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Prediction of balance perturbations and falls on stairs in older people using a biomechanical profiling approach: A 12-month longitudinal study

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1. Abstract

Background: Stair falls are a major health problem for older people, but presently there are no specific screening tools for stair fall prediction. The purpose of the present study was to investigate whether stair fallers could be differentiated from non-fallers by biomechanical risk factors or physical/psychological parameters and to establish the biomechanical stepping profile posing the greatest risk for a stair fall.

Methods: Eighty-seven older adults (age: 72.1±5.2 y) negotiated an instrumented seven-step staircase and performed a range of physical/psychological tasks. K-means clustering was used to profile the overall stair negotiation behaviour with biomechanical parameters indicative of fall risk as input. Falls and events of balance perturbation (combined “hazardous events”) were then monitored during a 12-month follow-up. Cox-regression analysis was performed to examine if physical/psychological parameters or biomechanical outcome measures could predict future hazardous events. Kaplan-Meier survival curves were obtained to identify the stepping strategy posing a risk for a hazardous event.

Results: Physical/psychological parameters did not predict hazardous events and the commonly used Fall Risk Assessment Tool (FRAT) classified only 1/17 stair fallers at risk for a fall. Single biomechanical risk factors could not predict hazardous events on stairs either. On the contrary, two particular clusters identified by the stepping profiling method in stair ascent were linked with hazardous events.

Conclusion: This highlights the potential of the stepping profiling method to predict stair fall risk in older adults against the limited predictability of single parameter approaches currently used as screening tools.

Keywords: fall risk, stair negotiation, clustering, stepping behaviour.

2. Introduction

A significant number of older people get injured or die every year following a fall, with stair falls accounting for 60% of all fall-related deaths (1). Identifying the individuals at risk for a fall is necessary to deliver effective fall prevention interventions. At community level, there are various fall risk screening tools available. In the UK, the Fall Risk Assessment Tool (FRAT) is most commonly used (2). Although the existing fall risk screening tests, including the FRAT, are not stair-specific, they encompass physical and psychological parameters that are associated with stair negotiation performance, such as parameters related to vision, vitality, dynamic balance, strength, fear of falling and balance confidence levels (1, 3, 4). Thus, the general fall risk screening tools assume that a person identified to be at risk for a general fall will also be at risk for a fall on stairs. However, it should be noted that stair negotiation is a complex and specific skill, and can be executed using different techniques that can be adjusted to the capabilities and deficits of the individual. For example, older adults with balance deficits could minimize stair fall risk by relying more on the handrails and/or negotiating the stairs in a step-by-step manner, as both strategies allow more effective balance control (5, 6). However, generic fall screening methods do not encompass this individual ability to adjust stepping technique and, thus, it is questionable whether they can identify older people at risk specifically for stair falls.

Fall risk detection using stair-specific biomechanical testing requires access to a lab and typically quantifies mean differences between subject groups for single biomechanical parameters indicative of risk for example, a reduced foot clearance to the stair edge, which increases the chances of a trip (7). However, this grouping approach overlooks the fact that certain individuals within a group may also display more conservative stepping strategies, which could potentially compensate for the risky strategies. For example, it has been reported that older adults displaying increased variability in foot clearance, which is a risky strategy for a trip, also displayed an increased foot clearance, which minimises trip risk (8). We recently established a novel multivariate approach that circumvents this limitation by profiling individual stepping strategies based on multiple parameters reflecting both risk and safety on stairs (8). The profiling approach showed that older adults display various stair negotiation behaviours that consist of both risky and conservative strategies. However, an overall biomechanical stepping profile at greatest risk for a stair fall has not been established yet. In addition, access to specialised lab facilities and instrumented staircases is a practical issue that would preclude the implementation of the biomechanical profiling method as a fall predictive tool at community level. Therefore, easily quantifiable physical/psychological parameters that underpin the overall stepping profile of an individual should be identified for stair fall risk detection in large-scale populations. A study of Tiedemann et al. (2007) identified a range of easily quantifiable physical/psychological parameters that are associated with stair negotiation performance (e.g. knee extension strength, contrast sensitivity, leaning balance, fear of falling and vitality scores) (4). However, at present we do not know which of these parameters are linked with a given biomechanical stepping profile.

Here we have, therefore, adopted a prospective study design to: 1) investigate whether participants who would go on to experience stair falls or balance perturbations on stairs over a 12-month follow up period could be differentiated by a biomechanical risk factor or physical/psychological parameters, 2) establish the overall stepping profile linked with the greatest number of falls and balance perturbations sustained and identify easily measurable physical/psychological parameters underpinning this stepping profile.

3. Methods

3.1 Participants

Eighty-seven older adults (28 Males; age: 72.1±5.2 y; body height: 1.66±0.20 m; body mass: 71.4±14.6 kg) participated in the study. All participants lived independently and were recruited from the local community of Liverpool, UK. Participants who were younger than 65 years of age, did not use stairs in daily life or used any other aid apart from the handrail to negotiate stairs were excluded. Written informed consent was obtained after the procedures and possible risks of the study were explained. The study was approved by the NHS research ethics committee in the UK (IRAS ID: 216671) and was conducted in accordance with the Declaration of Helsinki.

3.2 Staircase measurements

The measurements were taken on a custom-built instrumented seven-step staircase. This measurement set-up has been described in detail previously (8). Briefly, kinematics were obtained using a 24 infrared camera-system (16 MX T-series and 8 Bonita cameras, 120Hz, Vicon, Oxford Metrics, UK) and ground reaction forces were obtained through four force platforms (1080Hz, 9260AA, Kistler AG, CH) embedded in the lower four steps. The staircase configuration was set in accordance with the UK building regulations and represented a staircase in a typical private home (9, 10), with the rise set at 20 cm and run at 25 cm, resulting in a pitch of 38.7°.

