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1 **Abstract**

2 Stair falls, especially during stair descent, are a major problem for older people. Stair fall risk
3 has typically been assessed by quantifying mean differences between subject groups (e.g. older
4 vs. younger individuals) for a number of biomechanical parameters individually indicative of
5 risk, e.g., a reduced foot clearance with respect to the stair edge, which increases the chances
6 of a trip. This approach neglects that individuals within a particular group may also exhibit
7 other concurrent conservative strategies that could reduce the overall risk for a fall, e.g. a
8 decreased variance in foot clearance. The purpose of the present study was to establish a
9 multivariate approach that characterises the overall stepping behaviour of an individual.
10 Twenty-five younger adults (age: 24.5 ± 3.3 y) and 70 older adults (age: 71.1 ± 4.1 y) descended
11 a custom-built instrumented seven-step staircase at their self-selected pace in a step-over-step
12 manner without using the handrails. Measured biomechanical parameters included: 1) Maximal
13 centre of mass angular acceleration, 2) Foot clearance, 3) Proportion of foot length in contact
14 with stair, 4) Required coefficient of friction, 5) Cadence, 6) Variance of these parameters. As
15 a conventional analysis, a one-way ANOVA followed by Bonferroni post-hoc testing was used
16 to identify differences between younger adults, older fallers and non-fallers. To examine
17 differences in overall biomechanical stair descent behaviours between individuals, k-means
18 clustering was used. The conventional grouping approach showed an effect of age and fall
19 history on several single risk factors. The multivariate approach identified four clusters. Three
20 clusters differed from the overall mean by showing both risky and conservative strategies on
21 the biomechanical outcome measures, whereas the fourth cluster did not display any
22 particularly risky or conservative strategies. In contrast to the conventional approach, the
23 multivariate approach showed the stepping behaviours identified did not contain only older
24 adults or previous fallers. This highlights the limited predictive power for stair fall risk of
25 approaches based on single-parameter comparisons between predetermined groups.
26 Establishing the predictive power of the current approach for future stair falls in older people
27 is imperative for its implementation as a falls prevention tool.

28

29 **Keywords:** stair descent; aging; fall risk; clustering; stepping behaviour

30

31 **Abbreviations** *CoM: Centre of mass; CoP: Centre of pressure; CP: Cluster profile; PFLCS:*
32 *Proportion of foot length in contact with stair; K: Optimal number of clusters; NHS: National*
33 *health service; RCOF: Required coefficient of friction; SD: Standard deviation; SSQ: Sum of*
34 *squares*

1 **1. Introduction**

2 Falls are a major problem for older adults, resulting in a significant financial and social cost to
3 the individual and their caregivers. In addition, falls place escalating demands on the National
4 Health Service (NHS) and the Social Care System (Scuffham and others 2003; Startzell and
5 others 2000). The individual consequences of falling for an older adult include loss of
6 independence and physical injury that could eventually lead to death (Scuffham and others
7 2003; Startzell and others 2000).

8 Stair falls account for approximately 20% of all falls and are the leading cause of
9 accidental death in older people (Jacobs, 2016; Startzell and others 2000). To better understand
10 the mechanisms underlying stair falling in older people and develop evidence-based
11 interventions for improving stair safety, stepping biomechanics has been studied extensively
12 (Buckley and others 2013; Christina and Cavanagh 2002; Hamel and others 2005; Mian and
13 others 2007a; Mian and others 2007b; Templer 1995; Zietz and others 2011). The approach
14 typically adopted has been to compare predetermined groups, for example older vs younger
15 individuals (Christina and Cavanagh 2002; Hamel and others 2005; Mian and others 2007a;
16 Mian and others 2007b), and fallers vs non-fallers (Zietz and others 2011), for given
17 biomechanical parameters indicative of risk. For stair descent, which accounts for
18 approximately 75% of all stair falls (Svanström 1974) a fall may be caused by trip, slip or loss
19 of the centre of mass (CoM) control when stepping down (Templer 1995). Research indicates
20 that the risk for a trip increases when the foot clearance from the step edges decreases or the
21 variability of foot clearance increases (Hamel and others 2005; Roys 2001). It has also been
22 shown that a decreased proportion of foot length in contact with the stair or increased required
23 coefficient of friction (RCOF) increases the risk for a slip when placing the foot on the step
24 (Christina and Cavanagh 2002; Roys 2001). The risk for a loss of CoM control increases when
25 the centre of mass (CoM) acceleration increases or with an increased separation of the CoM
26 and the centre of pressure (CoP) when stepping down (Buckley and others 2013; Mian and
27 others 2007a; Mian and others 2007b; Templer 1995).

