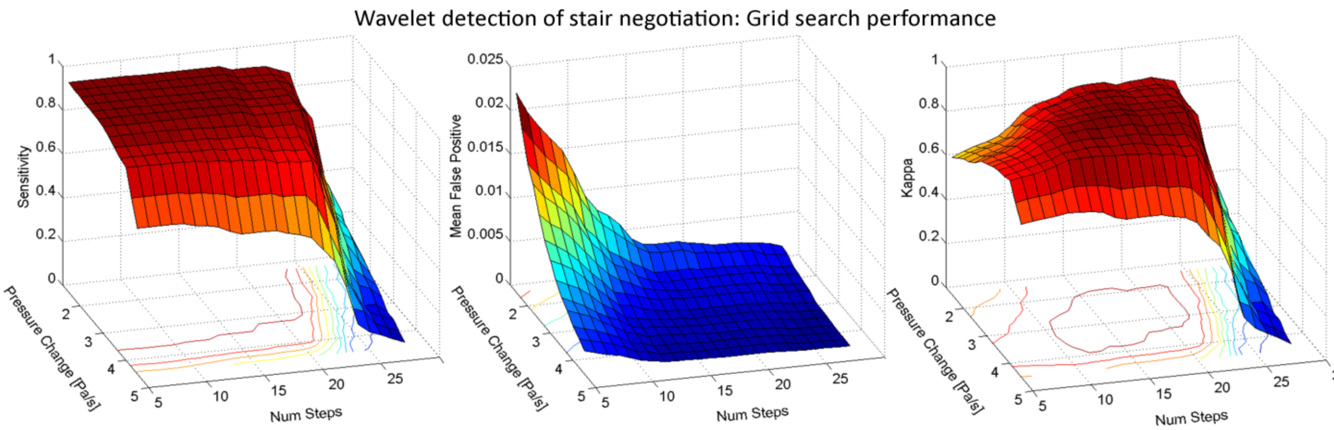

Fig. 2. Shows how accuracy of identifying stair negotiation depends on the number of steps and the pressure change thresholds ($3Pas^{-1} \approx 25cms^{-1}$).

F. *Assessment of functional stair ascent performance*

Bonafide stair ascent periods (including any pauses and steps taken to traverse the landing) were initially reprocessed with the heel-strike peak acceleration threshold halved to 0.25 ms^{-2} to ensure any shuffling steps by frailer participants were not missed. Only peaks at least 333ms apart were counted (allowing for a maximum possible cadence of 180 steps/min) to prevent double counting noise. Vertical oscillations during stair climbing (see Fig. 1B and 1D) were calculated by double integration of the vertical acceleration and high-pass filtering [37] with a cut-off frequency scaled by stair cadence.

Stair ascent performance was assessed using features derived exclusively from the wearable device data: **1) Stair ascent intensity,** measured using vertical ascent velocity (the barometric height change divided by the sensor derived ascent duration), mean cadence (the number of heel strikes divided by the sensor derived ascent duration), and acceleration peak mean (the mean of heel-strike peak height in the details 4 & 5 vertical acceleration). Greater intensity indicates more vigorous movements. **2) Stair ascent variability,** measured using step time variability (the standard deviation of step durations) and acceleration peak SD (the standard deviation of heel-strike peak heights in the details 4 & 5 vertical acceleration). In line with variability measured in level walking [38] lower variability was assumed to reflect reduced risk of falling. **3) Stair Ascent Stability,** measured by anteroposterior (AP) and vertical (VT) harmonic ratios [39].

G. *Stair negotiation strategy*

Handrail use, double stepping gait adaptions, or avoidance was categorized from the video footage. Non-parametric analysis of variance (Fig. 3) was used to investigate the association between stair strategy and duration (both derived from the video). Because significant differences were observed the follow coding based on increasing median stair duration was used: 1 = No handrail; 2 = Touch handrail; 3 = Grab handrail; 4 = Double steps (both feet on each step).

H. *Statistical analysis*

Conservative non-parametric statistics were used to compensate for the small sample size and skewed distributions. Participant characteristics were described with medians and interquartile ranges (IQR). Associations between factors were investigated using Spearman's rank correlations (Table 3), which is suitable for use with categorical variables. Post-hoc medians and IQR for sub-groups with different stair ascent strategies were investigated using the Kruskal-Wallis non-parameter analysis of variance. Significance was set at a p-value ≤ 0.05 for all tests.