Trials were performed with participants clothed in tight fitting shorts and shirt and wearing their own comfortable shoes (no boots, heels or sandals). Participants were fitted in a five-point safety harness, which was attached to the overhead belay safety system. To allow familiarisation with the experimental setup and safety harness, participants performed up to five practice trials. Afterwards, participants ascended and descended the staircase five times at their self-selected pace and manner. Participants who used the handrails either with one hand or both hands were asked, only if they were confident to do so, to negotiate the stairs five more times without using the handrails. The final three trials were used for analysis.

3.3 Data analysis staircase measurements

Full-body kinematics were obtained using a 15 segment (head, thorax, pelvis, upper arms, lower arms, hands, thighs, shanks, feet) full-body six-degree of freedom kinematic model defined by 76 reflective markers (diameter 14mm). The segmental data were based on Dempster's regression equations (11) and used geometrical volumes to represent each segment (12). The position of the whole body CoM was estimated as the weighted sum of the various body segments using Visual3D (C-Motion, Germantown, USA). For further analysis the ground reaction forces and kinematic data were filtered using a low-pass fourth order Butterworth filter with a cut-off frequency of 6 Hz. In each of the four force platforms, heel strike was determined in the first frame in which the vertical GRF was greater than 20 N and toe-off was determined in the first frame in which the vertical GRF was less than 20 N.

The methods used to obtain the biomechanical outcome measures of the present study have been presented in detail (8), therefore only a brief description of the relevant outcome measures will be presented here. The outcome measures included: *1) Foot clearance.* The foot clearance was calculated for both ascent and descent during the swing phase over steps 1-5 as the minimal clearance between the leading limb and the step edge (8). *2) Proportion of foot length in contact with stair (PFLCS).* PFLCS was calculated at touch-down on steps 2-4 for ascent and 1-4 for descent. The parameter was calculated using the distance of the horizontal projection of the most posterior aspect (distance x) and the most anterior aspect (distance y) of the shoe outline to the step edge (PFLCS = (distance x / (distance x + distance y))*100%). *3) Required coefficient of friction (RCOF).* The RCOF was calculated by dividing the resultant shear force (vector sum of the mediolateral and antero-posterior force) by the vertical force at each sample in time (13). The peak RCOF was determined during the push-of phase for stair ascent on steps 2-4 and during the loading phase of stance for stair descent on steps 1-4 using Visual3d (C-Motion, Germantown, USA) after a threshold of 50 N for the vertical force was exceeded. *4) Cadence.* The mean cadence of two gait cycles (one for the left limb and one for the right limb) across the three trials was considered for further analysis. 5*) Maximal CoM angular acceleration (only for stair descent)*. The angular acceleration was calculated for the angle between the CoM and CoP position of the trailing leg. The maximal angular acceleration of the CoM was obtained as the peak value during the swing phase for steps 1-4 during stair descent. *6)* In addition to the parameters listed (1-5), *the trial-to-trial variability of these parameters* were calculated as the mean of the variability across the three trials for each of the analysed steps separately. Variability in itself is a risk factor for falls, as higher variability can indicate a person's inability to maintain a steady/safe movement pattern (14).

3.4 Physical/psychological parameters

A range of physical/psychological parameters were measured following the stair measurements. These measurements were selected due to their relevance regarding stair negotiation performance and feasibility at community level (4). Relevant person-related factors such as age, body height, body mass, number of medications and number of falls in the previous 12-months were self-reported.

The following questionnaires were completed: the Activities-specific Balance Confidence Scale (ABC), to assess self-perceived balance confidence while performing daily activities (15), the Falls Efficacy Scale-International (FES-I), to assess concern about falling while completing activities of daily living (16), the Montreal Cognitive Assessment (MoCA) to assess the cognitive functioning (17) and the Nottingham extended Activities of Daily Living

(NADL) index to assess the functional status (18). The FRAT was completed to determine fall risk (2).

Measures of vision included visual acuity and contrast sensitivity and these were obtained using the Freiburg Vision Test (FRACT) (19).

Balance measures included the Berg Balance Scale (BBS), which addresses anticipatory balance control with and without a change in base of support during 14 different functional tasks (20), and the Functional reach test, which provides information related to anticipatory balance control without a change in base of support while reaching forward (21). In addition, the single leg stance test, which is included in the BBS, was also included as a separate measure and performed for a prolonged period of 30 seconds while the number of times the participant had to regain their balance was recorded.

The Range of Motion (RoM) was assessed actively and passively for the hip flexion, knee flexion and ankle plantar and dorsal flexion in the supine position using a goniometer (22).

Handgrip strength and lower body strength were measured. Handgrip strength was obtained using a handgrip dynamometer (TKK 5401, Takei Scientific Instruments, Tokyo, Japan). Isometric muscle forces of hip flexion, hip abduction, knee flexion and knee extension were obtained using a handheld myometer (M500 MyoMeter, Biometrics Ltd, UK). The participants performed a 'make' test with participant's position and dynamometer placement as described by Andrews et al. (1996) (23). The maximal torque was calculated and normalized for body mass (N·m/kg).