28 In several studies, older adults displayed not only riskier strategies, but also more
29 conservative strategies when descending stairs. For example, high risk older adults have been
30 found to display not only a decreased foot clearance, which increases fall risk, but also a
31 decreased cadence, which indicates a more conservative strategy that could reduce the risk for
32 a fall (Zietz and others 2011). Buckley (2013) showed that the increased risk for a fall due to a
33 diminished ability to generate high eccentric ankle torques of older adults was accompanied by
34 a reduced peak downwards CoM velocity, a more conservative strategy that could reduce the

1 risk for a fall (Buckley and others 2013). In these examples, the conservative strategies adopted
2 might mitigate the effect of the risky strategies and preserve stair safety. However, to generalise
3 such a conclusion to a whole subject group assumes that both the riskier and more conservative
4 strategies, identified by the inter-group comparisons, are displayed by the same individuals in
5 the groups. At present, there is no evidence that the individual in a group with, for example,
6 the smallest foot clearance is the same individual with the smallest variance in foot clearance.
7 Therefore, individual stepping behaviour should be determined based on multiple parameters
8 reflecting both risk and safety on stairs. However, such an approach has never been pursued
9 before.

10 The purpose of the present study was to establish a multivariate approach for profiling
11 individual stair negotiation behaviour during stair descent, avoiding the limitations introduced
12 by comparing mean values of single outcome measures between predetermined groups.

13

14 **2. Methods**

15 *2.1 Participants*

16 Twenty-five younger adults (age: 24.5 ± 3.3 y; body height: 1.74 ± 0.06 m; body mass: 70.1 ± 8.4
17 kg; mean and standard deviation (SD)) and 70 older adults (age: 71.1 ± 4.1 y; body height:
18 1.68 ± 0.08 m; body mass: 68.8 ± 14.2 kg) participated in the study. All participants lived
19 independently and were recruited from the local community of Liverpool, UK. Participants
20 were excluded if they could not descend stairs in a step-over-step manner, or were using the
21 handrails or any other aid to descend the stairs. Written informed consent was obtained from
22 all participants after the procedures and possible risks of the study were explained. The study
23 was approved by the NHS research ethics committee in the UK (IRAS ID: 216671) and was
24 conducted in accordance with the Declaration of Helsinki.

25

26 *2.2 Staircase configuration*

27 The measurements were conducted on a custom-built instrumented seven-step staircase with
28 four force platforms (1080Hz, 9260AA, Kistler AG, CH) embedded in the lower four steps (3-
29 6) (Fig. 1). Kinematics were obtained using a 24 infrared camera system (120Hz, Vicon,
30 Oxford Metrics, UK). The staircase configuration was set to represent a typical private home
31 staircase in agreement with the building regulations in the UK (British-Standards-Institute
32 1984; Department-of-the-Environment-and-The-Welsh-Office 1992), with the rise (the vertical
33 distance from one step to the next) set at 20 cm and the ‘going’ or run (the horizontal distance
34 between the edges of adjacent steps) at 25 cm, resulting in a pitch of 38.7 degrees. Handrails

1 on both sides of the staircase were in place during all tests (Fig. 1). The steps of the staircase
2 as well as the top landing and walkway were independent structures (Fig. 1). The position of
3 the top landing was fixed and the walkway was secured on the floor when placed in the desired
4 position (i.e. the wheels were raised from the floor, so the wooden structure rested on the floor).
5 The metal framework of the different steps was then connected by bolts to the top landing on
6 one side, to the walkway on the other side, and to each other. As a result, the structures did not
7 separate or roll away from each other.

8
9 **[Please insert 'Figure 1' here]**

10 11 *2.3 Procedures*

12 Participants descended the instrumented staircase at their self-selected pace in a step-over-step
13 manner (i.e. alternative limb lead on each step) without using the handrails. Following a
14 familiarisation trial we found that descending stairs step-over-step without handrail usage
15 would not have been the self-selected strategy for some individuals. However setting the above
16 constraints was necessary to standardise the task between individuals. Trials were performed
17 with participants clothed in tight fitting Lycra shorts and shirt and wearing their own
18 comfortable shoes (no boots, heels or sandals). All participants were fitted in a five point safety
19 harness, which was attached to the overhead belay safety system. A trained member of the
20 research team was attached to a rope on the floor and operated the rope of the belay system.
21 The member of the research team made sure there was no tension in the rope and the rope was
22 always behind the participant during the measurements. To allow familiarisation with the
23 experimental setup and safety harness, participants performed up to five practice trials. After
24 familiarisation, participants performed five more trials with the final three trials used for
25 analysis. All participants had a break after the familiarization trial and were allowed to take as
26 many breaks as they wanted during the following trials to avoid fatigue. In all trials, participants
27 executed at least one step approaching the top of the stairs before stepping down and at least
28 one step at the lower level away from the stairs.

29 30 *2.4 Data analysis*

31 Full body kinematics were obtained using a 15 segment (head, thorax, pelvis, upper arms, lower
32 arms, hands, thighs, shanks, feet) full-body six-degree of freedom kinematic model defined by
33 76 reflective markers (diameter 14 mm). The segmental data were based on Dempster's
34 regression equations (Dempster 1955) and used geometrical volumes to represent each segment

1 (Hanavan 1964). The position of the whole body CoM was estimated as the weighted sum of
2 the various body segments using Visual3D (C-Motion, Germantown, USA). For further
3 analysis all kinetic and kinematic data were filtered using a low-pass fourth order Butterworth
4 filter with a cut-off frequency of 6 Hz. The gait events were determined using force plate data.

