BIOMECHANICAL PROFILING OF STAIR NEGOTIATION AND FALL RISK DETECTION IN OLDER PEOPLE

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Abstract

Stair falls are a major cause of injury and loss of independence for older people and place escalating demands on the National Health Service (NHS). Individual (e.g. psychological and physiological) and environmental (e.g. stair design) factors influence the biomechanics of stair negotiation and thus, affect stair fall risk. In addition, stair-specific risk factors have been identified by comparing predetermined groups for single-parameters that underpin the potential mechanism of a stair fall through biomechanical research in a gait lab. However, it remains unknown if the existing screening tools and single biomechanical parameters have the predictive power to identify older individuals at risk for a stair fall specifically. Therefore, the overall purpose of this thesis was to develop a multivariate approach that has the ability to identify older adults at risk for a stair fall at community level.

The first study, which included 25 younger (20-30 years) and 70 older adults (>65 years), established a novel multivariate approach for profiling individual stair-negotiating behaviour. It was found that individual stepping behaviour could be profiled based on multiple biomechanical parameters reflecting risk and safety on stairs and that this approach circumvented the limitations of single-parameter comparisons between predetermined groups. The next study showed that of the 68 included older adults (>65 years) the majority maintained their stair-negotiating behaviour irrespective of step dimensions, which indicated that manipulating the demand of the task would not affect the underpinning mechanism of a potential stair fall. In the final prospective study, the multivariate approach was implemented on 87 older adults (>65 years) over a 12-month follow up period to identify the biomechanical stepping profile linked with the highest stair fall risk. As opposed to the limited predictability of stair fall risk using functional and single-parameter biomechanical approaches and general fall screening tools, the multivariate approach showed potential to predict fall risk, especially during stair ascent.

Future research should implement the multivariate approach in more people in real life stair negotiation conditions to improve the prediction of the method, so that targeted interventions for improving stair safety in older individuals can be developed.

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Contents

Publications

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- **Ackermans, T,** Francksen N, Casana-Eslava, R., Lees C, Baltzopoulos, B., Lisboa P., Hollands M.A., O'Brien T.D., Maganaris C.N. (2019) A novel multivariate approach for biomechanical profiling of stair negotiation. *Experimental Gerontology.* Doi: 110646/j.exger.2019.110646
- **Ackermans, T,** Francksen N, Casana-Eslava, R., Lees C, Baltzopoulos, B., Lisboa P., Hollands M.A., O'Brien T.D., Maganaris C.N. (2019) Stair negotiation behaviour of older individuals: Do step dimensions matter? *Journal of Biomechanics (under review).*

Conference papers

- **Ackermans T**, Francksen N, Casana-Eslava R, Lees C, Baltzopoulos V, Lisboa P, Hollands M, O'Brien T, Maganaris C. (2019). Prediction of stair falls in older people using a biomechanical profiling approach: A 12-month longitudinal study. Poster presentation submitted to European Orthopaedic Research Society meeting, Maastricht, the Netherlands.
- **Ackermans T**, Francksen N, Casana-Eslava R, Lees C, Baltzopoulos V, Lisboa P, Hollands M, O'Brien T, Maganaris C. (2019). Stair fall risk profiling using a novel multivariate approach. Paper presented at the XXVII Congress of the International Society of Biomechanics (ISB), Calgary, Canada, 2019.
- **Ackermans T**, Francksen N, Casana-Eslava R, Lees C, Baltzopoulos V, Lisboa P, Hollands M, O'Brien T, Maganaris C. (2019). A novel multivariate approach to characterise stair-negotiating behaviour and detect fall risk in older adults. Poster presented at the International Society of Posture and Gait Research (ISPGR) world congress, Edinburgh, Scotland, 2019.
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- **Ackermans T**, Francksen N, Casana-Eslava R, Lees C, Baltzopoulos V, Lisboa P, Hollands M, O'Brien T, Maganaris C. (2019). Older adults maintain their biomechanical stepping strategies irrespective of step dimensions when

negotiating stairs. Poster presented at the BASES Biomechanics Interest Group (BIG) meeting, Huddersfield, UK, 2019.

- **Ackermans T**, Francksen N, Lees C, Lisboa P, Hollands M, O'Brien T, Maganaris C. (2018). Differences in stair descent biomechanics between older fallers, older non-fallers and younger individuals. Paper presented at the 8th World Congress of Biomechanics, Dublin, Ireland, 2018.
- **Ackermans T**, Francksen N, Lees C, Lisboa P, Hollands M, O'Brien T, Maganaris C. (2018). Effect of ageing on the biomechanical control mechanisms that allow safe stair descent. Paper presented at the XV International Symposium on 3D Analysis of Human Movement, Manchester, UK, 2018.
- **Ackermans T**, Francksen N, Lees C, Lisboa P, Hollands M, O'Brien T, Maganaris C. (2018). Control mechanisms to offset risky stepping behaviour during stair descent in younger and older adults. Paper presented at the BASES Biomechanics Interest Group (BIG) meeting, Salford, UK, 2018.
- **Ackermans T**, Francksen N, Lees C, Baltzopoulos V, Hollands M, O'Brien T, Maganaris C. (2018). Control mechanisms to offset risky stepping behaviour during stair descent in younger and older adults. Paper presented at the Faculty of Science Postgraduate Research Day, Liverpool John Moores University, Liverpool, UK, 2018.
- **Ackermans T**, Francksen N, Lees C, Baltzopoulos V, Hollands M, O'Brien T, Maganaris C. (2017). From lab to the end-user: Using empirical research to develop a screening tool for assessing the risk of falls on stairs in older people at community level. Poster presented at the Faculty of Science Postgraduate Research Day, Liverpool John Moores University, Liverpool, UK, 2017.
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- Francksen N, **Ackermans T**, Holzer D, Maganaris C, Hollands M, Roys M, O'Brien T. (2018) Stair ascent: the influence of inconsistent rise step dimensions on younger and older adults' safety. Poster presented at the 8th World Congress of Biomechanics, Dublin, Ireland, 2018.
- Francksen N, **Ackermans T**, Holzer D, Maganaris C, Hollands M, Roys M, O'Brien T. (2018) Stair descent: the influence of inconsistent going step

dimensions on younger and older adults' safety. Poster presented at the 8th World Congress of Biomechanics, Dublin, Ireland, 2018.

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List of abbreviations

AUC	Area under the receiver operator characteristic curve
BBS	Berg balance scale
CoM	Centre of mass
CoP	Centre of pressure
GP	Group profile
FRAT	Fall Risk Assessment Tool
MoCa	Montreal cognitive assessment
NHS	National Health Service
PFLCS	Proportion of foot length in contact with stair
RCOF	Required coefficient of friction
ROM	Range of motion
SeCo	Separation concordance framework
SSQ	Sum of squares
UK	United Kingdom

CHAPTER 1:

General Introduction

1.1 Incidence and consequences of falls

One major problem associated with ageing is an increased susceptibility to falling (Lord, Sherrington, Menz, & Close, 2007). Approximately 1 in 3 older people over 65 living in the community (3.4 million people in the UK) are likely to fall once or more every year (Lord, Ward, Williams, & Anstey, 1993; Tinetti, Speechley, & Ginter, 1988). The individual cost of falling is likely to be injurious, disabling or fatal (Startzell, Owens, Mulfinger, & Cavanagh, 2000). Consequently, a lot of older adults develop a fear of falling, which can lead to the avoidance of many fundamental activities of daily living, contributing to a decline in physical function, independence and health-related quality of life (Cumming, Salkeld, Thomas, & Szonyi, 2000; Tinetti, De Leon, Doucette, & Baker, 1994). Almost 20% of all falls result in serious injuries that may require prolonged medical care, which includes hospital care and the use of rehabilitation services (Alexander, Rivara, & Wolf, 1992; Burns, Stevens, & Lee, 2016). As a result, falls are costly (Burns et al., 2016). In the UK alone, falls cost the National Health Service (NHS) and social services an estimated £6m per day or £2.3bn per year (Age-UK, 2010). Therefore, falls put a significant financial and social cost to caregivers and the NHS (Scuffham, Chaplin, & Legood, 2003; Startzell et al., 2000).

Stair negotiation has been identified as one of the most hazardous and demanding tasks for older adults, often resulting in falls. Falls on stairs are reported to represent circa 7-35% of falls, with studies typically reporting a percentage in the twenties (Ghodsi, Roudsari, Abdollahi, & Shadman, 2003; Gill, Kelley, Williams, & Martin, 1994; Jacobs, 2016; Kool, Ameratunga, Hazell, & Ng, 2010; S. W. Muir, K. Berg, B. M. Chesworth, N. Klar, & M. Speechley, 2010b; Talbot, Musiol, Witham, & Metter, 2005). Although, fewer falls occur on stairs compared to the level ground, stair falls are a leading cause of accidental death and account for the majority of fall costs (Startzell et al., 2000). Stair descent has been identified as the most hazardous aspect of stair negotiating, accounting for approximately 75% of all stair falls (Svanström, 1974). Older adults are more likely to suffer non-fatal and fatal injuries from a fall on stairs compared to younger adults (Hemenway, Solnick, Koeck, & Kytir, 1994; Startzell et al., 2000). Therefore, to improve stair safety in older people, it is important to understand the underlying mechanisms of stair falls in this population.

1.2 Underlying mechanisms of falls on stairs

The underlying mechanisms for a fall differ between stair negotiation and normal gait, as people have to select a different movement strategy when negotiating stairs compared to normal gait.

1.2.1 Falls during stair ascent

The gait in stair ascent encompasses a stance phase and swing phase. The swing phase is more risky than the stance phase because the rear foot has to pass two step edges, resulting in a high risk of falling induced by a trip (Figure 1.1A) (Templer, 1995). In the stance phase, most accidents occur when the individual is executing a vigorous push-off with the rear foot to complete the final part of the lift of the body onto the next step (Templer, 1995). During this push-off period the individual is at an increased risk for a fall caused by a slip of the foot (Figure 1.1B). Other causes for a fall include a misjudgement of the position of the next step, which could lead to under-stepping or completely missing the edge of the upper step. The consequences of a fall during stair ascent tend to be less serious compared to descent as the centre of gravity is positioned slightly forward, therefore any accident usually leads to the body falling forward towards the stairs, which are closer to the hands (Templer, 1995).

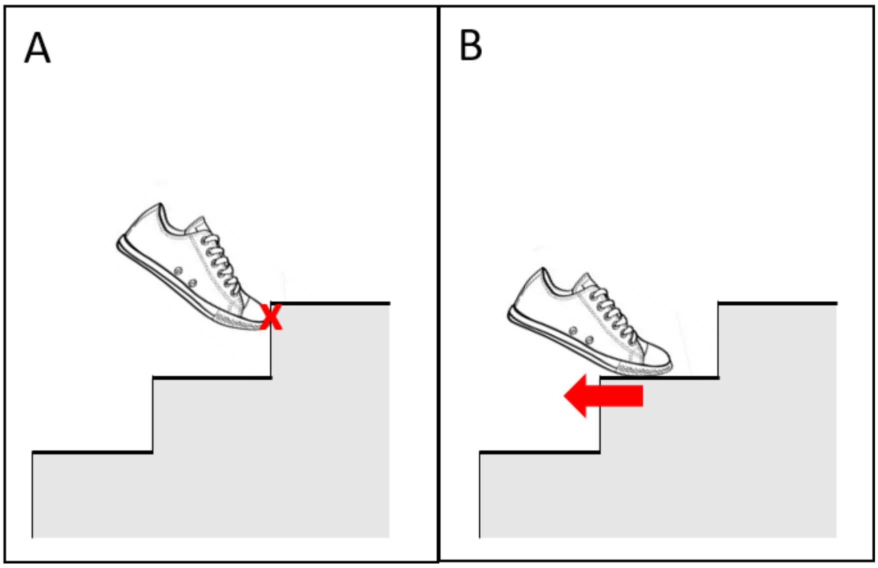

Figure 1.1. Schematic overview of the underlying mechanisms of a fall in stair ascent, with 'A' representing a trip during the swing phase and 'B' representing a slip during the push-off phase of the rear foot.