The six tests of the Fullerton Functional Fitness Test were included as single independent outcome measures (24): 1) The amount of chair stands performed in 30 sec., to measure functional lower body strength; 2) The amount of arm curls performed in 30 sec., to measure functional upper body strength; 3) The amount of steps performed within a 2-min step test, to measure physical stamina; 4) Chair sit and reach, to measure lower body flexibility; 5) Back scratch test, to measure upper body flexibility and 6) Timed up and go, to measure speed, agility and balance (24).

3.5 Recording of stair falls and balance perturbations

Subsequent to the baseline assessments, a 12-month follow-up with monthly contact via phone calls or email was made to register the occurrence, circumstances and self-perceived causes of falls and balance perturbations during both ascent and descent within this period. The participants were provided with a diary to record falls and balance perturbations daily and encouraged to contact the research team as soon as an incident had occurred. A fall was defined as the outcome of the person losing their balance, causing them to hit the stairs with their body (including hands) during ascent or descent. Instances of instability, including trips and slips, where balance was regained following the perturbation, were also recorded. Furthermore, any changes in living conditions (e.g. admission to a care home or installing a stair lift) and life events (e.g. a heavy accident that would prevent them from negotiating stairs) that could potentially result in dropping out of the follow-up were recorded.

3.6 Statistical analysis

A multivariate method (8) was applied to the data of the older adults that were confident enough to not use handrails (N=72) during the stair test. The older adults who were dependent on the handrails were excluded and clustered together as a separate group, as they already adopt a distinct overall stair-negotiating strategy. The multivariate method profiled the individual stepping strategies of the older adults based on the biomechanical outcome measures (1-6) using k-means clustering. The optimal number of clusters was determined through the SeCo framework, this method has previously been described in detail (25-27). To examine differences in the composition of each cluster, the cluster profiles (CP=($\text{Mean}_{\text{cluster}}$–$\text{Mean}_{\text{overall}}$)/$\text{SD}_{\text{overall}}$) were calculated for all outcome measures with a threshold set at 0.5. To determine the underlying physical/psychological capabilities of each cluster, including the handrail dependent cluster, we carried out a logistic regression analysis using a forward stepwise procedure for each cluster separately with the physical/psychological parameters as input. Presence in the specific cluster was used as the dependent variable for each cluster separately (0 = present within one of the other clusters, 1 = present in the analysed cluster). The potentially low sample size does not affect the outcome of the logistic regression, as the goal was to elucidate which variables explain the specific clusters, rather than to make decisions using predictions about individual subjects. In addition, no adjustments (e.g. Bonferroni correction) were deemed necessary for the logistic regression, as these apply to multivariate models. The predictive power of each logistic model was evaluated by the area under the receiver operator characteristic curve (AUC) (28).

Stair falls and events of balance perturbation were combined and referred to as “hazardous events”. Kaplan-Meier survival curves and log-rank tests were performed to identify the stepping strategy with the greater risk of falling. The time to, and occurrence of, the first hazardous event within 12 months of follow-up were used as factors. Subsequently, the hazard function was plotted to investigate how the hazard rate for obtaining a hazardous event amongst the ‘survivors’ changed over time (29). Furthermore, a forward stepwise Cox-regression analysis was executed to examine if the physical/psychological parameters could predict hazardous events on stairs. In addition, a Cox-regression analysis was performed to examine if the single biomechanical outcome measures (1-6) identified as risk factors in the literature could predict hazardous events during stair ascent and descent. Statistical analyses were performed using SPSS (version 24, SPSS Inc., California, USA) and Matlab (R2018a, Mathworks, Natick, USA). The significance level was set at α=0.05.

4. Results

4.1 Participants

Eighty-seven older adults (free from cognitive impairments; MoCa: 27.6±2.3) were recruited and completed the baseline assessments. Approximately 40% of the participants used the handrails the first time they negotiated the staircase, and 60% of these participants were confident enough to negotiate the staircase without handrails afterwards. The strategies of handrail use varied between participants, with some participants using one side and others both sides. Nonetheless, there were no significant differences in vertical GRF and CoM acceleration when the trials with handrail usage were compared to the trials without handrail usage.

Five participants dropped out, leaving 82 older adults who completed the 12-month follow up period. Reported reasons for dropping were: installing a stair lift at home (1 older adult), car accident that made them physically unable to negotiate stairs (2 independent older adults), unspecified reasons for losing contact (2 older adults). Stair fall and balance perturbation data up until participants dropped out were included in the analysis.

4.2 Hazardous events

During the 12-month follow-up period, 40 out of the 87 older adults reported at least one generic fall and 17 out of these 40 fallers reported at least one fall specifically on stairs. In addition, 12 older adults had an event of balance perturbation on the stairs. For stair ascent, 13 older adults (14.9%) reported at least one fall and 8 older adults (9.2%) had an event of balance perturbation (Table 1). These combined were predominantly caused by a trip (90.4%) and approximately 20% resulted in minor injuries, such as cuts and bruises. For stair descent, 4 older adults (4.6%) reported at least one fall and 4 other older adults (4.6%) had an event of balance perturbation (Table 2). These combined varied in terms of their cause between a trip

(37.5%), loss of CoM control (25.0%), missing a step (25.0%) and a slip (12.5%). Four hazardous events resulted in injuries (50.0%), with one stair fall resulting in two fractures in the foot, requiring hospital admission.