5 Kinetic and kinematic data were analysed to determine the following outcome measures:

- 6 i. *Maximal CoM angular acceleration.* This parameter reflects the ability to control the
7 body against gravity as it descends and a higher acceleration is associated with a greater
8 fall risk. The parameter takes both the CoM-CoP separation and the CoM acceleration
9 into account, which are two known risk factors for a stair fall (Buckley and others 2013;
10 Mian and others 2007a; Mian and others 2007b; Templer 1995). The angular
11 acceleration was calculated for the angle (a) between the CoM and CoP position of the
12 trailing leg (Fig. 2A). The maximal angular acceleration of the CoM was obtained as
13 the peak value during the swing phase for steps 3-5 for all three trials as these represent
14 steady state steps (McFadyen and Winter 1988). The mean value of maximal CoM
15 angular acceleration across the three trials was considered for further analysis.

16
17 **[Please insert 'Figure 2' here]**

- 18
19 ii. *Foot clearance.* This parameter reflects trip-induced fall risk, where a smaller foot
20 clearance is associated with a greater fall risk. The foot clearance was calculated by
21 manually digitising the two-dimensional outline of the subject's shoe, which was
22 obtained by taking a picture of the subject's shoe outline drawn on an A4 paper (Fig.
23 3A), using ImageJ (National Institutes of Health, Bethesda, USA). The coordinates of
24 up to 600 virtual markers representing the individual shoe sole outline were then
25 calculated in Matlab (R2018a, The Mathworks, Natick, USA) (Fig. 3B). The position
26 of three markers fixed on the shoe of the subject (first metatarsophalangeal joint, fifth
27 metatarsophalangeal joint and calcaneus lateralis) were digitized in the two-
28 dimensional drawing and using the static measurement, which included the position of
29 the three markers in a three-dimensional space, the position of the virtual outline of the
30 shoe relative to the markers could be determined. The virtual outline of the shoe was
31 then projected in the movement trials, again relative to the three markers (Fig. 3C). The
32 foot clearance was obtained during the swing phase when the virtual shoe outline of the
33 leading limb passed the vertical position (a) of the step edge up until the outline passed
34 the horizontal position of the step edge (b) (Fig. 3D). The minimal clearance of the

1 virtual shoe (dashed arrow in Fig. 3D) was determined within this time frame (*green*
2 shaded area in Fig. 3D) and thus, could be the horizontal foot clearance, the vertical
3 foot clearance or a resultant of the two in-between. The minimal foot clearance was
4 determined for steps 1-5 in all three trials. The mean value across the three trials was
5 considered for further analysis.

6
7 **[Please insert 'Figure 3' here]**
8

- 9 iii. *Proportion of foot length in contact with stair (PFLCS)*. This parameter reflects slip-
10 induced fall risk due to foot positioning relative to the step edge, where a reduced
11 PFLCS is associated with a greater fall risk. PFLCS was calculated using the rigid
12 virtual shoe outline introduced above (orange line in Fig. 2B), which was not influenced
13 by foot deformation, at touch-down on steps 3-6 for all three trials (Fig. 2B). The
14 parameter was calculated using the distance of the horizontal projection of the most
15 posterior aspect (distance x) and the most anterior aspect (distance y) of the virtual shoe
16 outline to the step edge (Fig. 2B). The PFLCS was calculated as a percentage using the
17 following equation: $PFLCS = (\text{distance } x / (\text{distance } x + \text{distance } y)) * 100\%$ (Fig. 2B).
18 The mean value of PFLCS across the three trials was considered for further analysis.
- 19 iv. *Required coefficient of friction (RCOF)*. This parameter also reflects propensity for a
20 slip between the shoe-surface interaction, as a higher friction is associated with a greater
21 fall risk. It was calculated by dividing the resultant shear force (vector sum of the
22 mediolateral and antero-posterior force) by the vertical force at each sample in time
23 (Christina and Cavanagh 2002). The peak RCOF was determined during the loading
24 phase of stance on steps 3-5 for all three trials using Visual3d (C-Motion, Germantown,
25 USA) after a threshold of 50 N for the vertical force was exceeded to prevent erroneous
26 results (Buczek and others 1990; Christina and Cavanagh 2002). The mean value of
27 RCOF across the three trials was considered for further analysis.
- 28 v. *Cadence*. Descending stairs fast may result in a fall as an increased speed could
29 negatively modify the four parameters above. The duration of one gait cycle was
30 obtained for the right and left limb. Cadence was calculated as the average for the left
31 and right limb for the three trials and the mean value was considered for further analysis.
- 32 vi. In addition to the five biomechanical parameters listed (i-v), *the trial-to-trial variance*
33 values of these parameters for the three trials were calculated for each step separately.
34 Higher variance between trials may indicate a person's inability to maintain a

1 steady/safe movement pattern, which increases the risk for a fall (Hausdorff and others
2 2001). The trial-to-trial variance values for the steps were averaged and the mean value
3 for each parameter (i-v) was used for further analysis.