1.2.2 Falls during stair descent

The underlying mechanisms for a fall during stair descent differ from ascent. During the swing phase in descent, a fall can occur due to tripping when the heel of the leading foot catches the step edge (Figure 1.2A). In the stance phase, there is a risk for slipping shortly after touchdown of the leading leg when the weight is being transferred to the leading leg (Figure 1.2B) (Templer, 1995). Furthermore, there is a risk for a loss of centre of mass (CoM) control in the stance phase. At initial contact of the leading leg the body is moving forward and the weight of the body is transferred to the leading leg, a loss of control in this phase will therefore lead to the body falling forward (Figure 1.2C) (Templer, 1995). Additionally, falls could occur as result of overstepping on the subsequent step (Templer, 1995). In stair descent, falls tend to result in more serious injuries as a fall could cause the individual to fall down all subsequent steps of the staircase.

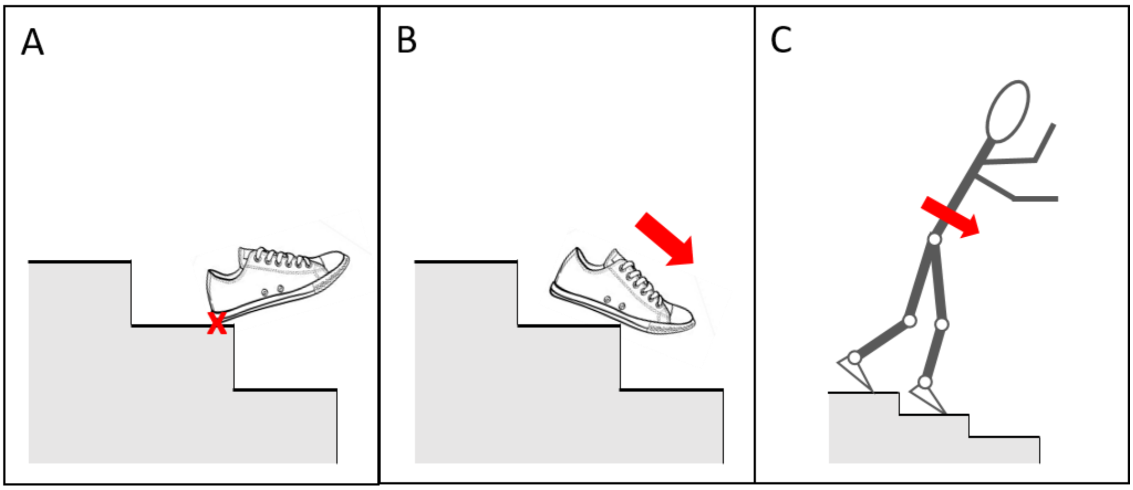

Figure 1.2. Schematic overview of the underlying mechanisms of a fall in stair descent, with 'A' representing a trip during the swing phase, 'B' representing a slip shortly after initial contact and 'C' representing a loss of balance in the lowering phase.

1.3 Identification of risk factors for stair falls

Previous research has aimed to identify risk factors of a fall on stairs by linking the underlying mechanisms of a stair fall to single biomechanical factors. In addition, research has focussed on individual and environmental factors that could be linked with the occurrence of falls on stairs.

1.3.1 Risk factors for falling during stair ascent

For stair ascent, the underlying mechanisms for a stair fall are a trip and a slip. The risk for a trip has typically been linked to the clearance of the front of the foot from the edge of the step (Kesler, Horn, Rosengren, & Hsiao-Wecksler, 2016). The risk for a trip increases when the vertical foot clearance from the step edge is decreased (Di Fabio, Zampieri, & Tuite, 2008; Kesler et al., 2016). Additionally, the risk of trip increases when the variability of foot clearance increases, as this can indicate a person's inability to maintain a safe foot trajectory (Hamel, Okita, Higginson, & Cavanagh, 2005; M. S. Roys, 2001). The risk for a slip in ascent is linked to the frictional forces between the step and the proportion of foot in contact with it (Hamel, Okita, Bus, & Cavanagh, 2005; M. Roys & Wright, 2005). High frictional forces during push-off increase the risk for a slip of the step. In addition, the risk for a slip increases when the proportion of the foot length in contact with the step is reduced, for example, in case a large portion of the foot is hanging over the step edge. Furthermore, the risk for a slip is increased when the variability in the proportion of the foot length in contact with the step and required frictional forces increases, as this can indicate an inability to consistently place the foot safely on the step.

1.3.2 Risk factors for falling during stair descent

For stair descent, the underlying mechanisms for a fall include tripping, slipping and loss of CoM control. The risk for a trip is, similar to stair ascent, linked to the foot clearance, but during descent this is typically the horizontal clearance of the heel of the foot in regards to the step edge. The stair fall risk increases when foot clearance is decreased and the variability of foot clearance is increased (Hamel, Okita, Higginson, et al., 2005; Zietz, Johannsen, & Hollands, 2011). The risk for a slip is linked to the frictional forces between the step and the proportion of the foot in contact with it during the loading phase (Christina & Cavanagh, 2002; Hamel, Okita, Bus, et al., 2005; M. Roys & Wright, 2005). Similar to stair ascent, the risk for a slip during descent increases when the frictional forces increase, when the proportion of foot in contact with the step is reduced, and when the variability in both parameters increases (Christina & Cavanagh, 2002; Hamel, Okita, Bus, et al., 2005; M. Roys & Wright, 2005). The risk for a loss of CoM control depends on the ability of the individual to control the CoM against gravity when the body is lowered on the subsequent step. The risk for a loss of CoM control is increased during instants of high acceleration of the CoM or when the separation between the CoM and the centre of pressure (CoP) is increased (Buckley, Cooper, Maganaris, & Reeves, 2013; Mian, Thom, Narici, & Baltzopoulos, 2007). Furthermore, the risk for a loss of CoM control is increased when the variability in CoM acceleration and CoM - CoP separation increases, as this can indicate a person's inability to maintain a safe CoM trajectory.

1.3.3 Other individual and environmental risk factors

In addition to the task specific risk factors mentioned above, there are some other individual and environmental factors that could increase the risk for a fall in both stair ascent and descent. Individual factors include visual, psychological and physiological factors. Acquiring visual information of the stair properties and surrounding environment is crucial for safe stair negotiation, and therefore impairments in visual acuity and contrast sensitivity or not selecting the appropriate gaze behaviour, for example not looking at the right places at the right time, could increase the risk of falling on stairs (Zietz & Hollands, 2009). Psychological factors, such as anxiety and an increased fear of falling are associated with prospective stair falls (Freeman, Munoz, Rubin, & West, 2007; Jacobs, 2016). Unimpaired cognitive function is also important for successful stair navigation, due to the need to integrate the multiple forms of sensory input received during this complex locomotor task (Templer, 1995). Therefore, cognitive impairments are suggested to contribute to an increased risk for falls (Startzell et al., 2000). The most common physiological factors that have been associated with prospective stair falls include: 1) muscle strength, as low muscle strength could limit the strength reserve available to cope with unexpected perturbations increasing the risk for a fall (Hemenway et al., 1994; Lord, Ward, Williams, & Anstey, 1994; Reeves, Spanjaard, Mohagheghi, Baltzopoulos, & Maganaris, 2008a, 2009; Whipple, Wolfson, & Amerman, 1987); 2) joint range of motion (RoM), as stair negotiation requires a large joint RoM, which could be at the limits of individuals with a diminished mobility increasing the risk for a fall (Lord et al., 1994; Reeves et al., 2008a, 2009; Startzell et al., 2000); 3) balance, as a fall will occur if the individual is unable to make postural adjustments to recover a safe stance following a perturbation (Lord et al., 1994; Startzell et al., 2000). Ageing-induced deterioration in the above functional abilities may explain the high incidence of falling in older people (Startzell et al., 2000).

Environmental factors that increase the risk for a fall on stairs include poor illumination of the stair treads, as this reduces the probability that an individual will position the foot safely on the tread (Cohen, LaRue, & Cohen, 2009), poor maintenance of staircases or staircases with slippery surfaces, as this may cause individuals to unexpectedly slip or lose their CoM control when negotiating stairs (Johnson & Pauls, 2010; Svanström, 1974). However, the most prominent environmental factor that has been extensively linked with stair falls is stair geometry (Cohen et al., 2009). Stair geometry, i.e. the step dimensions, vary between staircases and, as a result, the demands of the stair negotiation task also vary, with steps of increased riser height (rise) or shorter run (going) being more demanding to negotiate (Figure 1.3) (Wright & Roys, 2005). At present, it remains unknown if the stair negotiation strategy of an older adult varies between staircases with different dimensions, as the studies that implemented different step dimension configurations are limited to comparisons of single biomechanical risk factors (Johnson & Pauls, 2010; Nemire, Johnson, & Vidal, 2016; Novak, Komisar, Maki, & Fernie, 2016; Riener, Rabuffetti, & Frigo, 2002; Wright & Roys, 2005). If an individual maintains a certain stepping behavior when exposed to staircases with different dimensions due to a preprogrammed movement pattern, which is the case for over-ground gait over different terrains as suggested by biometric gait studies (Bouchrika, Goffredo, Carter, & Nixon, 2011; Gafurov, 2007), then the risk for a fall in that individual would be similar in all staircases. Alternatively, the individual could alter their stepping behaviour between staircases to accommodate the altered demand, and therefore, the risk and mechanisms for a stair fall could be dependent on stair geometry. If the latter holds true, step dimensions should be considered when identifying stair-specific risk factors.

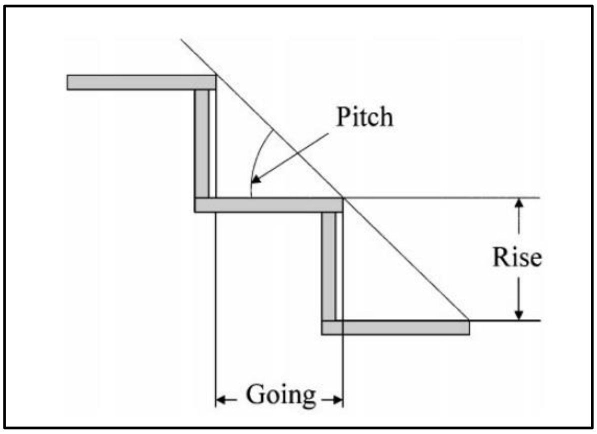

Figure 1.3. Simple stair geometry (this figure was adopted from Roys, 2001).

1.4 Fall prevention tools

1.4.1 Current fall prevention tools

The problem of falling is widely acknowledged, as shown by the different fall prevention services for older adults that exist within the community (Gates, Smith, Fisher, & Lamb, 2008). However, a major limitation of fall prevention services is that they are often delivered retrospectively, to people who have already fallen. As a result, the fall could already have impacted on the wellbeing of the individual. Referrals to fall prevention services are typically made by health professionals at community level after evaluating an individual's risk for falling. Different identification tools that aim to identify a person at risk for a fall have been developed. A systematic review of Gates et al. (2008) identified 29 different screening tests for identifying fall risk among independently living older adults (Gates et al., 2008). In the UK, the Falls Risk Assessment Tool (FRAT (NHS-UK, 2018)) is commonly used. This is a screening tool which is based on the identification of five risk factors: 1) general falls within the previous year, 2) the use of more than four medications, 3) a diagnosis of stroke or Parkinson's disease, 4) self-reported balance problems, 5) inability to rise from a chair. Positive identification of any three of the five risk factors above is the cut-off for referring this person to the falls service as they are considered at risk for a future fall.