4.3 Stair ascent stepping strategies

The SeCo framework revealed that 3 was the optimal number of clusters for stair ascent (cluster 1: 37; cluster 2: 24; cluster 3: 11 older adults). The CP revealed that cluster 1 differed from the overall mean by displaying higher PFLCS (CP=0.66) and lower cadence (CP=-0.60) (Table 3). Cluster 2 differed from the overall mean by displaying less PFLCS (CP=-0.71), higher RCOF (CP=0.57) and higher cadence (CP=0.78) (Table 3). Cluster 3 differed from the overall mean by displaying a higher variability in foot clearance (CP=1.44), less PFLCS (CP=-0.67), a higher variability in PFLCS (CP=0.66), a higher variability in RCOF (CP=1.10) and a higher variability in cadence (CP=1.72) (Table 3). Cluster 4 included the participants (N=15) which differed from the other clusters in their overall stepping strategy by depending fully on the handrails.

The logistic model for cluster 1 during stair ascent (χ^2=34.01; p<0.001) revealed that membership of this cluster could be predicted by a lower score on the visual acuity test (OR=0.128, CI=0.016–0.991, p=0.049), lower hip flexion strength (OR=0.002, CI=0.000–0.107, p=0.002), greater passive knee flexion RoM (OR=1.116, CI=1.021–1.219, p=0.015), higher score on the BBS (OR=2.387, CI=1.466–3.886, p<0.001) and greater number of medications (OR=1.515, CI=1.087–2.110, p=0.014), resulting in a high prediction accuracy (AUC=0.822, p < 0.001). The logistic model for cluster 2 (χ^2=14.86; p<0.001) revealed that membership of this cluster could be predicted by a smaller number of medications (OR=0.551; CI=0.379–0.803; p=0.002), resulting in a high prediction accuracy (AUC=0.748, p<0.001). The logistic model for cluster 3 (χ^2=18.51; p<0.001) revealed that membership of this cluster could be predicted by a greater hip flexion strength (OR=239.874; CI=4.503–12777.112; p=0.007), higher score on the functional reach test (OR=1.145; CI=1.008–1.302; p=0.037) and lower score on the back scratch test (OR=0.920; CI=0.852–0.992; p=0.031), resulting in a high prediction accuracy (AUC=0.853, p < 0.001). The logistic model for the handrail-dependent cluster 4 (χ^2=71.71; p<0.001) revealed that membership of this cluster could be predicted with 100% accuracy (Nagelkerke R^2=1.0) by a smaller passive knee flexion RoM, smaller active hip flexion RoM and lower score on the BBS, resulting in a very high prediction accuracy (AUC=0.990, p<0.001).

4.4 Stair descent stepping strategies

For stair descent, 4 was the optimal number of clusters (cluster 1: 8; cluster 2: 21; cluster 3: 17; cluster 4: 26 older adults). The CP revealed that cluster 1 differed from the overall mean by displaying a higher variability in foot clearance (CP=0.52), less PFLCS (CP=-0.62), a higher variability in PFLCS (CP=1.95), less RCOF (CP=-0.91), higher cadence (CP=1.03) and a higher variability in cadence (CP=1.66) (Table 3). Cluster 2 differed from the overall mean by displaying less foot clearance (CP=-0.73) (Table 3). Cluster 3 differed from the overall mean by displaying a higher CoM angular acceleration (CP=1.25) and a higher variability in CoM angular acceleration (CP=1.41) (Table 3). Cluster 4 differed from the overall mean by displaying a higher foot clearance (CP=0.78), lower CoM angular acceleration (CP=-0.54), a lower variability in CoM angular acceleration (CP=-0.54) and lower cadence (CP=-0.79) (Table 3). Cluster 5 included the participants (N=15) which differed from the other clusters in their overall stepping strategy by depending fully on the handrails.

The logistic model for cluster 1 (χ^2=10.50; p=0.001) revealed that the presence of an older adult in this cluster could be predicted by a greater hip flexion strength (OR=330.320, CI=6.896–15822.421, p=0.003), resulting in a high prediction accuracy (AUC=0.854, p=0.001). The logistic model for cluster 2 (χ^2=17.56; p<0.001) revealed that membership of this cluster could be predicted by a higher score on the visual acuity test (OR=6.648; CI=0.976–45.298; p=0.053) and a higher number of steps on the 2 min step test (OR=1.026; CI=1.010–1.042; p=0.002), resulting in a high prediction accuracy (AUC=0.801, p<0.001). The logistic model for cluster 3 (χ^2=20.06; p<0.001) revealed that membership of this cluster could be predicted by a greater active dorsi-flexion RoM (OR=1.202; CI=1.034–1.397; p=0.017), a lower score on the back scratch test (OR=0.935; CI=0.881–0.992; p=0.026) and a higher score on the ABC scale (OR=1.275; CI=0.998–1.630; p=0.052), resulting in a high prediction accuracy (AUC=0.830, p<0.001). None of the physical/psychological parameters could predict the presence of an older adult in cluster 4. Since the handrail-dependent individuals were grouped separately the logistic model for cluster 5 during stair descent was the same as the logistic model of cluster 4 during stair ascent.

4.5 Prediction of hazardous events

Overall, there was a constant risk for a hazardous event during stair ascent and descent (Figure 1A, B). For stair ascent, hazardous events could not be predicted by any of the physical/psychological parameters as no significant Cox-regression model could be obtained. Similar to stair ascent, none of the physical/psychological parameters on their own could predict hazardous events in stair descent, as the obtained Cox-regression model (χ^2=22.922; p=0.003) included eight non-significant physical tests (contrast sensitivity, hip abduction strength, passive plantar flexion RoM, active knee flexion RoM, timed up and go, single leg stance test, 2-minute step test and handgrip strength; p=0.360–0.479). The single biomechanical outcome measures could also not predict hazardous events, as the obtained cox-regression models were non-significant for stair ascent (χ^2=7.925; p=0.441) and descent (χ^2=10.070; p=0.434).