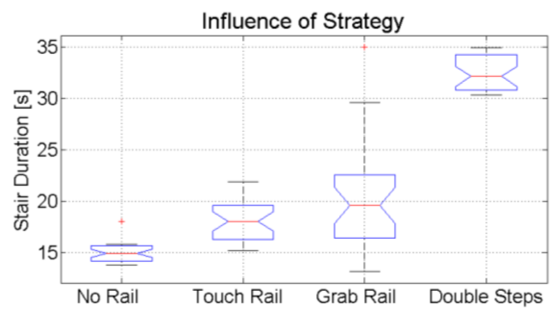

Fig. 3. Strategy significantly (p=0.001) affected time taken on stairs. Post hoc, participants who grabbed the hand rail or were double steppers took significantly ($p \leq 0.05$) longer than participants who did not use the rail.

III. Results

A. *Participants*

The median age was 82 (Table 1). In the year preceding testing, eleven people (21%) reported at least one fall and three people (6%) at least two falls. In the twelve month follow up period 43 falls were recorded; 22 people (42%) recorded at least one fall and 9 people (17%) at least two falls.

TABLE II: Stair climbing performance

N=48	Median	IQR
Stair Ascent Intensity		
Ascent Velocity [cms^{-1}]	18.1	5.7
Cadence [steps/min]	80	12
Acceleration Peak Mean [ms^{-2}]	2.61	0.77
Stair Ascent Variability		
Step Time Variability [s]	0.11	0.08
Acceleration Peak SD [ms^{-2}]	0.91	0.46
Stair Ascent Stability		
Harmonic Ratio AP	1.30	0.32
Harmonic Ratio VT	1.87	0.62

TABLE III
CORRELATIONS BETWEEN FUNCTIONAL STAIR PERFORMANCE AND PARTICIPANT CHARACTERISTICS (* SIGNIFICANT AT $P \leq 0.05$)

N=48	Stair Ascent Intensity			Stair Ascent Variability		Stair Ascent Stability		Behavior
	Ascent Velocity	Cadence	Acceleration Peak Mean	Step Time Variability	Acceleration Peak SD	Harmonic Ratio AP	Harmonic Ratio VT	Ascent Strategy
Demographics								
Age	**-0.41***	**-0.44***	**-0.40***	**0.37***	-0.20	**-0.30***	**-0.30***	**0.33***
Height	**0.32***	0.15	0.22	**-0.35***	-0.01	0.09	**0.31***	-0.17
Weight	0.12	0.06	0.16	-0.05	0.18	0.10	0.19	0.04
Gender	-0.07	-0.10	0.26	0.10	**0.41***	0.05	0.02	0.01
Health and Falls								
Co-morbidities	-0.15	-0.02	0.05	0.11	0.18	-0.13	-0.09	0.14
Falls History	0.09	0.24	0.14	-0.08	0.17	0.00	0.05	-0.24
Falls Follow-up	-0.20	-0.04	0.16	0.22	0.26	**-0.35***	-0.13	0.21
Psychological Health								
Concern (FES-I)	**-0.43***	-0.22	-0.18	**0.34***	0.04	**-0.30***	-0.27	**0.37***
Depression (PHQ-9)	-0.11	-0.09	-0.13	0.17	-0.03	-0.02	-0.12	0.15
Anxiety (GAD-7)	0.07	0.05	0.09	-0.09	0.04	-0.03	0.06	0.02
Processing Speed								
Hand Reaction Time	-0.24	**-0.30***	**-0.38***	**0.36***	-0.10	-0.25	**-0.29***	**0.43***
Physiological Capacity (Frailty)								
Leg Strength	0.20	0.18	-0.06	-0.21	-0.17	0.05	0.09	-0.08
Contrast Sensitivity	0.19	0.13	**0.31***	-0.07	**0.32***	0.05	0.19	-0.19
Sway on Foam	0.05	-0.18	-0.23	-0.05	-0.13	-0.02	0.00	-0.12
Proprioception	-0.04	-0.08	-0.16	0.05	-0.13	-0.04	-0.15	-0.17
Falls Risk Score	-0.08	-0.25	**-0.41***	0.14	-0.26	**-0.32***	-0.28	0.22
Behavior (Hand rail use – double stepping – avoidance)								
Ascent Strategy	**-0.67***	**-0.51***	**-0.41***	**0.63***	0.00	**-0.40***	**-0.36***	N/A