1.4.2 Limitations of current fall prevention tools

The current fall prevention tools are neither stair-specific nor do they include risk factors linked to the underlying mechanisms of stair falls. They do encompass clinical and functional parameters that are considered to be important for safe stair negotiation (highlighted as individual risk factors above), such as balance and muscle strength, so they 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 task, which can be executed using different techniques, according to the capabilities and deficits of the individual. For example, older adults with balance deficits could minimize the risk for a fall by relying more on the handrails and/or negotiating the stairs in a step-by-step manner, as both these strategies allow a more effective balance control (King, Underdown, Reeves, Baltzopoulos, & Maganaris, 2018; Reeves, Spanjaard, Mohagheghi, Baltzopoulos, & Maganaris, 2008b). Generic fall screening methods do not encompass this individual adjustability in stepping technique and, thus, it is questionable whether they can identify older people at risk for stair falls specifically.

1.5 Stair-specific fall prevention tools

One way to improve the predictability of general fall screening tools for stair fall risk is to include stair-specific risk factors that are linked to the underlying mechanisms of stair falls. Current knowledge on stair-specific biomechanical risk factors has been acquired through comparisons between predetermined subject groups for single biomechanical risk factors. Typically, older adults have been grouped together and classified as the at risk group and their mean values for single biomechanical risk factors have been compared against younger “safer” adults. However, it is known that falls are a multifactorial problem and fall rates can be reduced through interventions at multiple levels that require individual risk assessment (Gillespie et al., 2012; Lord, Menz, & Tiedemann, 2003). Presently, no conclusion can be drawn regarding the individual stair fall risk using the available literature, as there is no information regarding the performance of the individual in relation to all the different biomechanical factors. This is a major limitation, as an individual who, for example, displays no or moderate risk for a given biomechanical factor may in fact be at a high risk for a stair fall because they also adopt one other highly risky stepping strategy with a greater impact on safety. Alternatively, an individual displaying a marked risk in one of the biomechanical risk factors could also display a more conservative strategy in another biomechanical factor that could mitigate the increased risk. The limited number of studies that did apply a multivariate analysis, aimed to predict stair negotiation performance in terms of speed using clinical and biomechanical factors, without identifying any stair-specific risk factors (Bonnyaud, Zory, Pradon, Vuillerme, & Roche, 2013; Larsen, Sørensen, Puggaard, & Aagaard, 2009; Tiedemann, Sherrington, & Lord, 2007). Therefore, to identify older adults at risk for a stair fall, an individual approach is needed that can group individuals based on multiple biomechanical factors indicative of risk and safety. This will allow profiling the overall stair-negotiating behaviour of the individual and make it possible to target the specific functional factors underpinning the biomechanical deficit identified.

1.6 Implementation of stair-specific risk factors

To successfully identify people at risk for a fall at community level, the screening tool needs to meet the following criteria: 1) Simple to administer; 2) Short administration time; 3) Feasible for older people to undertake; 4) Valid and reliable measurements; 5) Low-tech and robust; 6) Portable and 7) Quantitative measurements (Lord et al., 2003). Most of these criteria are not met in the biomechanical measurements of the stair fall risk factors specified earlier (section 1.3.1 and 1.3.2), as these require the availability of a gait lab and instrumented staircase. To circumvent this limitation, the stair-specific biomechanical risk factors should be linked with simple outcome measures that underpin the specific biomechanical deficit of the individual. However, at present no study has attempted to relate the biomechanical stair-specific risk factors to underlying functional capabilities that can be pragmatically assessed at community level.

1.7 Prospective fall monitoring

To identify older adults at risk for a stair fall it is vital that the individuals screened are followed up for a prolonged period of time, so that falls on stairs occurring post-screening can be documented. Although, a range of prospective studies which monitored falls to identify people at risk using biomechanical and clinical outcome measures are available (Hausdorff, Rios, & Edelberg, 2001; Hilliard et al., 2008; Lord et al., 1994; Maki, Holliday, & Topper, 1994; S. W. Muir, K. Berg, B. Chesworth, N. Klar, & M. Speechley, 2010a; Muir et al., 2010b), there is no prospective study that specifically focused on stair falls which are a leading cause of accidental death and account for the majority of fall costs (Startzell et al., 2000). As a result, none of the biomechanical or clinical risk factors associated with stair fall risk have been validated. Acquiring prospective fall information after profiling the biomechanical stair negotiation behaviour of the individual would allow identification of the biomechanical stair-specific risk factors that differentiate stair fallers from non-fallers. Furthermore, the prospective stair fall data could be used to investigate whether any of the individual risk factors targeted by the current general fall risk identification tools could differentiate stair fallers from non-fallers.

1.8 Conclusion

Falls on stairs are a major cause of injury and loss of independence for older people and place escalating demands on the NHS and social services. The underlying mechanisms for a fall during both stair ascent and descent have been studied extensively, and as a result stair-specific risk factors have been identified. However, existing fall risk screening tools do not include any stair-specific risk factors and it is unknown if these general screening approaches are sensitive enough to detect people at risk for a fall on stairs specifically. Therefore, there is a need for systematic research to fill these gaps and work towards the development of stair-specific fall risk assessment tools at community level.

1.9 Purpose and outline of the thesis

The overall purpose of this thesis was to develop a novel multivariate approach that has the ability to identify older adults at risk for a fall on stairs at community level. For this purpose, a prospective study-design was adopted following measurements of stair biomechanics and functional abilities that were taken in older adults at baseline. The background of the statistical methods used is provided in Chapter 2. In Chapter 3, I describe a novel multivariate approach for profiling the overall stair-negotiating behaviour of an individual based on different biomechanically risky and conservative strategies. In Chapter 4, I investigate if the identified stair-negotiating behaviours of older adults are maintained, irrespective of the step dimensions of the staircase. The prospective fall information is applied in Chapter 5, 1) to investigate whether participants who sustained a stair fall in the 12-month follow-up period could be differentiated by a mutual biomechanical risk factor or clinical and functional parameter, and 2) to establish the overall stepping profile at the greatest risk for a stair fall and identify easily measurable clinical and functional parameters underpinning this profile. Following the three experimental chapters, a general discussion is presented in Chapter 6 where the findings are synthesized and future recommendations to improve stair safety and predictability of older adults at risk for a stair fall are made.

CHAPTER 2:

Background in statistical methods.

2.1. K-means clustering

In Chapter 1, the need for a multivariate approach that can group individuals based on multiple biomechanical factors indicative of risk and safety is highlighted. A method that is typically used to differentiate groups or profiles is k-means clustering (Lisboa, Etchells, Jarman, & Chambers, 2013). The k-means algorithm is known for putting N data points in an I dimensional space into K clusters/groups. Each cluster is parameterized by a vector $m^{(k)}$ called its mean. To start the k-means algorithm, the K means are initialized in some way (see example in Figure 2.1). K-means is then an iterative two-step algorithm (see example in Figure 2.1) (MacKay, 2003). In the assignment step (Figure 2.1), each data point n is assigned to the nearest mean. In the update step (Figure 2.1), the means are adjusted to match the sample means of the data points that they are responsible for. The algorithm in Figure 2.1 converges after three iterations, at which point the assignments are unchanged so the means remain unmoved when updated. In the present thesis k-means clustering is used to examine differences in biomechanical stair descent behaviours between individuals in Chapter 3, 4 and 5.

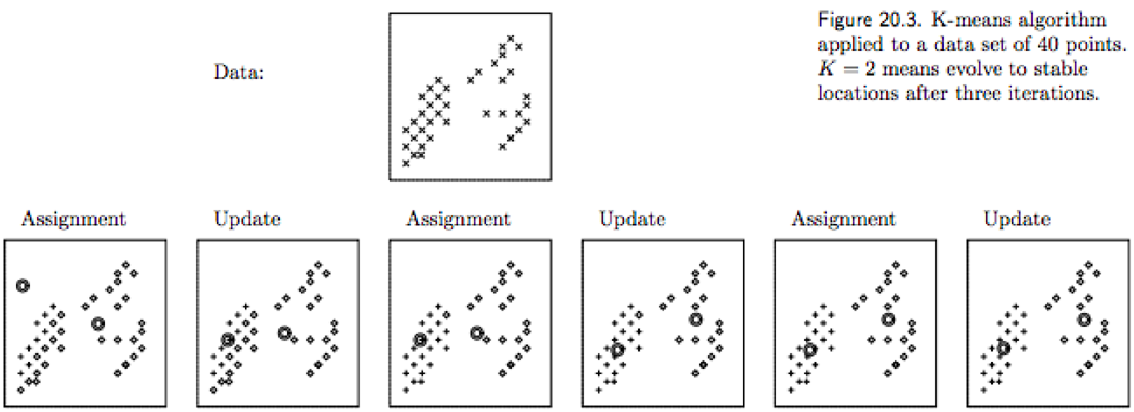

Figure 2.1. An example of the k-means clustering algorithm (this figure was adopted from MacKay, 2003).

2.2. Separation-Concordance framework

Previous evaluation of the k-means algorithm has shown it to be strongly dependent upon the initial starting points of the algorithm, as well as on the pre-set number of clusters/groups, represented by the value of K (Lisboa et al., 2013). Therefore, in order to obtain a stable and thus reproducible number of groups, a separation-concordance (SeCo) framework has been developed (Lisboa et al., 2013). The SeCo framework takes a dual measure approach to clustering, using both an internal measure of separation, and an external measure of cluster stability. Solutions where the recovery of partitions are repeatable will have a high proportion of solutions with greater consistency. The SeCo framework works as follows (Chambers, Jarman, Etchells, & Lisboa, 2013; Lisboa et al., 2013), for each dataset a range of K values is chosen, and the following process is applied:

1. Perform k-means on the data 500 times, reinitializing the centres for each iteration.
2. Calculate the separation measure, the Total Within Cluster Sum of Squares (SSQ) for each solution
3. Select the top 10% of these solutions by the Within Cluster Sum of Squares.
4. Calculate the stability measure, the pairwise Cramérs' V statistic for each combination of these solutions.
5. Produce the SeCo map of these solutions.

The SeCo map details the stability and separation of the solutions found for the dataset and the specified values of K. Producing a plot of the proportion of solutions with a given consistency allows the user to gauge the relative performance of the solutions for a given value of K. An example of a SeCo map is shown in Figure 2.2 (Lisboa et al., 2013) this map highlights that stable structure can be developed from the data for values of K between 2 and 8 (highlighted in Figure 2.2), that as the value of K is increased beyond this level, the structure becomes less stable, with more variation within the solutions obtained. In the present thesis the SeCo map is obtained for all k-means algorithms and the optimal number of K is decided using the above guidelines.

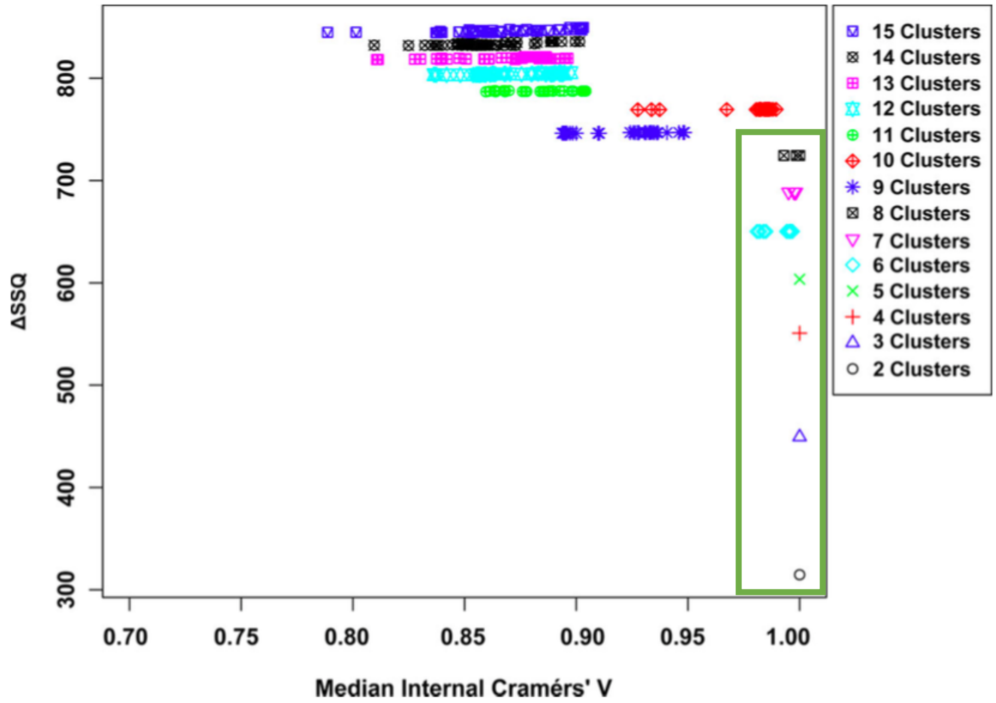

Figure 2.2. A Separation-Concordance (SeCo) map with the optimal solutions K2-8 indicated by the green rectangle (this figure was adopted from Lisboa et al., 2003).