For both stair ascent and descent, hazardous events were spread over the clusters identified (Table 1, 2). The stepping strategy at a greater risk for a hazardous event could not be identified using the Kaplan-Meier survival analysis for either stair ascent (log rank test: χ^2=2.324; p=0.508) or descent (log rank test: χ^2=1.100; p=0.894) (Figure 1C, D). However, it is evident that clusters 1 and 2 during stair ascent (Figure 1C) display an exponential distribution, indicating that the hazard rate, which is the probability of a hazardous event (30), does not change with time ($h(t)=\lambda$). This is confirmed by plotting the hazard function over time for these clusters (Figure 2A), which indicates that the hazardous events are directly related to the stair-negating strategy of these clusters (29). For stair descent, cluster 2 appeared to display an exponential distribution, indicating a constant hazard (Figure 1D). However, the hazard rate of this cluster was low compared to the rate of the cluster 1 and 2 in stair ascent (Figure 2A) and did not differ from cluster 4 and 5 in descent, which also showed a tendency for an exponential distribution (Figure 2B). Therefore, it is not possible to relate the hazardous events directly to the stair-negating strategy of cluster 2 (29).

5 Discussion

In the present study, we adopted a 12-month prospective design and sought to establish 1) the predictability of stair fall risk from easily quantifiable physical/psychological parameters and 2) the overall stepping profile that predisposes to a risk for a hazardous event on stairs. Hazardous events in ascent or descent could not be predicted using the physical/psychological parameters, or the FRAT. In contrast, the multivariate method revealed that two out of the four overall stair ascent strategies were predictive of hazardous events. For stair descent, the hazardous events were not directly associated with the identified stepping behaviours. Although not all the hazardous events could be related to a specific stepping strategy, the underlying physical/psychological parameters of most of the specific stepping strategies were identified for both stair ascent and descent.

5.1 Biomechanical stepping strategies and underlying physical/psychological capabilities

The multivariate biomechanical approach identified three clusters for stair ascent. Cluster 1 displayed a higher PFLCS, which reduces the risk for a slip, and a lower cadence, which reduces the risk for both a slip and trip (31). This more conservative strategy was linked with a lower visual acuity, lower hip flexion strength, higher passive knee flexion RoM, higher score on the BBS and polypharmacy. The reduced visual acuity and strength, and polypharmacy could possibly outweigh the improved balance and knee RoM and, therefore, explain why individuals in cluster 1 adopted a more conservative stepping strategy (1, 4, 32, 33). Cluster 2 adopted a more risky strategy by displaying a lower PFLCS, a higher RCOF and higher cadence, which increase the risk for both a slip and a trip (31, 34). This more risky strategy is linked to a reduced medication intake, which indicates a better overall fitness that could potentially offset some of the risky strategies adopted (33). Cluster 3 displayed a lower PFLCS and a higher variability in foot clearance, PFLCS, RCOF and cadence; the risk for a slip combined with greater variability can indicate a person’s inability to maintain a steady/safe movement pattern (14). This overall riskier strategy was linked to higher hip flexion strength, increased functional reach and reduced back scratch performance. The greater strength and improved balance could outweigh the reduced upper body flexibility and allow the individuals to adopt a riskier overall strategy (1, 4). Cluster 4 depended fully on the handrails and therefore displayed an overall conservative strategy, which was linked with a reduced active hip RoM, a reduced passive knee RoM and poorer performance on the BBS. This suggests that for cluster 4, the handrails were necessary to improve stability and mitigate the negative effect of reduced RoM on stair ascending ability (4, 32).

For stair descent, the multivariate approach identified four clusters. Cluster 1 displayed a higher variability for foot clearance, PFLCS and cadence, indicating that the individual has a limited ability to maintain a steady movement pattern (14) increasing the risk for a trip and slip. Furthermore, cluster 1 displayed less PFLCS, increasing the risk for a slip (31), and a greater mean cadence, increasing the risk for a trip, slip or loss of CoM control (35). These riskier strategies were accompanied by a smaller RCOF that could mitigate the risk for a slip (13). This overall riskier strategy was linked to a greater hip flexion strength, which could potentially offset some of the risky strategies adopted by the individuals in cluster 1 (4). Cluster 2 was at an increased risk for a trip due to a smaller foot clearance (34). This more risky stepping strategy was linked to an improved visual acuity and more steps performed on the 2-minute stepping task. The improved visual functioning and higher fitness levels could potentially offset the risky strategies adopted by the individuals in cluster 2 (4). Cluster 3 displayed a greater peak and variability in CoM angular acceleration, which both increase the risk for a loss of CoM control when stepping down (36-39). This riskier stepping strategy was linked to a greater active dorsiflexion RoM, higher values on the ABC-scale and a reduced performance on the back-scratch test. The increased RoM and higher confidence levels could offset the increased risk for a stair fall (1, 40). Cluster 4 displayed solely conservative strategies, such as a higher foot clearance, a lower cadence, and a lower peak and variability in CoM angular acceleration (34, 36, 37). This stepping strategy could not be linked to any of the physical/psychological parameters. Therefore, the selection of this conservative overall stepping strategy of these individuals could potentially reflect a deficit in physical/psychological capabilities that were not assessed in the present study or a general pre-disposition to stepping strategies deemed to be “safer” biomechanically. Cluster 5 displayed an overall conservative stepping strategy, as handrails were used throughout. Similar to the handrail dependent group for stair ascent, use of the handrails was necessary to improve stability and mitigate the negative effect of reduced RoM on stair descending ability (4, 40).