B. *Classification performance*

Using 4-fold grid search optimization (Fig. 2) medians and ranges of thresholds for the decision tree were: Minimum steps 17 (15 to 17); barometer threshold 3 Pas^{-1} (2.75 to 3.0 Pas^{-1}); and landing pauses of shorter than 6 s (5 to 6s). In the hold out data, performance medians and ranges were: Kappa 0.92 (0.90 to 0.94); accuracy 99.8% (99.6 to 99.8%); sensitivity 94.7% (89.3 to 95.4%); and false positive errors of 0.10% (0.07 to 0.32%).

C. *Functional stair ascent performances*

Four participants avoided the stairs and gave the following reasons; "blocked aorta causes discomfort and not comfortable on stairs", "had cerebellum removed, balance is not the same as before", and "my husband says I am very frail". For the remaining 48 participants; median ascent velocity was 18.1 cm/s, median stair cadence was 80 steps/min, and step time variability was 0.11 s (Table 2). With respect to strategy; seven participants did not use the rail, six touched the rail, thirty-one grabbed the rail, and four were double steppers.

D. *Correlations with clinical assessments*

Functional stair ascent performances across all domains (intensity, variability, and stability) were significantly correlated with age, concern about falling, processing speed and ascent strategy (Table 3). Participants who ascended the stairs with reduced intensity, greater variability, and decreased stability took more protective measures (r = -0.67), were older (r = -0.44), had greater concern about falling (r = -0.43), and had slower hand reaction times (r = -0.38).

For our participants, height was an advantage. Increased height was correlated with reduced step time variability (r = -0.35), increased stair ascent velocity (r = 0.32), and increased stability (r = 0.31). Increased ascent performances were also correlated to increased contrast sensitivity (r = 0.32) and decrease fall risk scores (r = -0.41).

Falls in the follow-up period was significantly correlated with reduced stair ascent stability (r = -0.35). Health with respect to number of co-morbidities and falls history was not significantly correlated to stair climbing performance. Ascent strategy was significantly correlated with slower hand reaction times (r = 0.43), increased concern about falling (r = 0.37) and increased age (r = 0.33), but not measures of health, falls, physiological capacity or frailty.

E. *Subgroup analysis; falls, avoidance, and double stepping*

The four people who avoided stairs had significantly higher concern about falling (FES-I median 27.5, IQR 4.5) but similar fall risk scores (median 0.29, IQR 1.42) and all suffered adverse outcomes in the follow-up year; one died, and the other three recorded a total of five falls. Conversely, the four people who were double steppers (both feet on each step) all recorded no falls over the follow up period, but had significantly higher fall risk scores (median 1.52, IQR 0.51) and lower contrast sensitivity (MET median 18.5, IQR 5).

IV. DISCUSSION

A. *Validation of stair even classification*

Building on previous work using fixed sensors [23-26], we found stairs between floors could be identified using a pendant device. Classification performance was insensitive to small changes in step count or pressure thresholds (Fig. 2). Sensitivity (left panel) dropped when the step threshold exceeded 20 because the staircase contained 19 steps. False positive errors (middle panel) increased when the step threshold dropped below 8 steps or the pressure threshold dropped below 2 Pas^{-1} possibly because of barometer noise [28]; when participants entered different areas of the climate controlled building, walked quickly towards the end of a corridor (possibly causing pressure build up) or vigorously down an inclining corridor. Higher step thresholds (≥17 steps) prevented such noise affecting classification performance.

The range of classification accuracy of the pendant device (99.6-99.8%) during ADL in our sample of 48 older people agrees with the best cases reported in more controlled settings and for younger people: 98% for a shoe device in 9 adults [24]; 98% for body mounted devices in 20 adults [25]; and 99% for a foot mounted device in 4 adults [26].

Improving on previous research using a smart-phone during ADL [29]; no cautious stair negotiations by ‘frail’ people were missed and no vigorous movements by ‘athletic’ people were mistaken for stairs. Instead, errors related to defining the exact beginning or end of each stair negotiation. Scaling the fixed barometer threshold by stair cadences gave the decision tree algorithm greater adaptability to identify both fast and slow stair negotiation by both ‘athletic’ and ‘frail’ people (Fig. 1).