2.3. Cramer's V

In the present thesis, we aimed to investigate whether older adults maintain their stair-negotiating behaviours irrespective of the step dimensions of the staircase (Chapter 4). A method that can measure the degree of association for nominal variables (the group numbers obtained by the k-means clustering in the present thesis) is the Cramer's V test (Cramér, 2016). The Cramer's V estimation is based on the Pearson chi-square statistic (Cramér, 2016), which is a statistical test to evaluate how likely it is that any observed difference between the data sets arose by chance. The Cramer's V test results in a value between 0 and 1. A value of 0 indicates that there is no association and a value of close to 1 indicates a high association.

2.4. Kaplan-Meier survival modeling

In Chapter 5, we aimed to establish the overall stepping profile at the greatest risk for a stair fall. The survival experience for a group of participants is most often analysed using the Kaplan-Meier survival function, which plots the probability that an individual will survive to time, t, as a function of t (Christensen, 1987). Kaplan–Meier estimates of the survival function express in the present thesis the risk of a hazardous event in terms of cumulative probabilities. These cumulative probabilities and thus the probability of surviving (i.e. not suffering from a hazardous event) will differ between groups and can be compared using a log-rank test in order to establish the stepping profile at the greatest risk.

2.5. Cox-regression survival modeling

In order to investigate whether participants who sustained a hazardous event on stairs in the 12-month follow-up period could be differentiated by a mutual biomechanical risk factor or clinical and functional parameter, a Cox regression analysis was executed (Chapter 5). The Cox regression analysis is a method for investigating the effect of several variables upon the time a specified event (a hazardous event in the present thesis) takes to happen (Barros & Hirakata, 2003). The method assumes that the effects of the predictor variables upon survival are constant over time and explores the relationship between the 'survival' of a participant and the predictor variables. Unlike logistic regression, the Cox regression model is dependent on time, meaning that the hazard of an 'event' happening changes with time, which is in contrast to the fixed outcome of the event in the logistic regression (Barros & Hirakata, 2003).

CHAPTER 3:

A novel multivariate approach for biomechanical profiling of stair negotiation.

The information presented in this chapter has been reported in the paper:

Ackermans, T, Francksen N, Casana-Eslava, R., Lees C, Baltzopoulos, B., Lisboa P., Hollands M.A., O'Brien T.D., Maganaris C.N. (2019) A novel multivariate approach for biomechanical profiling of stair negotiation. *Experimental Gerontology*. Doi: 110646/j.exger.2019.110646.

3.1 Abstract

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

risk of approaches based on single-parameter comparisons between predetermined groups. Establishing the predictive power of the current approach for future stair falls in older people is imperative for its implementation as a falls prevention tool.

3.2. Introduction

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

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

In several studies, older adults displayed not only riskier strategies, but also more conservative strategies when descending stairs. For example, high risk older adults have been found to display not only a decreased foot clearance, which increases fall risk, but also a decreased cadence, which indicates a more conservative strategy that could reduce the risk for a fall (Zietz et al., 2011). Buckley (2013) showed that the increased risk for a fall due to a diminished ability to generate high eccentric ankle torques of older adults was accompanied by a reduced peak downwards CoM velocity, a more conservative strategy that could reduce the risk for a fall (Buckley et al., 2013). In these examples, the conservative strategies adopted might mitigate the effect of the risky strategies and preserve stair safety. However, to generalise such a conclusion to a whole subject group assumes that both the riskier and more conservative strategies, identified by the inter-group comparisons, are displayed by the same individuals in the groups. At present, there is no evidence that the individual in a group with, for example, the smallest foot clearance is the same individual with the smallest variance in foot clearance. Therefore, individual stepping behaviour should be determined based on multiple parameters reflecting both risk and safety on stairs. However, such an approach has never been pursued before.

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

3.3 Methods

3.3.1 Participants

Twenty-five younger adults (age: 24.5±3.3 y; body height: 1.74±0.06 m; body mass: 70.1±8.4 kg; mean and standard deviation (SD)) and 70 older adults (age: 71.1±4.1 y; body height: 1.68±0.08 m; body mass: 68.8±14.2 kg) participated in the study. All participants lived independently and were recruited from the local community of Liverpool, UK. Participants were excluded if they could not descend stairs in a step-over-step manner, or were using the handrails or any other aid to descend the stairs. Written informed consent was obtained from all participants 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.

3.3.2 Staircase configuration

The measurements were conducted on a custom-built instrumented seven-step staircase with four force platforms (1080Hz, 9260AA, Kistler AG, CH) embedded in the lower four steps (3-6) (Figure 3.1). Kinematics were obtained using a 24 infrared camera system (120Hz, Vicon, Oxford Metrics, UK). The staircase configuration was set to represent a typical private home staircase in agreement with the building regulations in the UK (British-Standards-Institute, 1984; Department-of-the-Environment-and-The-Welsh-Office, 1992), with the rise (the vertical distance from one step to the next) set at 20 cm and the 'going' or run (the horizontal distance between the edges of adjacent steps) at 25 cm, resulting in a pitch of 38.7 degrees. Handrails on both sides of the staircase were in place during all tests (Figure 3.1). The steps of the staircase as well as the top landing and walkway were independent structures (Figure 3.1). The position of the top landing was fixed and the walkway was secured on the floor when placed in the desired position (i.e. the wheels were raised from the floor, so the wooden structure rested on the floor). The metal framework of the different steps was then connected by bolts to the top landing on one side, to the walkway on the other side, and to each other. As a result, the structures did not separate or roll away from each other.

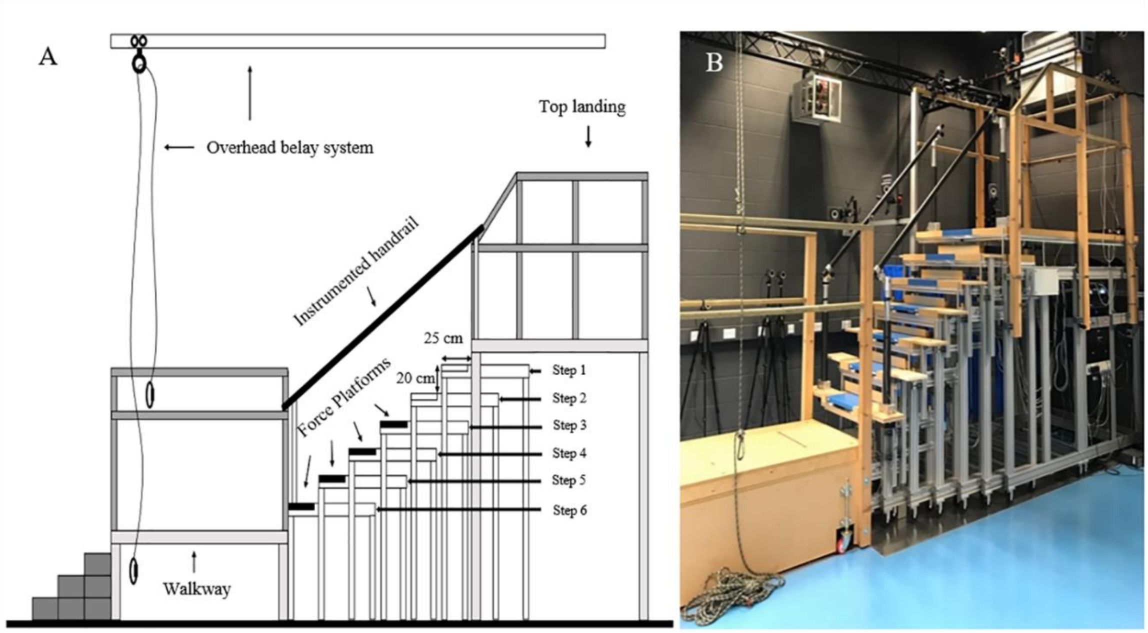

Figure 3.1. A schematic representation (A) and image (B) of the custom-built instrumented seven-step staircase.

3.3.3 Procedures

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

3.3.4 Data analysis

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 14 mm; Appendix A). The segmental data were based on Dempster's regression equations (Dempster, 1955) and used geometrical volumes to represent each segment (Hanavan, 1964). 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 all kinetic and kinematic data were filtered using a low-pass fourth order Butterworth filter with a cut-off frequency of 6 Hz. The gait events were determined using force plate data.

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

i. *Maximal CoM angular acceleration*. This parameter reflects the ability to control the body against gravity as it descends and a higher acceleration is associated with a greater fall risk. The parameter takes both the CoM-CoP separation and the CoM acceleration into account, which are two known risk factors for a stair fall (Buckley et al., 2013; Mian, Narici, et al., 2007; Mian, Thom, et al., 2007; Templer, 1995). The angular acceleration was calculated for the angle (*a)* between the CoM and CoP position of the trailing leg (Figure 3.2A). The maximal angular acceleration of the CoM was obtained as the peak value during the swing phase for steps 3-5 for all three trials as these represent steady state steps (McFadyen & Winter, 1988). The mean value of maximal CoM angular acceleration across the three trials was considered for further analysis.

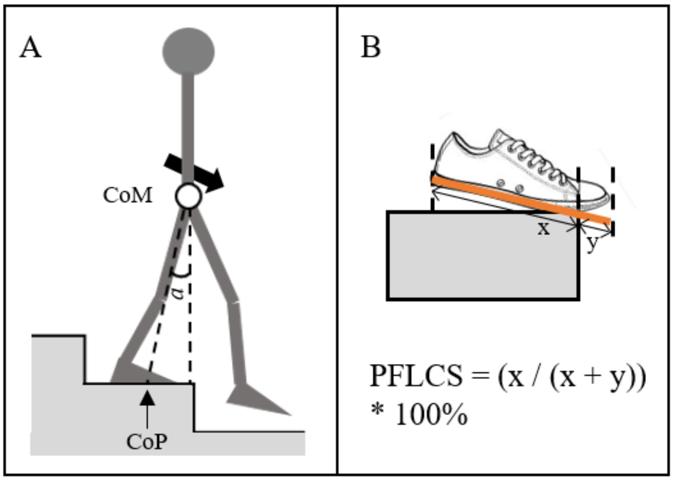

*Figure 3.2. Schematic overview of the calculation of the CoM angular acceleration (A) and proportion of foot length in contact with stair (PFLCS) (B). The CoM angular acceleration was calculated over the angle (a) between the CoM and CoP position of the trailing leg during the lowering phase. The PFLCS was calculated at touch-down using the rigid virtual shoe (orange line) as: PFLCS = (x / (x + y)) * 100%.*

ii. *Foot clearance*. This parameter reflects trip-induced fall risk, where a smaller foot clearance is associated with a greater fall risk. The foot clearance was calculated by manually digitising the two-dimensional outline of the subject's shoe, which was obtained by taking a picture of the subject's shoe outline drawn on an A4 paper (Figure 3.3A), using ImageJ (National Institutes of Health, Bethesda, USA). The coordinates of up to 600 virtual markers representing the individual shoe sole outline were then calculated in Matlab (R2018a, The Mathworks, Natick, USA) (Figure 3.3B). The position of three markers fixed on the shoe of the subject (first metatarsophalangeal joint, fifth metatarsophalangeal joint and calcaneus lateralis) were digitized in the two-dimensional drawing and using the static measurement, which included the position of the three markers in a three-dimensional space, the position of the virtual outline of the shoe relative to the markers could be determined. The virtual outline of the shoe was then projected in the movement trials, again relative to the three markers (Figure 3.3C). The foot clearance was obtained during the swing phase when the virtual shoe outline of the leading limb passed the vertical position (*a*) of the step edge up until the outline passed the horizontal position of the step edge (*b)* (Figure 3.3D). The minimal clearance of the virtual shoe (dashed arrow in Figure 3.3D) was determined within this time frame (*green* shaded area in Figure 3.3D) and thus, could be the horizontal foot clearance, the vertical foot clearance or a resultant of the two in-between. The minimal foot clearance was determined for steps 1-5 in all three trials. The mean value across the three trials was considered for further analysis.