The above findings indicate that the physical/psychological capabilities of an older adult play a role in determining the stepping strategy adopted, with better physical/psychological scores “affording” an older adult to adopt a riskier overall behaviour.

5.2 Prediction of hazardous events

A total of 40 older adults (46%) sustained at least one generic fall within the 12-month follow-up period, with 17 out of the 40 fallers (43%) sustaining a fall specifically on stairs. This large proportion of stair fallers together with the resulting high injury rate (46% of stair falls resulted in injuries) reinforces the need for establishing specific screening tools for stair fall risk in older people.

For both stair ascent and descent, hazardous events could not be predicted based on the individual physical/psychological parameters or the existing FRAT, as shown by the Cox-regression models. This could be explained by adjustments that the older individuals made to their overall behaviour based on their physical/psychological capacities. For example, the participants with the poorest performance in the physical/psychological tests adopted the most conservative strategy by depending fully on the handrails. This is supported by the FRAT, as five out of the six older adults who were identified at risk for a fall by the FRAT adopted the most conservative overall stepping behaviour by depending fully on the handrail. As a result, only one of the six older adults at risk for a fall went on to actually experience a stair fall, resulting in a very low sensitivity (0.17) of the FRAT to predict stair fall risk. From the 17 older adults who sustained a stair fall, 16 were classified as not being at risk for a fall by the FRAT. This highlights that the current screening approaches are not specific enough to detect older adults at risk for a stair fall, as they cannot account for adjustments in the stair negotiation technique that an individual can make to minimise the risk for a fall. Equally important, individual biomechanical parameters specific to the stair negotiation task were not able predict hazardous events for either stair ascent or descent, which supports the use of a multivariate profiling approach.

An overall stepping profile with a higher risk for a hazardous event during stair ascent could not be identified. However, in the survival curves it is evident that cluster 1 and 2 display an exponential distribution for fall risk (Figure 1C), resulting in a constant hazard rate (Figure 2A) indicating that the stepping strategy of cluster 1 and 2 can be directly linked to the hazardous event sustained. This suggests that the conservative strategy of cluster 1 does not outweigh the reduced physical/psychological capabilities, which include reduced visual acuity, less hip flexion strength, and polypharmacy. For cluster 2, the findings suggest that having a lower medication intake compared to the other clusters, does not lead to them adopting a riskier overall stepping strategy. Similar to stair ascent, an overall stepping strategy that was particularly at risk for a hazardous event during stair descent could not be identified. Although, cluster 2 shows a tendency for an exponential distribution for fall risk (Figure 1D), the hazard rate of cluster 2 (Figure 2B) was low compared to the hazard rate of the clusters in stair ascent (Figure 2A) and did not differ from clusters 4 and 5 in descent (Figure 2B).

The above findings suggest that, for stair ascent, the multivariate profiling approach has the ability to link the hazardous events of cluster 1 and 2 to their overall stepping behaviour. Individuals in cluster 1 would reduce their risk for a stair fall by improving visual acuity (e.g. by wearing corrective glasses) and hip flexor muscle strength (4). To offset the negative effect of polypharmacy, adopting conservative strategies such as reducing the cadence might also reduce the stair fall risk. Participants in cluster 2 had no physical/psychological deficits present compared to the other older adults in this study, hence a reduction in stair fall risk would require adopting a more conservative stepping behaviour, for example, by using the handrails, which allows a more effective balance control (6). Adequate physical/psychological capabilities were also evident in clusters 1-4 for stair descent, which might explain the low number of hazardous events sustained. Adopting more conservative stepping behaviours might further reduce the risk for a fall during stair descent. Participants in cluster 5, who already display an overall conservative strategy by depending on the handrails, might further reduce their risk for a stair fall by improving their balance and ROM through targeted exercise training (41) and by a step-by-step manner, which decreases the demand of the task in terms of joint loading (5).

The implicit assumption in the present analysis is that the stepping strategies of the older adults profiled in controlled lab conditions is representative of their stepping behaviour in real life. Clearly, however, these constraints do not apply when negotiating stairs daily. It has been shown that the overall stepping profile is not modified when negotiating stairs with different step dimensions than those examined here (42), but there are other factors that could have an influence, such as environmental factors (e.g. lighting and stair surface (7, 43)), individual factors (e.g. less attention for the task due to dual tasking (44)), or other factors (e.g. number of people on the stairs (45)). Simulating in the lab all the external conditions that may modify the biomechanical stepping profile of an individual is challenging. One more pragmatic approach could be to apply the stepping profiling method in real life staircases. Advancements in marker-less motion capture and wearable sensors could allow recording of various input parameters for the identification of the stepping profile, for example, foot clearance, foot placement, cadence and CoM trajectories (46-48). Using stair-specific biomechanical parameters measured in real life conditions together with a higher sample size (i.e. increasing the number of hazardous events) could improve the predictive power of the multivariate approach. Once the stepping profile linked to the highest risk is identified in real life conditions, the underlying easily quantifiable physical/psychological parameters should be identified and implemented in screening tools to identify people at risk for a fall on stairs.

Falls and balance perturbations throughout the follow-up period were self-recorded. In order to minimize inaccuracies with self-recording, we provided the participants with a diary on which they were asked to record falls and balance perturbations daily. The participants were encouraged to contact by phone the lead researcher as soon as possible after they suffered a fall or balance perturbation.