4 5 *2.5 Statistics*

6 To investigate differences between the multivariate clustering approach and the common
7 approach of single parameter comparisons using average group data, the analysed older adults
8 were first classified into two groups (older fallers and older non-fallers) based on the
9 occurrence of a fall in the past 12 months. A fall was self-reported and defined as an event that
10 resulted in a person coming to rest inadvertently on the ground or floor or other lower level. A
11 one-way analysis of variance (ANOVA) followed by Bonferroni post-hoc testing was used to
12 identify differences in the biomechanical outcome measures between younger adults, older
13 fallers and older non-fallers.

14 To examine differences in biomechanical stair descent behaviours between individuals
15 (independent of age or fall history) k-means clustering was applied, a method that is typically
16 used to differentiate categories or profiles (Lisboa and others 2013). First, the mean value of
17 every participant for all outcome measures (i-vi) separately was normalised using Z score
18 transformation. The method used to determine the appropriate number of k was the SeCo
19 framework (Lisboa and others 2013), which has been previously described in detail (Casana-
20 Eslava and others 2017; Chambers and others 2013; Lisboa and others 2013). Briefly, for a
21 range of k values (k = 2-10), which represent the possible number of clusters created, K-means
22 clustering was performed on the data 500 times. The centres of each cluster were reinitialised
23 for each iteration. The total within cluster Sum of Squares (SSQ), which is a measure of
24 separation, was calculated for each solution and the top 10% of these solutions was selected by
25 the within cluster SSQ. The stability measure, the pairwise Cramér's V statistic, was calculated
26 for every pair of clustering solutions. This was used to determine the highest value of k before
27 the stability of the clustering solutions breaks down. The Separation Concordance (SeCo) map
28 that combined the separation and stability measure of these solutions was produced to
29 determine the optimal number of clusters (k). To visualise the clusters in a three-dimensional
30 space, a principal components analysis (PCA) was executed on the dataset and the first three
31 principal components were plotted after the k-means clustering was completed. Furthermore,
32 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.

1 Statistical analyses were performed using SPSS (version 24, SPSS Inc., California, USA) and
2 Matlab (R2018a, The Mathworks, Natick, USA). The significance level was set at $\alpha = 0.05$.

3 4 **3. Results**

5 The one-way ANOVA revealed a group effect ($p < 0.05$) for foot clearance, variance in foot
6 clearance, PFLCS, variance in PFLCS, RCOF and variance in RCOF (Table 1). The post-hoc
7 analysis (Table 1) revealed lower ($p < 0.05$) mean and variance in foot clearance in younger
8 adults compared to older fallers. In addition, the younger adults showed greater ($p < 0.05$)
9 variance in PFLCS and lower RCOF compared to the older non-fallers. The older fallers and
10 older non-fallers showed greater ($p < 0.05$) PFLCS compared to the younger adults. There were
11 no statistical differences between older fallers and non-fallers.

12
13 **[Please insert 'Table 1' here]**

14
15 The stability and separation of the specified values of k , displayed in the SeCo map
16 (Fig. 4), revealed that $k=4$ was the optimal number of clusters for the present dataset. This was
17 in agreement with the visualization of the clusters using the first three principal components of
18 the PCA, showing four segmenting clusters in the 3D environment (Fig. 5). All four clusters
19 contained younger adults, older non-fallers and older fallers (Table 2). The CP (Table 3) with
20 a threshold set at 0.5 revealed that cluster 1 differed from the overall mean by showing a higher
21 CoM angular acceleration (CP = 1.19), more variance in CoM angular acceleration (CP = 1.48),
22 lower RCOF (CP = -0.61) and a higher cadence (CP = 0.57). Cluster 2 differed from the overall
23 mean by showing a higher foot clearance (CP = 0.85), more variance of RCOF (CP = 0.52) and
24 a lower cadence (CP = -0.82) (Table 3). Cluster 3 differed from the overall mean by showing
25 a higher foot clearance (CP = -0.57), less PFLCS (CP = -0.59), more variance in PFLCS (CP
26 = 1.22), less RCOF (CP = -0.66), higher cadence (CP = 1.21) and more variance in cadence
27 (CP = 2.60) (Table 3). In contrast, cluster 4 did not exceed the threshold and therefore did not
28 show detectable differences in any of the parameters compared to the overall mean (Table 3).

29
30 **[Please insert 'Table 2, 3 and Figure 4, 5' here]**

31 32 **4. Discussion**

33 This study aimed, for the first time, to establish a multivariate approach that characterises the
34 stair negotiation behaviour during stair descent based on multiple factors that include both

1 biomechanically risky and conservative strategies. Four clusters were identified. Clusters 1-3
2 differed from the overall mean by showing both risky and conservative strategies on the
3 biomechanical outcome measures, whereas cluster 4 did not display any particularly risky or
4 conservative strategies in the biomechanical outcome measures compared to the overall mean.
5 In contrast to the common approach of comparing single parameters between groups that
6 showed an effect of age and fall history on several individual risk factors (Table 1), the
7 multivariate approach showed that none of the clusters contained only (or all) older non-fallers
8 or older fallers (Table 2). Instead, older fallers and older non-fallers were spread over the four
9 clusters, as they did not present a similar particularly risky overall behaviour that would group
10 them in the same cluster.