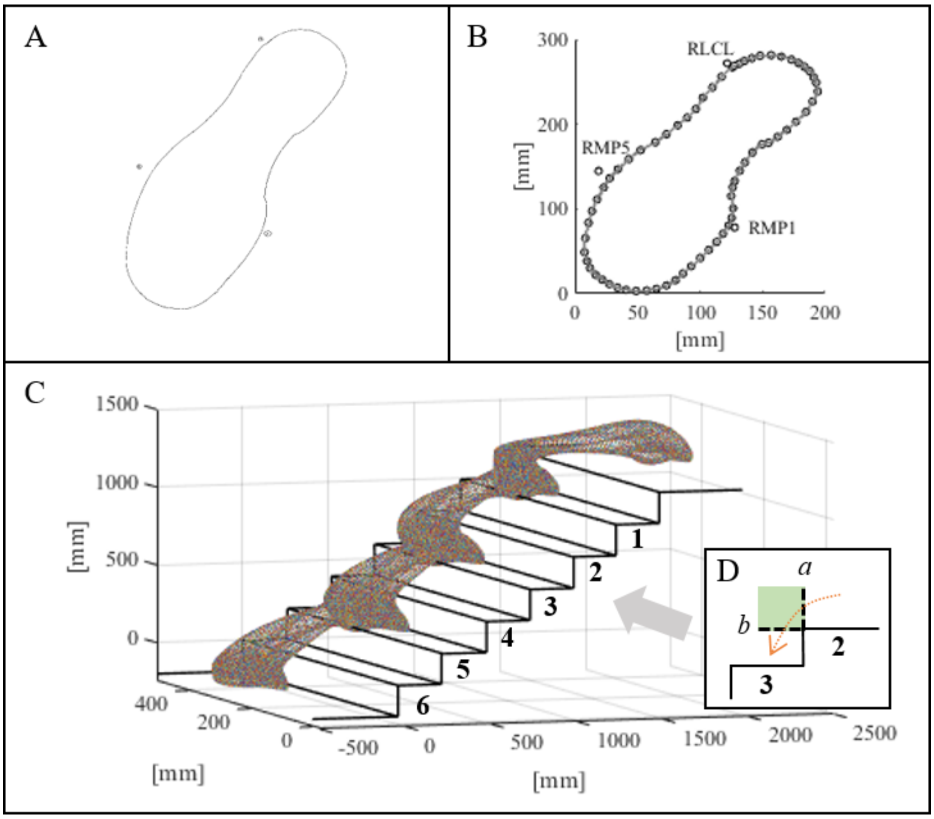

Figure 3.3. Example of the foot clearance calculation of the right foot. First, a two-dimensional outline of the shoe (A) was digitized and linked to three markers (first metatarsophalangeal joint: RMP1, fifth metatarsophalangeal joint: RMP5 and calcaneus lateralis: RLCL) of the static measurement (B). The virtual outline of the shoe was then projected in the movement trials (C). Foot clearance was calculated as the minimal distance between the virtual shoe and the step edge, within the green shaded area between a and b shown in inset D.

iii. *Proportion of foot length in contact with stair (PFLCS).* This parameter reflects slip-induced fall risk due to foot positioning relative to the step edge, where a reduced PFLCS is associated with a greater fall risk. PFLCS was calculated using the rigid virtual shoe outline introduced above (orange line in Figure 3.2B), which was not influenced by foot deformation, at touch-down on steps 3-6 for all three trials (Figure 3.2B). 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 virtual shoe outline to the step edge (Figure 3.2B). The PFLCS was calculated as a percentage using the following equation:

PFLCS = (distance x / (distance x + distance y))*100% (Figure 3.2B). The mean value of PFLCS across the three trials was considered for further analysis.

iv. *Required coefficient of friction (RCOF).* This parameter also reflects propensity for a slip between the shoe-surface interaction, as a higher friction is associated with a greater fall risk. It 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 (Christina & Cavanagh, 2002). The peak RCOF was determined during the loading phase of stance on steps 3-5 for all three trials using Visual3d (C-Motion, Germantown, USA) after a threshold of 50 N for the vertical force was exceeded to prevent erroneous results (Buczek, Cavanagh, Kulakowski, & Pradhan, 1990; Christina & Cavanagh, 2002). The mean value of RCOF across the three trials was considered for further analysis.

v. *Cadence*. Descending stairs fast may result in a fall as an increased speed could negatively modify the four parameters above. The duration of one gait cycle was obtained for the right and left limb. Cadence was calculated as the average for the left and right limb for the three trials and the mean value was considered for further analysis.

vi. In addition to the five biomechanical parameters listed (i-v), *the trial-to-trial variance* values of these parameters for the three trials were calculated for each step separately. Higher variance between trials may indicate a person's inability to maintain a steady/safe movement pattern, which increases the risk for a fall (Hausdorff et al., 2001). The trial-to-trial variance values for the steps were averaged and the mean value for each parameter (i-v) was used for further analysis.

3.3.5 Statistics

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

To examine differences in biomechanical stair descent behaviours between individuals (independent of age or fall history) k-means clustering was applied, a method that is typically used to differentiate groups or profiles and has been explained in detail in Chapter 2 (Lisboa et al., 2013). First, the mean value of every participant for all outcome measures (i-vi) separately was normalised using Z score transformation. The method used to determine the appropriate number of k was the SeCo framework (Lisboa et al., 2013), which has been previously described in detail (Casana-Eslava, Jarman, Lisboa, & Martin-Guerrero, 2017; Chambers et al., 2013; Lisboa et al., 2013). Briefly, for a range of k values (k = 2-10), which represent the possible number of clusters/groups created, K-means clustering was performed on the data 500 times. The centres of each cluster were reinitialised for each iteration. The total within cluster Sum of Squares (SSQ), which is a measure of separation, was calculated for each solution and the top 10% of these solutions was selected by the within cluster SSQ. The stability measure, the pairwise Cramérs' V statistic, was calculated for every pair of clustering solutions. This was used to determine the highest value of k before the stability of the clustering solutions breaks down. The Separation Concordance (SeCo) map that combined the separation and stability measure of these solutions was produced to determine the optimal number of clusters/groups (k), which has been explained in detail in Chapter 2. To visualise the groups in a three-dimensional space, a principal components analysis (PCA) was executed on the dataset and the first three principal components were plotted after the k-means clustering was completed. Furthermore, to examine differences in the composition of each group, the group profiles (GP = ($Mean_{group}$ – $Mean_{overall}$) / $SD_{overall}$) were calculated for all outcome measures with a threshold set at 0.5. Statistical analyses were performed using SPSS (version 24, SPSS Inc., California, USA) and Matlab (R2018a, The Mathworks, Natick, USA). The significance level was set at α = 0.05.

Table 3.1. Mean (± SD) biomechanical outcome measures assessed for the younger adults, older non-fallers and older fallers.

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

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

** Significant group effect (P<0.05)*

[a] Significant difference between younger adults and older adult fallers (P<0.05)

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

3.4. Results

The one-way ANOVA revealed a group effect ($p<0.05$) for foot clearance, variance in foot clearance, PFLCS, variance in PFLCS, RCOF and variance in RCOF (Table 3.1).

The post-hoc analysis (Table 3.1) revealed lower ($p<0.05$) mean and variance in foot clearance in younger adults compared to older fallers. In addition, the younger adults showed greater ($p<0.05$) variance in PFLCS and lower RCOF compared to the older non-fallers. The older fallers and older non-fallers showed greater ($p<0.05$) PFLCS compared to the younger adults. There were no statistical differences between older fallers and non-fallers.

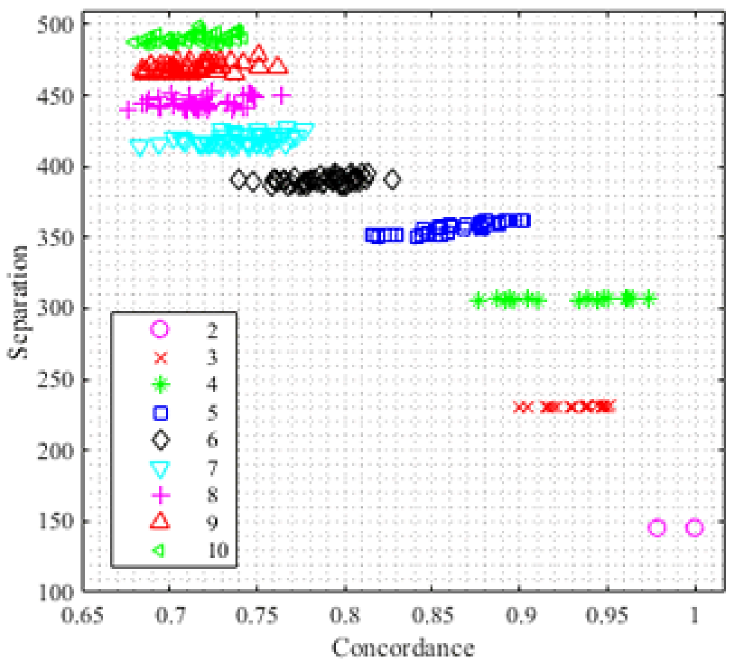

Figure 3.4. Separation-Concordance map for the biomechanical outcome measures, highlighting the top 10% (of 500 initialisations of the k-means algorithm) ΔSSQ on the y-axis and the internal median Cramer's V on the x-axis for each value of k (2-10).

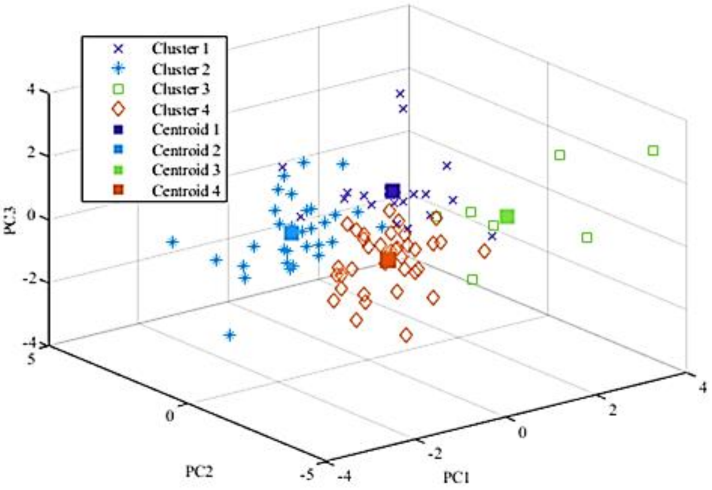

Figure 3.5. Three-dimensional plot of the first three principal components (PC1, PC2 and PC3) of the biomechanical outcome measures visualizing the segmenting groups 1-4 including the centroids of each group.