B. Comparisons with previous stair negotiation studies

In agreement with previous research [1, 4, 6-13] we found stair ascent performances were correlated with multiple health, physiological and psychological factors. In previous clinical studies stair performance has been measured by time taken [1, 6-8], gait kinematics [4, 9-10, 19-20], and extrapolated center of mass [12]. Wearable devices attached to the lower back and ankles have also been used to quantify stair performance using dominant frequency, dominant peak width, and signal variance [13]. Previously stair performance has been correlated with age [1, 6, 10-11, 13], leg strength [1, 6-8], fear [1, 11], visual acuity [1, 9], ambient lighting [10-11] and postural sway [13].

Similar to previously reported r-values up to -0.45 for age [13] and -0.33 for leg strength [1], we observed mostly weak univariate relationships. Previously multiple regression models [1, 6] have revealed stronger relationships (with r^2 values up to 0.50), which suggests performance decline in older people may be a complex multi-factorial problem [40].

C. Advantage of the free-living protocol

Different to previous stair negotiation studies [1, 4, 6-12], our free-living experiment may have enabled measurement of usual rather than optimum performance [14]. Since stairs were only a part of the protocol, performances may have been less affected by motivation to perform well in a laboratory “test situation” and more related to usual daily-life performances.

In contrast to most previous research measuring optimum stair performance, we found no significant correlation between leg strength and usual stair performance. Apart from contrast sensitivity, no other univariate measures of physiological capacity, depression, anxiety, falls history, or health had a significant correlation with usual stair ascent performance. In our group of relatively healthy older people, we found usual stair ascent performance during ADL was most associated (r = -0.67) with ascent strategy. Furthermore, both ascent strategy and usual ascent performances had a greater number of significant correlations with mental factors, concern about falling, processing speed, and age than any correlations with frailty, health, or leg strength.

By analyzing vertical oscillations [37], it was possible to identify the more cautious double stepping strategy used by four participants. During normal stair ascent we observed a one-to-one relationship between stepping and vertical oscillations (Fig 1B) but for double steppers a two-to-one relationship was observed (Fig. 1D). Interestingly, participants who chose to ascend the stairs using a careful double stepping strategy (possibly appropriate response to their reduced contrast sensitivity) recorded no follow-up falls, despite their increased physiological fall risk scores. In contrast, participants who avoided the stairs had significantly higher concern about falling, but not higher physiological fall risk scores, and all had poor 12 month health outcomes.

For most of our relatively healthy older people the stair ascent strategies (ranked by ascent duration) may partly reflect an appropriate behavioral response to slower cognitive processing speeds and increased concerns about falling. Conversely, our observations suggest complete avoidance of stairs during ADL may be associated with poor longer term health outcomes in some people.

D. Limitations

We acknowledge certain limitations. Not all observations may be generalizable for all people. Sample characteristics need to be considered when interpreting the results (Table 1). Participants were mostly ‘fit octogenarian survivors’. Median age was 82 years and 42 of the 52 were over eighty. Participants were 70+ years when they initially took part in the Sydney Memory and Ageing Study and had survived to the fourth study wave. Furthermore, the participants volunteered for a thirty minute free-living experiment, which implicitly may have excluded people with mobility impairments. Fall risk scores (median 0.85, IQR 1.07) were marginally better than expected for the age-range of the group [31].

Analysis revealed that both ascent strategy and participant height were confounding factors that affected pendant derived measures of functional stair ascent performance, which may need consideration in future analyses of remote activity data. Subgroup observations related to cautious double stepping and avoidance need to be confirmed using larger data sets. Future research should also investigate stair descents, hill climbing, transfer movements, other ADL, and adherence to the pendant device during long-term monitoring of larger populations.

V. CONCLUSIONS

Using a freely worn pendant device, stair events were identified with sufficient accuracy to make long term remote monitoring during ADL feasible. Scaling the barometer threshold by stair cadence made the decision tree robust to barometer noise and various stair ascent strategies by both frail and athletic people. Complementary to over-ground walking, remote monitoring of ADL provides insights into usual rather than optimal performance and to the extent that age, fear, frailty, and behavior may interact influencing falls and healthy aging. As acceptance of wearable devices is increasing, it is likely that reduced functional performances and altered strategies for undertaking ADL may soon be routinely tracked to augment health care of older people.

VI. Conflict of Interest

The SMM devices were provided by Philips Research.

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