11

12 *4.1 Traditional group comparisons*

13 The commonly used comparisons between age and fall history groups showed that ageing had
14 an impact on stair biomechanics during stair descent. The older adults who had a previous fall
15 showed more variance in foot clearance compared to the younger adults (younger adults: 36.5
16 vs. older fallers: 68.2), which is a known risk factor for a trip on stairs (Hamel and others 2005).
17 Moreover, the older adults who had not had a previous fall showed a greater RCOF compared
18 to the younger adults (younger adults: 0.10 μ vs. older non-fallers: 0.11 μ); these increased
19 frictional demands for the older adults might put them at a greater risk of a slip (Christina and
20 Cavanagh 2002). These findings are in line with current literature showing that older adults
21 display a more risky behaviour in several biomechanical outcome measures during stair descent
22 (Christina and Cavanagh 2002; Hamel and others 2005; Mian and others 2007a; Mian and
23 others 2007b). For the younger adults these biomechanical parameters indicate a more
24 conservative strategy that could reduce the fall risk. In addition to the risky strategies above,
25 the older adults had a greater foot clearance (younger adults: 20.1 mm vs. older non-fallers:
26 24.8 mm vs. older fallers: 29.8 mm), higher PFLCS (younger adults: 80.7 % vs. older non-
27 fallers: 85.1 % vs. older fallers: 85.9 %) and less variance in PFLCS (younger adults: 18.4 vs.
28 older non-fallers: 12.6 vs. older fallers: 15.2) than the younger adults. These are all
29 biomechanical factors that indicate a more conservative strategy for the older adults compared
30 to the younger adults and could potentially reduce the fall risk (Hamel and others 2005; Roys
31 2001). Furthermore, contrary to the differences in stair biomechanics between high risk and
32 low risk older adults reported by Zietz (2011), our results revealed that a previous fall, which
33 on its own is a risk factor for a future fall (Startzell and others 2000), had no impact on stair
34 biomechanics (Table 1) (Zietz and others 2011). This discrepancy might suggest that the older

1 fallers in the present study did not adopt more conservative stepping strategies during stair
2 descent compared to older non-fallers. The results of the group comparisons suggest that both
3 older and younger adults adopted not only biomechanically risky strategies, but also
4 biomechanically conservative strategies that could mitigate the overall falling risk. However,
5 based on these group means it cannot be established whether the individuals who adopted a
6 riskier strategy, based on one parameter within a group, were the same individuals who adopted
7 a more conservative strategy for another parameter.

8

9 *4.2 Novel multivariate approach*

10 The current multivariate clustering approach circumvents the above limitation and allows
11 identification of the specific biomechanically risky and safer strategies that a particular
12 individual exhibits. Three individual clusters (1-3) differed from the mean behaviour
13 considering both the risky and the conservative strategies displayed. Cluster 1 differed from
14 the mean by displaying a greater peak and variance in CoM angular acceleration, which both
15 increase the risk for an of loss of CoM control when stepping down (Buckley and others 2013;
16 Mian and others 2007a; Mian and others 2007b; Templer 1995). The greater cadence compared
17 to the overall mean could increase the risk for a slip, trip or loss of CoM control. However,
18 these riskier strategies were accompanied by a smaller RCOF, which is a more conservative
19 strategy that could mitigate the risk for a slip (Christina and Cavanagh 2002). Cluster 2 differed
20 from the mean by displaying more variance in the RCOF. More variance indicates a person's
21 inability to maintain a steady movement pattern and could result in a slip (Hausdorff and others
22 2001). However, this increased risk for a slip was accompanied by a lower cadence, which is a
23 more conservative strategy (Hamel and others 2005; Roys 2001), and a greater foot clearance,
24 which decreases the risk for a trip. Cluster 3 was at increased risk for a trip due to a smaller
25 foot clearance compared to the overall mean (Hamel and others 2005). There were also lower
26 mean and variance values for PFLCS indicating a greater risk for a slip when placing the foot
27 on the step (Roys 2001). In addition, cluster 3 had greater mean and variance values for
28 cadence, which indicate an increased risk for a trip, slip or loss of CoM control. However, these
29 differences in cluster 3 were accompanied by one conservative strategy when compared to the
30 overall mean, namely a decreased RCOF that reduces the risk for a slip (Christina and
31 Cavanagh 2002). Cluster 4 did not show any great differences from the overall mean.
32 Therefore, cluster 4 did not show anything particularly risky, but also did not show any
33 particularly conservative compensations. These findings show that the stair negotiation
34 behaviour is based on a mix of biomechanically risky and safer strategies.