The stability and separation of the specified values of k, displayed in the SeCo map (Figure 3.4), revealed that k=4 was the optimal number of groups for the present dataset. This was in agreement with the visualization of the groups using the first three principal components of the PCA, showing four segmenting groups in the 3D environment (Figure 3.5). All four groups contained younger adults, older non-fallers and older fallers (Table 3.2). The GP (Table 3.3) with a threshold set at 0.5 revealed that group 1 differed from the overall mean by showing a higher CoM angular acceleration (GP = 1.19), more variance in CoM angular acceleration (GP = 1.48), lower RCOF (GP= -0.61) and a higher cadence (GP = 0.57). Group 2 differed from the overall mean by showing a higher foot clearance (GP = 0.85), more variance of RCOF (GP = 0.52) and a lower cadence (GP = -0.82) (Table 3.3). Group 3 differed from the overall mean by showing a higher foot clearance (GP = -0.57), less PFLCS (GP = -0.59), more variance in PFLCS (GP = 1.22), less RCOF (GP = -0.66), higher cadence (GP = 1.21) and more variance in cadence (GP = 2.60) (Table 3.3). In contrast, group 4 did not exceed the threshold and therefore did not show detectable differences in any of the parameters compared to the overall mean (Table 3.3).

Table 3.2. Group composition of all four groups.

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

Table 3.3. Group profiles (GP) of the biomechanical outcome measures assessed for the four groups. Those exceeding the threshold of 0.5 are highlighted bold and coloured 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
Group 1	-0.23	-0.36	0.17	-0.11	**1.19**	**1.48**	**-0.61**	-0.22	**0.57**	-0.10
Group 2	**0.85**	0.47	0.49	-0.42	-0.37	-0.43	0.49	**0.52**	**-0.82**	-0.35
Group 3	**-0.57**	0.38	**-0.59**	**1.22**	0.04	-0.37	**-0.66**	0.21	**1.21**	**2.60**
Group 4	-0.48	-0.29	-0.39	0.15	-0.35	-0.37	0.06	-0.37	0.12	-0.22

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

3.5. Discussion

This study aimed, for the first time, to establish a multivariate approach that characterises the stair negotiation behaviour during stair descent based on multiple factors that include both biomechanically risky and conservative strategies. Four groups were identified. Groups 1-3 differed from the overall mean by showing both risky and conservative strategies on the biomechanical outcome measures, whereas group 4 did not display any particularly risky or conservative strategies in the biomechanical outcome measures compared to the overall mean. In contrast to the common approach of comparing single parameters between groups that showed an effect of age and fall history on several individual risk factors (Table 3.1), the multivariate approach showed that none of the groups contained only (or all) older non-fallers or older fallers (Table 3.2). Instead, older fallers and older non-fallers were spread over the four groups, as they did not present a similar particularly risky overall behaviour that would group them in the same group.

3.5.1 Traditional group comparisons

The commonly used comparisons between age and fall history groups showed that ageing had an impact on stair biomechanics during stair descent. The older adults who had a previous fall showed more variance in foot clearance compared to the younger adults (younger adults: 36.5 vs. older fallers: 68.2), which is a known risk factor for a trip on stairs (Hamel, Okita, Higginson, et al., 2005). Moreover, the older adults who had not had a previous fall showed a greater RCOF compared to the younger adults (younger adults: 0.10 μ vs. older non-fallers: 0.11 μ); these increased frictional demands for the older adults might put them at a greater risk of a slip (Christina & Cavanagh, 2002). These findings are in line with current literature showing that older adults display a more risky behaviour in several biomechanical outcome measures during stair descent (Christina & Cavanagh, 2002; Hamel, Okita, Higginson, et al., 2005; Mian, Narici, et al., 2007; Mian, Thom, et al., 2007). For the younger adults these biomechanical parameters indicate a more conservative strategy that could reduce the fall risk. In addition to the risky strategies above, the older adults had a greater foot clearance (younger adults: 20.1 mm vs. older non-fallers: 24.8 mm vs. older fallers: 29.8 mm), higher PFLCS (younger adults: 80.7 % vs. older non-fallers: 85.1 % vs. older fallers: 85.9 %) and less variance in PFLCS (younger adults: 18.4 vs. older non-fallers: 12.6 vs. older fallers: 15.2) than the younger adults. These are all biomechanical factors that indicate a more conservative strategy for the older adults compared to the younger adults and could potentially reduce the fall risk (Hamel, Okita, Higginson, et al., 2005; M. S. Roys, 2001). Furthermore, contrary to the differences in stair biomechanics between high risk and low risk older adults reported by Zietz (2011), our results revealed that a previous fall, which on its own is a risk factor for a future fall (Startzell et al., 2000), had no impact on stair biomechanics (Table 3.1) (Zietz et al., 2011). This discrepancy might suggest that the older fallers in the present study did not adopt more conservative stepping strategies during stair descent compared to older non-fallers. The results of the group comparisons suggest that both older and younger adults adopted not only biomechanically risky strategies, but also biomechanically conservative strategies that could mitigate the overall falling risk. However, based on these group means it cannot be established whether the individuals who adopted a riskier strategy, based on one parameter within a group, were the same individuals who adopted a more conservative strategy for another parameter.

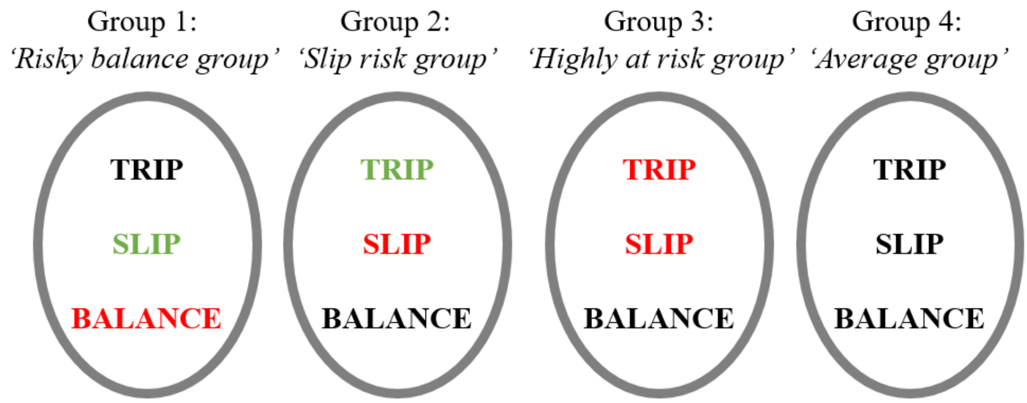

Figure 3.6. A simplified overview of the group profiles obtained, with the underlying mechanisms of a potential fall coloured in terms of the risks identified (red = riskier strategy; green = more conservative strategy; black = not particularly risky or conservative strategy).

3.5.2 Novel multivariate approach

The current multivariate grouping approach circumvents the above limitation and allows identification of the specific biomechanically risky and safer strategies that a particular individual exhibits. Three individual groups (1-3) differed from the mean behaviour considering both the risky and the conservative strategies displayed. Group 1 differed from the mean by displaying a greater peak and variance in CoM angular acceleration, which both increase the risk for an of loss of CoM control when stepping down (Buckley et al., 2013; Mian, Narici, et al., 2007; Mian, Thom, et al., 2007; Templer, 1995). Therefore, this group will be referred as the 'risky balance group' (Figure 3.6). The greater cadence compared to the overall mean could increase the risk for a slip, trip or loss of CoM control. However, these riskier strategies were accompanied by a smaller RCOF, which is a more conservative strategy that could mitigate the risk for a slip (Christina & Cavanagh, 2002). Group 2 differed from the mean by displaying more variance in the RCOF. More variance indicates a person's inability to maintain a steady movement pattern and could result in a slip (Hausdorff et al., 2001). Therefore, this group will be referred as the 'slip risk group' (Figure 3.6). However, this increased risk for a slip was accompanied by a lower cadence, which is a more conservative strategy (Hamel, Okita, Higginson, et al., 2005; M. S. Roys, 2001), and a greater foot clearance, which decreases the risk for a trip. Group 3 was at increased risk for a trip due to a smaller foot clearance compared to the overall mean (Hamel, Okita, Higginson, et al., 2005). There were also lower mean and variance values for PFLCS indicating a greater risk for a slip when placing the foot on the step (M. S. Roys, 2001). In addition, group 3 had greater mean and variance values for cadence, which indicate an increased risk for a trip, slip or loss of CoM control. Therefore, this group will be referred as the 'highly at risk group' (Figure 3.6). However, these differences were accompanied by one conservative strategy when compared to the overall mean, namely a decreased RCOF that reduces the risk for a slip (Christina & Cavanagh, 2002). Group 4 did not show any great differences from the overall mean. Therefore, group 4 did not show anything particularly risky, but also did not show any particularly conservative compensations as a result this group will be referred to as the ‘average group’ (Figure 3.6).These findings show that the stair negotiation behaviour is based on a mix of biomechanically risky and safer strategies.

Furthermore, the four behaviours all contained older adults who had previously fallen (group 1: 3; group 2: 13; group 3: 2; group 4: 9; total 27 older fallers), at least one older adult who did not have a previous fall (group 1: 9; group 2: 17; group 3: 5; group 4: 12; total 43 older non-fallers) and at least one younger individual (group 1: 8; group 2: 1; group 3: 1; group 4: 15; total 25 younger adults) (Table 3.2). Therefore, we conclude that the younger adults, the older adult non-fallers and the older adult fallers did not present a similar overall behaviour per group that would assign them in the same group. This is in marked contrast with the commonly used grouping methods that differentiate cohorts based on fall-history and age to compare mean values for single outcome measures. The current approach allows profiling of overall stair fall risk based on multiple risky and conservative stepping strategies exhibited by the stair user.

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

At present, we are not able to quantify the effectiveness of the compensations or to determine which of the combined behaviours is safer for the older adults. Additionally, we are unable to state whether older adults who display no risky behaviour, but show an ‘average’ behaviour in all parameters (group 4), are at less risk for a fall. To reach this important conclusion, future research should implement the current method on older participants and link the groups with some relevant metric for stair falls, for example number of stair falls and graded severity of the fall documented over a follow-up period.

It is also important that further research aims to identify the specific functional deficits underpinning the biomechanically risky stepping strategies adopted, so that fall predictive and preventive programs can then be delivered to the older adults at risk.

3.6. Conclusions

In conclusion, for the first time a multivariate approach was able to characterise stair descent behaviour. In contrast to commonly used single-parameter comparative approaches, it was found that the older fallers and older non-fallers were spread over the four stepping behaviours identified. Three of the four identified behaviours were found to be a combination of biomechanically risky and safer components, whereas one 'average' behaviour without any particularly risky or safer characteristics was identified. Further research should implement this method on older adults using a longitudinal approach to identify the behaviours that can differentiate those who will go on to experience an actual stair fall from those who will not, so that targeted cost-saving interventions for improving stair safety in older individuals can then be designed and implemented.

CHAPTER 4:

Stair negotiation behaviour of older individuals: Do step dimensions matter?

The information presented in this chapter has been reported in the paper:

Ackermans, T, Francksen N, Casana-Eslava, R., Lees C, Baltzopoulos, B., Lisboa P., Hollands M.A., O'Brien T.D., Maganaris C.N. (2019) Stair negotiation behaviour of older individuals: Do step dimensions matter? *Journal of Biomechanics.* Under review

4.1. Abstract

Stair falls are a major health problem for older people. Most studies on identification of stair fall risk factors are limited to staircases set in given step dimensions. However, it remains unknown whether the conclusions drawn would still apply if the dimensions had been changed to represent more challenging or easier step dimensions that could be encountered in domestic and public buildings. The purpose was to investigate whether the self-selected biomechanical stepping behaviours are maintained when the dimensions of the staircase are altered. Sixty-eight older adults (>65 years) negotiated a seven-step staircase set in two step dimensions (*shallow* staircase: rise 15cm, going 28cm; *steep* staircase: rise 20cm, going 25cm). Six biomechanical outcome measures indicative of stair fall risk were measured. K-means clustering profiled the overall stair negotiation behaviour and group profiles were calculated (this method has been explained in detail in Chapter 2). A Cramer's V measured the degree of association in membership between groups (this statistical method has been explained in detail in Chapter 2). The group profiles revealed that the biomechanically risky and conservative factors that characterized the overall behaviour in the groups did not differ for the majority of older adults between staircases for ascent and descent. A strong association of membership between the groups on the *shallow* staircase and *steep* staircase was found for stair ascent (Cramer's V: 0.412, $p<0.001$) and descent (Cramer's V: 0.380, $p=0.003$). The findings indicate that for the majority of the older adults, manipulating the demand of the task would not affect the underpinning mechanism of a potential stair fall. Therefore, detection of stair fall risk might not require testing using a staircase with challenging step dimensions.