In conclusion, for the first time, the individual stepping strategies of older adults were profiled and linked with fall risk in a prospective longitudinal study. Single physical/psychological parameters did not predict hazardous events on stairs sustained in the 12-month follow up period, and the FRAT classified only 1 out of the 17 stair fallers as being at risk for a fall. In addition, single biomechanical risk factors could not predict hazardous events on stairs sustained in the follow up period, most likely due to their multifactorial nature. However, the multivariate method used in this study, revealed that two out of the four overall stair ascent strategies were predictive of hazardous events.

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Conflict of interest

The authors have no conflicts of interests to declare.

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Tables

Table 1. The number, circumstances and self-perceived causes of the hazardous events for the four clusters during stair ascent, with cluster 4 representing the handrail dependent cluster (HR dep.).

	Cluster 1	**Cluster 2**	**Cluster 3**	**Cluster 4** (HR dep.)	**Total**
Number of ascent fallers	5	5	2	1	13
Balance perturbations	2	3	2	1	8
Cause					
- Trip	6	8	3	2	19
- Loss of CoM control	0	0	1	0	1
- Missed step	1	0	0	0	1
Location					
- Home	5	5	1	2	13
- Public building	2	3	3	0	8
- Outside	2	2	0	1	5
- Inside	5	6	4	1	16
Injuries					
- Yes (hospital admission)	1 (0)	2 (0)	0	1 (0)	4 (0)
- No	6	6	4	1	17

Table 2. The number, circumstances and self-perceived causes of the hazardous events for the five clusters during stair descent, with cluster 5 representing the handrail dependent cluster (HR dep.).

	Cluster 1	**Cluster 2**	**Cluster 3**	**Cluster 4**	**Cluster 5** (HR dep.)	**Total**
Number of descent fallers	0	2	0	2	0	4
Balance perturbations	1	1	1	0	1	4
Cause						
- Trip	1	0	1	1	0	3
- Loss of CoM	0	0	0	1	1	2
control	0	2	0	0	0	2
- Missed step	0	1	0	0	0	1
- Slip						
Location						
- Home	0	1	1	2	0	4
- Public building	1	2	0	0	1	4
- Outside	1	0	0	1	1	4
- Inside	0	3	1	1	0	4
Injuries						
- Yes (hospital admission)	1 (0)	2 (0)	0	1 (1)	0	4 (1)
- No	0	1	1	1	1	4

Table 3. Cluster profiles (CP) of the biomechanical outcome measures assessed for the three clusters for stair ascent and four clusters for stair descent. Those exceeding the threshold of 0.5 are highlighted bold and highlighted in terms of risk (red = riskier strategy; green = more conservative strategy).

	Foot clearance	**Var. Foot clearance**	**PFLCS**	**Var. PFLCS**	**CoM ang. acc.**	**Var. CoM ang. acc.**	**RCOF**	**Var. RCOF**	**Cadence**	**Var. Cadence**
Stair ascent										
Cluster 1	0.06	-0.21	**0.66**	-0.29	-	-	-0.38	-0.11	**-0.60**	-0.30
Cluster 2	-0.06	-0.34	**-0.71**	0.15	-	-	**0.57**	-0.33	**0.78**	-0.32
Cluster 3	-0.08	**1.44**	**-0.67**	**0.66**	-	-	0.04	**1.10**	0.31	**1.72**
Stair descent										
Cluster 1	-0.44	**0.52**	**-0.62**	**1.95**	0.13	-0.44	**-0.91**	-0.28	**1.03**	**1.66**
Cluster 2	**-0.73**	-0.47	-0.10	-0.18	-0.39	-0.30	-0.08	-0.40	0.40	-0.22
Cluster 3	-0.09	-0.25	0.02	-0.30	**1.25**	**1.41**	0.00	-0.05	0.23	0.07
Cluster 4	**0.78**	0.38	0.26	-0.25	**-0.54**	**-0.54**	0.35	0.44	**-0.79**	-0.38

Notes: *Var*: variability; *PFLCS*: proportion of foot contact length in contact with stairs; *CoM:* centre of mass; *ang:* angular; *acc:* acceleration; *RCOF:* required coefficient of friction.

Figures

Figure 1. Kaplan–Meier survival curves for sustaining a hazardous event during the 12-month follow-up for stair ascent (A), stair descent (B), the clusters identified for stair ascent (C) and the clusters identified for stair descent (D).

Figure 2. The hazard rate for a hazardous event of cluster 1 and 2 for stair ascent (A) and cluster 2, 4 and 5 for stair descent (B).