1 Furthermore, the four behaviours all contained older adults who had previously fallen
2 (cluster 1: 3; cluster 2: 13; cluster 3: 2; cluster 4: 9; total 27 older fallers), at least one older
3 adult who did not have a previous fall (cluster 1: 9; cluster 2: 17; cluster 3: 5; cluster 4: 12;
4 total 43 older non-fallers) and at least one younger individual (cluster 1: 8; cluster 2: 1; cluster
5 3: 1; cluster 4: 15; total 25 younger adults) (Table 2). Therefore, we conclude that the younger
6 adults, the older adult non-fallers and the older adult fallers did not present a similar overall
7 behaviour per group that would assign them in the same cluster. This is in marked contrast with
8 the commonly used grouping methods that differentiate cohorts based on fall-history and age
9 to compare mean values for single outcome measures. The current approach allows profiling
10 of overall stair fall risk based on multiple risky and conservative stepping strategies exhibited
11 by the stair user.

12 The measurements of the present study were conducted on an experimental staircase
13 using a safety harness in a lab environment, which differs from private home staircases and
14 this might have had psychological effects on the stair performance of the participants.
15 However, since the participants familiarised themselves with the experimental staircase and all
16 were confident to negotiate the experimental staircase, we do not believe this was a substantial
17 limitation.

18 At present, we are not able to quantify the effectiveness of the compensations or to
19 determine which of the combined behaviours is safer for the older adults. Additionally, we are
20 unable to state whether older adults who display no risky behaviour, but show an ‘average’
21 behaviour in all parameters (cluster 4), are at less risk for a fall. To reach this important
22 conclusion, future research should implement the current method on older participants and link
23 the clusters with some relevant metric for stair falls, for example number of stair falls and
24 graded severity of the fall documented over a follow-up period. It is also important that further
25 research aims to identify the specific functional deficits underpinning the biomechanically
26 risky stepping strategies adopted, so that fall predictive and preventive programs can then be
27 delivered to the older adults at risk.

28

29 **5. Conclusions**

30 In conclusion, for the first time a multivariate approach was able to characterise stair descent
31 behaviour. In contrast to commonly used single-parameter comparative approaches, it was
32 found that the older fallers and older non-fallers were spread over the four stepping behaviours
33 identified. Three of the four identified behaviours were found to be a combination of
34 biomechanically risky and safer components, whereas one ‘average’ behaviour without any

1 particularly risky or safer characteristics was identified. Further research should implement this
2 method on older adults using a longitudinal approach to identify the behaviours that can
3 differentiate those who will go on to experience an actual stair fall from those who will not, so
4 that targeted cost-saving interventions for improving stair safety in older individuals can then
5 be designed and implemented.

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12 foot clearance and proportion of foot length in contact with stair and to the members of the
13 RISCS (Research to Improve Stair Climbing Safety) group of Liverpool John Moores
14 University for their help during the data collection.

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4
 5 **Tables**

6 **Table 1.**

7 Mean (\pm SD) biomechanical outcome measures assessed for the younger adults, older non-
 8 fallers and older fallers.

	Younger adults (N=25)	Older adult non-fallers (N=43)	Older adult fallers (N=27)
Foot clearance [mm] *	20.1 \pm 8.5 ^a	24.8 \pm 9.4	29.8 \pm 10.1
Var. foot clearance *	36.5 \pm 21.9 ^a	48.1 \pm 28.0	68.2 \pm 53.6
PFLCS *	80.7 \pm 6.2 ^{a,b}	85.1 \pm 6.4	85.9 \pm 7.9
Var. PFLCS *	18.4 \pm 7.6 ^b	12.6 \pm 7.4	15.2 \pm 11.9
CoM ang. acc. [rad/s ²]	7.3 \pm 3.4	6.6 \pm 2.1	6.5 \pm 1.7
Var. CoM ang. acc.	7.2 \pm 5.9	7.0 \pm 5.1	4.9 \pm 3.4
RCOF [μ] *	0.10 \pm 0.02 ^b	0.11 \pm 0.02	0.10 \pm 0.02
Var. RCOF (x 10 ⁻⁴) *	2.2 \pm 2.9	5.0 \pm 6.0	5.8 \pm 5.8
Cadence [cycle/s]	0.95 \pm 0.10	0.91 \pm 0.15	0.92 \pm 0.18
Var. Cadence (x 10 ⁻³)	2.6 \pm 3.0	4.6 \pm 6.4	3.1 \pm 3.0

9 Notes: *Var*: variance; *PFLCS*: proportion of foot length in contact with stair; *ang*: angular; *acc*:
 10 acceleration; *RCOF*: required coefficient of friction.

11 * Significant group effect (P<0.05)

12 ^a Significant difference between younger adults and older adult fallers (P<0.05)

13 ^b Significant difference between younger adults and older adult non-fallers (P<0.05)

14
 15
 16
 17 **Table 2.**

18 Cluster composition of all four clusters.

	Younger adults (n=25)	Older adult non-fallers (n=43)	Older adult fallers (n=27)	Total (n=95)
Cluster 1	8	9	3	20
Cluster 2	1	17	13	31
Cluster 3	1	5	2	8
Cluster 4	15	12	9	36

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1 **Table 3.**

2 Cluster profiles (CP) of the biomechanical outcome measures assessed for the four clusters.
 3 Those exceeding the threshold of 0.5 are highlighted bold and coloured in terms of risk (red =
 4 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
Cluster 1	-0.23	-0.36	0.17	-0.11	1.19	1.48	-0.61	-0.22	0.57	-0.10
Cluster 2	0.85	0.47	0.49	-0.42	-0.37	-0.43	0.49	0.52	-0.82	-0.35
Cluster 3	-0.57	0.38	-0.59	1.22	0.04	-0.37	-0.66	0.21	1.21	2.60
Cluster 4	-0.48	-0.29	-0.39	0.15	-0.35	-0.37	0.06	-0.37	0.12	-0.22

5: *Var.*: variance; *PFLCS*: proportion of foot length in contact with stair; *ang.*: angular; *acc.*: acceleration; *RCOF*:
 6 required coefficient of friction.