4.2. Introduction

Stair negotiation is one of the most hazardous daily tasks for older adults, often resulting in falls (M. S. Roys, 2001). Indeed, falls on stairs have been identified as the leading cause of accidental death and place a substantial financial burden on the National Health Service (Scuffham et al., 2003; Soriano, DeCherrie, & Thomas, 2007; Startzell et al., 2000). The literature has identified tripping during the swing phase and slipping during push-off as the main underlying mechanisms for a fall during stair ascent (Templer, 1995). During stair descent, the underlying mechanisms include tripping and slipping during the loading phase, or a loss of centre of mass (CoM) control during the lowering phase (Templer, 1995).

A compromised safety on stairs has been primarily linked with deficiencies in physical capabilities, behaviour and stair design (Jacobs, 2016; M. S. Roys, 2001). In terms of stair design, staircases with a large step riser create additional demands for joint moment generation during stair ascent (Stacoff, Diezi, Luder, Stüssi, & Kramers-de Quervain, 2005) and control of the CoM during descent (Novak et al., 2016). Staircases with a small going are thought to increase the risk for a slip during descent by reducing the available area to safely land the leading limb (M. S. Roys, 2001). Although, stair design affects safety, the majority of studies on identification of risk factors for a stair fall are limited to a staircase set in given step dimensions (Buckley et al., 2013; Christina & Cavanagh, 2002; Hamel, Okita, Higginson, et al., 2005; Mian, Narici, et al., 2007; Mian, Thom, et al., 2007). Thus, it remains unknown whether the conclusions drawn regarding stair fall risk would still apply if the demand of the task had been changed by implementing more or less challenging step dimensions, within the range of step dimensions that could be encountered in various domestic and public buildings.

The few studies that have compared risk factors between staircases with different step dimensions are limited to comparisons of single biomechanical factors, such as foot positioning or dynamic balance (Johnson & Pauls, 2010; Nemire et al., 2016; Novak et al., 2016; Riener et al., 2002; M. Roys & Wright, 2005; M. S. Roys, 2001; Wright & Roys, 2005, 2008). However, it has been shown that risky stepping strategies may be adopted at the same time with more conservative strategies (Ackermans et al., 2019). For example, older adults descending stairs have been reported to display not only a decreased clearance, which increases fall risk, but also a decreased required coefficient of friction, which indicates a more conservative strategy that could reduce fall risk (Ackermans et al., 2019). Therefore, multiple parameters, reflecting both more risky and more conservative strategies on stairs, should be used to understand the effect of different step dimensions on safety. Furthermore, the studies that compared different step dimensions used mean values, either for a single group (Riener et al., 2002; Wright & Roys, 2005), or between predetermined groups, typically, younger vs older individuals (Novak et al., 2016; Stacoff et al., 2005). Following this approach would not allow establishing whether a particular individual would maintain the stepping behaviour selected or would adopt a different stepping strategy when exposed to a staircase with different step dimensions. To circumvent this limitation a recently developed multivariate approach for profiling individual stepping behaviour should be used(Ackermans et al., 2019).

The purpose of the present study was to apply a multivariate approach to investigate whether the selected biomechanical stepping behaviours of older individuals are maintained when negotiating staircases with two different step dimension configurations.

4.3. Methods

4.3.1 Participants

Sixty-eight older adults (age: 71.2±4.0y; body height: 1.68±0.08m; body mass: 70.2±13.4kg; males: 24) participated in the study. All participants lived independently and were recruited from the local community of Liverpool, UK. Participants were excluded if they could not negotiate both staircases in a step-over-step manner, or were using handrails or any other aid to negotiate the stairs. Written informed consent was obtained from all participants 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.

4.3.2 Staircase configuration

The measurements were conducted on a custom-built instrumented seven-step staircase (Ackermans et al., 2019). The kinematics were obtained using a 24 infrared camera-system (120Hz, Vicon, Oxford Metrics, UK) and kinetics were obtained through four force platforms (1080Hz, 9260AA, Kistler AG, CH) embedded in the lower four steps. The staircase was set in two different step dimension configurations. The *"shallow"* staircase was set at a rise of 15cm and going of 28cm resulting in a pitch of 28.2 degrees and the "*steep"* staircase was set at a rise of 20cm and going of 25cm resulting in a pitch of 38.7 degrees. The step dimensions of both staircases conformed to relevant building regulations in the UK (British-Standards-Institute, 1984; Department-of-the-Environment-and-The-Welsh-Office, 1992), with the *shallow* staircase representing an 'easier' public staircase and the *steep* staircase a more 'challenging' private staircase (M. S. Roys, 2001).

4.3.3 Procedures

Participants visited the lab on two occasions. During the first visit, they ascended and descended the *shallow* staircase at their self-selected pace in a step-over-step manner without using the handrails. Only the older adults who were confident to negotiate the *shallow* staircase in this manner were invited for the second visit, in which they ascended and descended the *steep* staircase in a similar manner. All trials were performed with the volunteers clothed in tight fitting clothes and wearing their own comfortable shoes. They were fitted in a five-point safety harness, which was attached to the overhead belay safety system. A trained member of the research team operated the belay system, ensuring that there was no tension in the rope during the measurements. To allow familiarisation, the older adults performed up to five practice trials on each staircase. Afterwards, they performed five more trials with the final three trials used for analysis. There was a break after the familiarization and the older adults tested were allowed to take as many breaks during the following trials to avoid fatigue. In all trials, at least one step approaching the top of the stairs was executed before stepping on the stairs and at least one step away from the stairs.

4.3.4 Data analysis

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 14 mm; Appendix A). The segmental data were based on Dempster's regression equations (Dempster, 1955) and used geometrical volumes to represent each segment (Hanavan, 1964). 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 kinetic and kinematic data were filtered using a low-pass fourth order Butterworth filter with a cut-off frequency of 6Hz. The gait events on the steps were determined using force plate data.

Kinetic and kinematic data were analysed to determine the following outcome measures, which have been described in detail previously(Ackermans et al., 2019):

1) Foot clearance. The foot clearance was calculated by projecting a virtual outline of the participant's shoe in the movement trials (Ackermans et al., 2019). The foot clearance was obtained during the swing phase when the virtual shoe outline of the leading limb passed the vertical position of the step edge up until the outline passed the horizontal position of the step edge. The minimal clearance was determined within this time frame for steps 2-6 for stair ascent and descent.

2) Proportion of foot length in contact with stair (PFLCS). PFLCS was calculated using the virtual shoe outline at touch-down on steps 2-4 for stair ascent and steps 1-4 for stair 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 virtual shoe outline to the step edge. The PFLCS was calculated as a percentage using the following equation: PFLCS=(distance x / (distance x + distance y))*100%.

3) Required coefficient of friction (RCOF). This parameter 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 (Christina & Cavanagh, 2002). The peak RCOF was determined using Visual3d (C-Motion, Germantown, USA) after a threshold of 50 N for the vertical force was exceeded. For stair ascent, this parameter was calculated during the push-of phase for steps 2-4 and for stair descent, the parameter was calculated during the loading phase in stance for steps 1-4.

4) Cadence. Cadence was taken as the average duration of two gait cycles (one of the left limb and one of the right limb) for stair ascent and stair descent.

5) Maximal CoM angular acceleration (only during stair descent). The angular acceleration was calculated for the angle between the CoM and centre of pressure (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 only for stair descent.

6) In addition to the five parameters listed (1-5), *the trial-to-trial variances of these parameters* were also calculated as the average of the variance across the three trials for each of the analysed steps. Variance in itself is a risk factor for falls, as more variance can indicate a person's inability to maintain a steady/safe movement pattern (Hausdorff et al., 2001).

4.3.5 Statistics

To examine differences in biomechanical stepping strategies between staircases a multivariate method was applied for stair ascent and descent (Ackermans et al., 2019). The multivariate method profiled the individual stepping strategies of older adults based on the mean values of outcome measures (1-6) using k-means clustering (this method has been explained in detail in Chapter 2). The optimal number of cluster/groups was determined through the SeCo framework that used a measure of separation and concordance, which has been explained in detail in Chapter 2 (Casana-Eslava et al., 2017; Chambers et al., 2013; Lisboa et al., 2013). To examine differences in group composition, the group profiles ($GP = Mean_{group} – Mean_{overall})/SD_{overall}$) were calculated for all outcome measures with a threshold set at 0.5. In order to measure the degree of association between groups obtained on the *shallow* staircase and groups obtained on the *steep* staircase, a Cramer's V index (explained in detail in Chapter 2) was calculated and cross-tabulations were obtained for stair ascent and descent (Cramér, 2016). Statistical analyses were performed using SPSS (version 24, SPSS Inc., California, USA) and Matlab (R2018a, Mathworks, Natick, USA). The significance level was set at $\alpha=0.05$.

4.4 Results

4.4.1 Number of groups

The SeCo framework revealed that during stair ascent the optimal number of groups for both staircases was three (Figure 4.1A, C). For stair descent, the SeCo framework revealed that the optimal number of groups for the *shallow* staircase was three and for the *steep* staircase was four (Figure 4.1B, D).

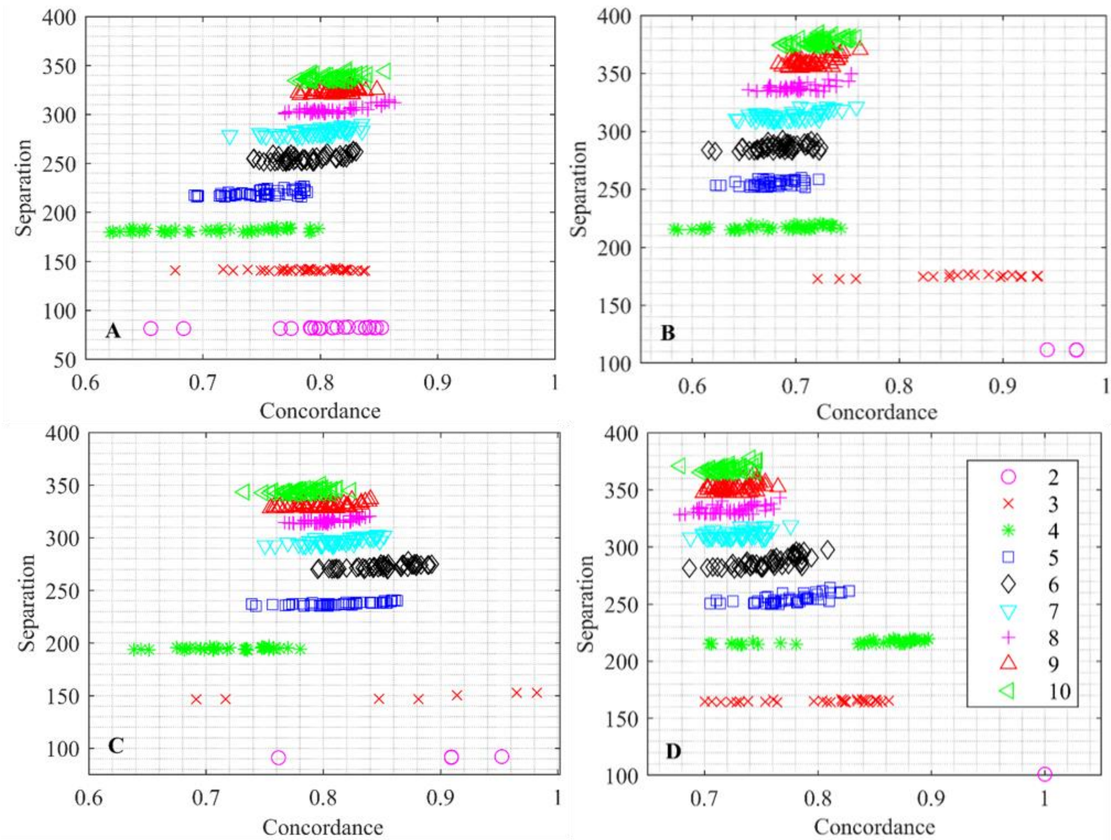

Figure 4.1. Separation-Concordance (SeCo) maps for the biomechanical outcome measures for both staircases for ascent and descent, highlighting the top 10% (of 500 initialisations of the k-means algorithm) with ΔSum of Squares (SSQ) on the y-axis and the internal median Cramer's V on the x-axis for each value of k (2-10). (A: shallow staircase ascent; B: shallow staircase descent; C: steep staircase ascent; D: steep staircase descent).