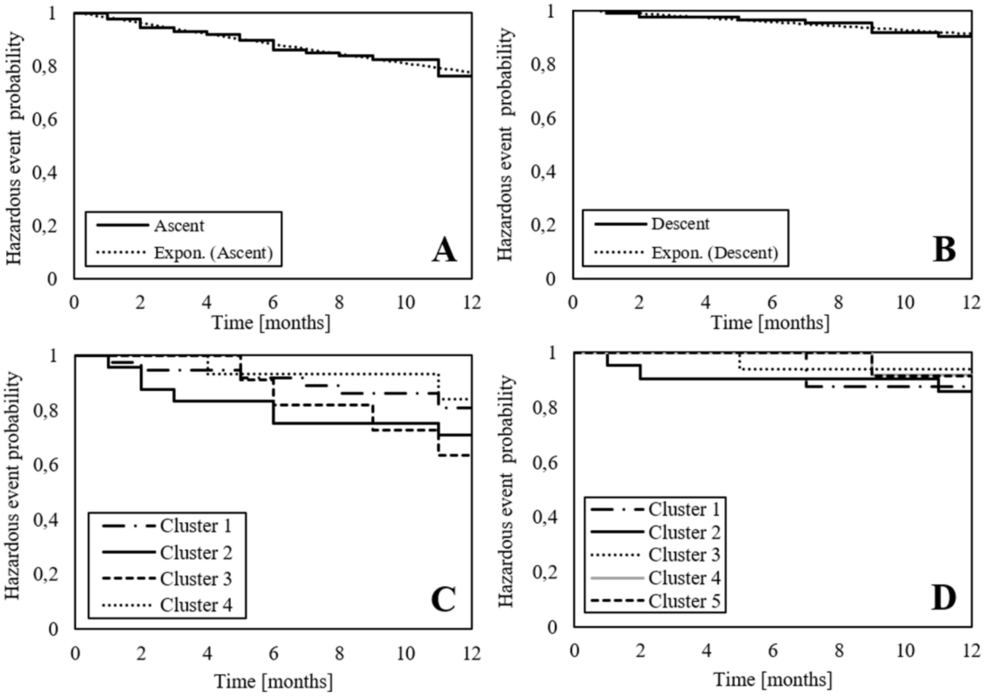

Figure 1. Kaplan–Meier survival curves for sustaining a hazardous event during the 12-month follow-up for stair ascent (A), stair descent (B), the clusters identified for stair ascent (C) and the clusters identified for stair descent (D).

150x106mm (300 x 300 DPI)

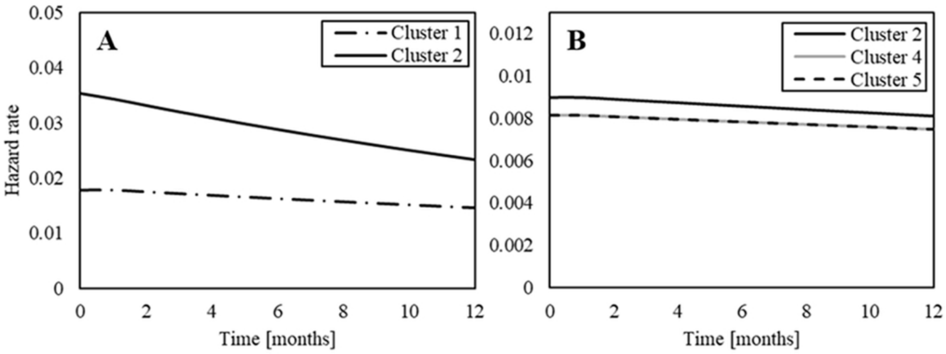

Figure 2. The hazard rate for a hazardous event of cluster 1 and 2 for stair ascent (A) and cluster 2, 4 and 5 for stair descent (B).

149x62mm (300 x 300 DPI)

Table 1. Correlation matrix (r) between all biomechanical parameters studied for stair ascent.

	FC	**FC_v**	**PFLCS**	**PFLCS_v**	**RCOF**	**RCOF_v**	**Cad**	**Cad_v**
FC	■	0.14	0.16	-0.21	0.09	-0.08	-0.10	-0.02
FC_v	-	■	-0.15	0.13	-0.00	0.47	-0.09	0.27
PFLCS	-	-	■	-0.05	-0.24	-0.12	-0.56	-0.18
PFLCS_v	-	-	-	■	0.08	0.04	0.05	0.36
RCOF	-	-	-	-	■	0.16	0.41	-0.06
RCOF_v	-	-	-	-	-	■	-0.09	0.14
Cad	-	-	-	-	-	-	■	0.14
Cad_v	-	-	-	-	-	-	-	■

var: variability; *FC*: foot clearance; *PFLCS*: proportion of foot length in contact with stairs; *RCOF:* required coefficient of friction; *Cad:* cadence.
Light grey shading indicates moderate correlations r = 0.4-0.7 p<.05, and dark grey shading indicates strong correlations r = 0.7-1.0 p<.05.

Table 2. Correlation matrix (r) between all biomechanical parameters studied for stair descent.

	FC	**FC_v**	**PFLCS**	**PFLCS_v**	**COM**	**COM_v**	**RCOF**	**RCOF_v**	**Cad**	**Cad_v**
FC	■	0.26	0.04	-0.15	-0.07	-0.01	-0.04	0.13	-0.32	-0.22
FC_v	-	■	0.05	0.20	-0.05	-0.09	-0.04	-0.00	-0.02	0.03
PFLCS	-	-	■	-0.22	-0.12	-0.06	0.13	0.12	-0.16	-0.22
PFLCS_v	-	-	-	■	0.02	-0.14	-0.10	-0.13	0.25	0.29
COM	-	-	-	-	■	0.62	-0.15	-0.11	0.27	0.11
COM_v	-	-	-	-	-	■	0.05	-0.08	0.08	0.16
RCOF	-	-	-	-	-	-	■	0.38	-0.51	-0.19
RCOF_v	-	-	-	-	-	-	-	■	-0.25	-0.05
Cad	-	-	-	-	-	-	-	-	■	0.36
Cad_v	-	-	-	-	-	-	-	-	-	■

var: variability; *FC*: foot clearance; *PFLCS*: proportion of foot length in contact with stairs; *COM*: Centre of mass angular acceleration; *RCOF:* required coefficient of friction; *Cad:* cadence.
Light grey shading indicates moderate correlations r = 0.4-0.7 p < .05, and dark grey shading indicates strong correlations r = 0.7-1.0 p<.05.