7

8

9 **Figure captions**

10 **Figure 1.** (2-column fitting image)

11 A schematic representation (A) and image (B) of the custom-built instrumented seven-step
 12 staircase.

13

14 **Figure 2.** (single column fitting image)

15 Schematic overview of the calculation of the CoM angular acceleration (A) and proportion of
 16 foot length in contact with stair (PFLCS) (B). The CoM angular acceleration was calculated
 17 over the angle (a) between the CoM and CoP position of the trailing leg during the lowering
 18 phase. The PFLCS was calculated at touch-down using the rigid virtual shoe (orange line) as:
 19 $PFLCS = (x / (x + y)) * 100\%$.

20

21 **Figure 3.** (1.5 column fitting image)

22 Example of the foot clearance calculation of the right foot. First, a two-dimensional outline of
 23 the shoe (A) was digitized and linked to three markers (first metatarsophalangeal joint: RMP1,
 24 fifth metatarsophalangeal joint: RMP5 and calcaneus lateralis: RLCL) of the static
 25 measurement (B). The virtual outline of the shoe was then projected in the movement trials
 26 (C). Foot clearance was calculated as the minimal distance between the virtual shoe and the
 27 step edge, within the *green* shaded area between *a* and *b* shown in inset D.

28

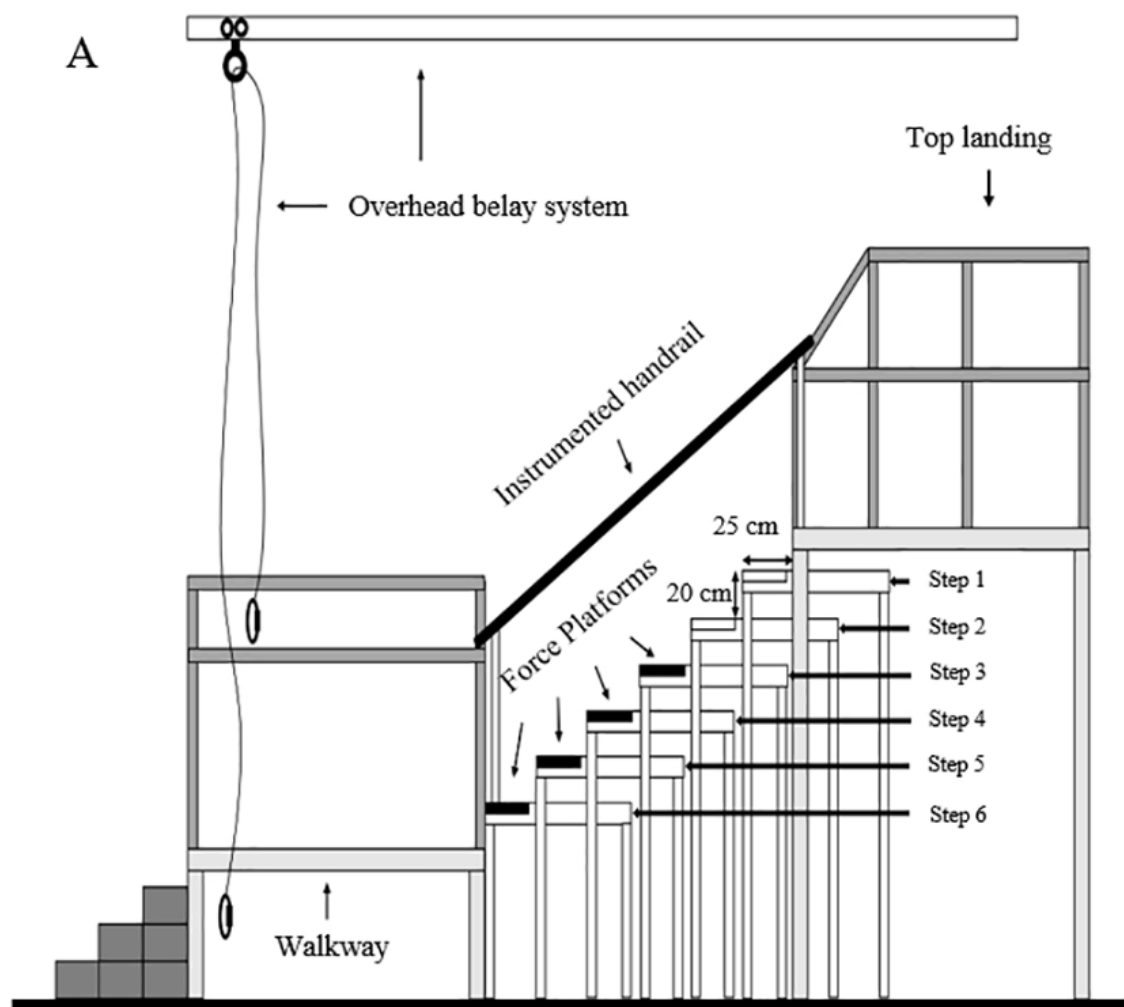
29 **Figure 4.** (single column fitting image)

30 Separation-Concordance map for the biomechanical outcome measures, highlighting the top
 31 10% (of 500 initialisations of the k-means algorithm) Δ SSQ on the y-axis and the internal
 32 median Cramer's V on the x-axis for each value of k (2-10).

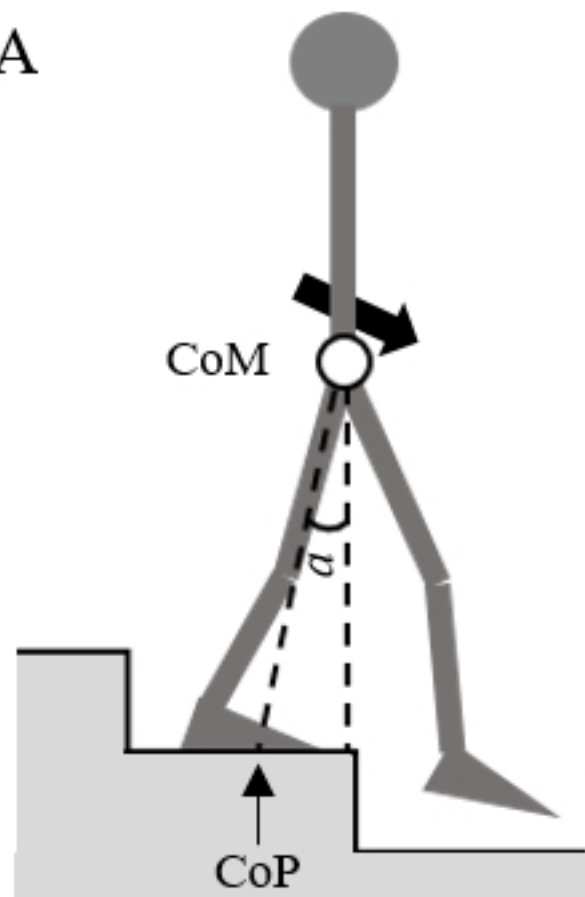
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34 **Figure 5.** (1.5 column fitting image)

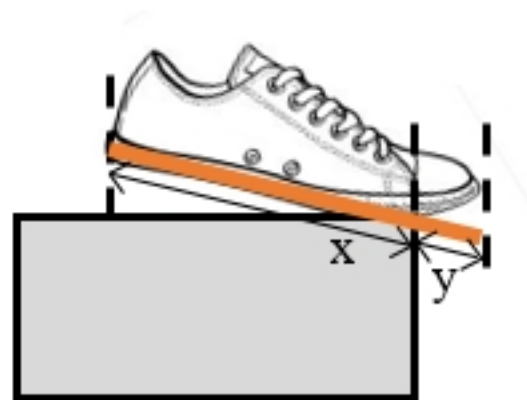
- 1 Three-dimensional plot of the first three principal components (PC1, PC2 and PC3) of the
- 2 biomechanical outcome measures visualizing the segmenting clusters 1-4 including the
- 3 centroids of each cluster.



A



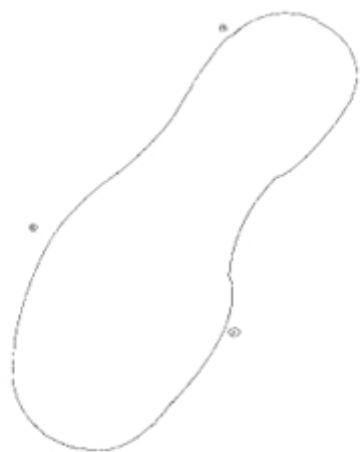
B



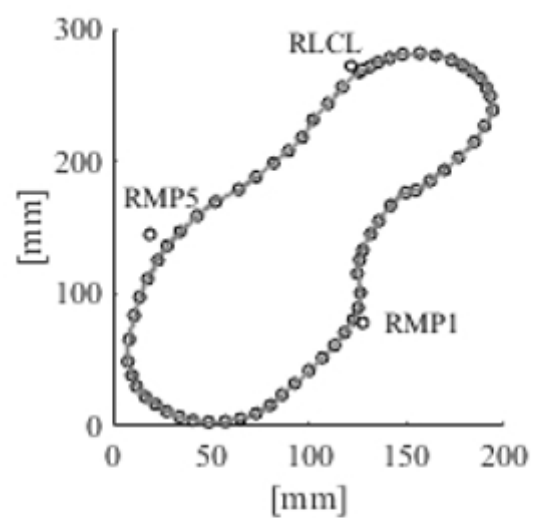
$$\text{PFLCS} = (x / (x + y))$$

* 100%

A



B



C