4.4.2 Group profiles for stair ascent

For the *shallow* staircase during ascent, the GP revealed that group 1 differed from the overall mean by showing higher PFLCS (GP=0.61) (Table 4.1). Group 2 differed from the overall mean by showing higher foot clearance (GP=0.53), more variance in PFLCS (GP = 1.53), higher RCOF (GP = 0.84), more variance in RCOF (GP=0.81) and more variance in cadence (GP=1.48) (Table 4.1). Group 3 differed from the overall mean by showing lower foot clearance (GP=-0.62), less PFLCS (GP=-1.19) and higher cadence (GP=0.67) (Table 4.1).

Table 4.1. Group profiles (GP) for stair ascent of the biomechanical outcome measures assessed for the two staircases. Those exceeding the threshold of ±0.5 are highlighted bold and coloured in terms of risk (red = more risky strategy; green = more conservative strategy).

	Foot clearance	Var. Foot clearance	PFLCS	Var. PFLCS	RCOF	Var. RCOF	Cadence	Var. Cadence
***Shallow* staircase**								
Group 1	0.19	-0.07	**0.61**	-0.29	-0.12	-0.15	-0.44	-0.31
Group 2	**0.53**	0.42	0.07	**1.53**	**0.84**	**0.81**	0.33	**1.48**
Group 3	**-0.62**	-0.07	**-1.19**	-0.20	-0.19	-0.12	**0.67**	-0.15
***Steep* staircase**								
Group 1	-0.05	-0.32	**-0.67**	0.17	**0.54**	-0.31	**0.74**	-0.33
Group 2	0.06	-0.24	**0.66**	-0.31	-0.37	-0.14	**-0.59**	-0.31
Group 3	-0.10	**1.42**	**-0.64**	**0.62**	0.02	**1.07**	0.28	**1.65**

Notes: *Var*: variance; *PFLCS*: proportion of foot length in contact with stair; *RCOF:* required coefficient of friction.

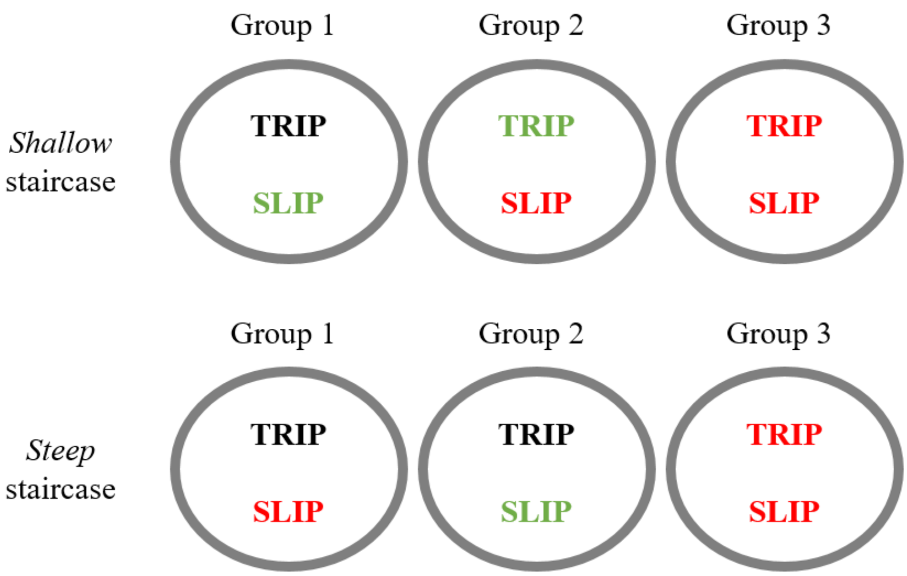

Figure 4.2. A simplified overview of the group profiles obtained for the Shallow and Steep staircase for ascent, with the underlying mechanisms of a potential fall coloured in terms of the risks identified (red = riskier strategy; green = more conservative strategy; black = not particularly risky or conservative strategy).

For the *steep* staircase during ascent, group 1 differed from the overall mean by showing less PFLCS (GP=-0.67), more RCOF (GP=0.54) and higher cadence (GP=0.74) (Table 4.1). Group 2 differed from the overall mean by showing higher PFLCS (GP=0.66) and lower cadence (GP=-0.59) (Table 4.1). Group 3 differed from the overall mean by showing more variance in foot clearance (GP=1.42), less PFLCS (GP=-0.64), more variance in PFLCS (GP=0.62), more variance in RCOF (GP=1.07) and more variance in cadence (GP=1.65) (Table 4.1).

4.4.3 Group profiles for stair descent

For stair descent, the GP of the *shallow* staircase revealed that group 1 differed from the overall mean by showing higher foot clearance (GP=0.56), less CoM angular acceleration (GP = -0.63), less variance in CoM angular acceleration (GP=-0.64), more RCOF (GP = 1.26), more variance in RCOF (GP = 1.20) and lower cadence (GP=-1.14) (Table 4.2). Group 2 differed from the overall mean by showing less RCOF (GP=-0.56) (Table 4.2). Group 3 differed from the overall mean by showing higher CoM angular acceleration (GP=0.95), more variance in CoM angular acceleration (GP=0.98) and higher cadence (GP=0.50) (Table 4.2).

Table 4.2. Group profiles (GP) for stair descent of the biomechanical measures assessed for the two staircases. Those exceeding the threshold of ±0.5 are highlighted bold and coloured in terms of risk (red = more risky 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
***Shallow* staircase**										
Group 1	**0.56**	0.02	0.25	-0.05	**-0.63**	**-0.64**	**1.26**	**1.20**	**-1.14**	-0.41
Group 2	0.09	0.31	0.16	-0.13	-0.47	-0.49	**-0.56**	-0.35	0.13	0.18
Group 3	-0.43	-0.40	-0.35	0.19	**0.95**	**0.98**	-0.04	-0.26	**0.50**	0.01
***Steep* staircase**										
Group 1	**-0.77**	-0.43	-0.05	-0.17	-0.48	-0.31	0.02	**-0.51**	0.31	-0.23
Group 2	-0.07	-0.24	0.02	-0.30	**1.20**	**1.35**	0.03	0.00	0.20	0.05
Group 3	**0.80**	0.34	0.23	-0.29	**-0.50**	**-0.55**	0.26	0.49	**-0.73**	-0.39
Group 4	-0.41	**0.52**	**-0.61**	**1.90**	0.10	-0.48	**-0.90**	-0.25	**1.03**	**1.59**

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

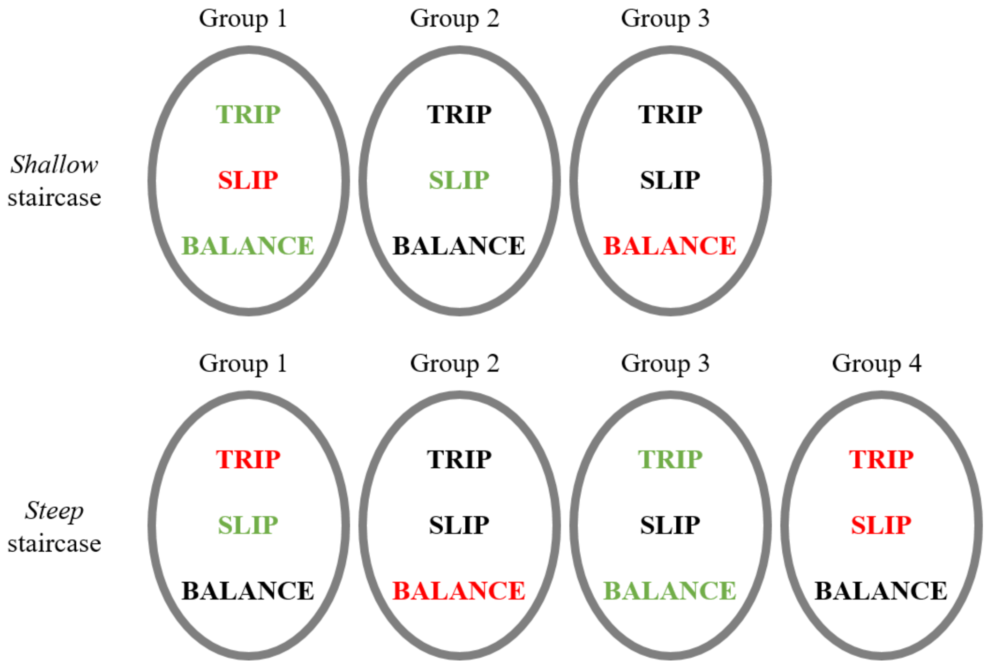

Figure 4.3. A simplified overview of the group profiles obtained for the Shallow and Steep staircase for descent, with the underlying mechanisms of a potential fall coloured in terms of the risks identified (red = riskier strategy; green = more conservative strategy; black = not particularly risky or conservative strategy).

For the *steep* staircase during descent, the GP revealed that group 1 differed from the overall mean by showing less foot clearance (GP=-0.77) and less variance in RCOF (GP=-0.51) (Table 4.2). Group 2 differed from the overall mean by showing higher CoM angular acceleration (GP=1.20) and more variance in CoM angular acceleration (GP=1.35) (Table 4.2). Group 3 differed from the overall mean by showing a higher foot clearance (GP=0.80), less CoM angular acceleration (GP=-0.50), less variance in CoM angular acceleration (GP=-0.55) and lower cadence (GP=-0.73) (Table 4.2). Group 4 differed from the overall mean by showing more variance in foot clearance (GP=0.52), less PFLCS (GP=-0.61), more variance in PFLCS (GP=1.90), less RCOF (GP=-0.90), higher cadence (GP=1.03) and more variance in cadence (GP=1.59) (Table 4.2).

4.4.4 Group association

For stair ascent, the Cramer's V (0.412, $p<0.001$) revealed a strong association of membership of individuals grouped on the *shallow* staircase with those grouped on the *steep* staircase (Table 4.3). Group 1 for the *steep* staircase contained predominantly individuals from group 3 for the *shallow* staircase (56.5%) (Table 4.3). Group 2 for the *steep* staircase contained predominantly individuals from group 1 for the *shallow* staircase (82.4%) (Table 4.3). Similar to group 1, group 3 contained predominantly individuals from group 3 for the *shallow* staircase (45.5%) (Table 4.3).

Table 4.3. Cross-tabulations of the groups identified on the shallow staircase with the groups identified on the steep staircase during stair ascent. A Cramer's V is calculated to measure the degree of association between the groups.

Ascent	***Shallow* staircase**			
	Group 1	Group 2	Group 3	Total
***Steep* staircase**				
Group 1	7[a]	3	13	23
	30.4%[b]	13.0%	56.5%	100.0%
Group 2	28	4	2	34
	82.4%	11.8%	5.9%	100.0%
Group 3	3	3	5	11
	27.3%	27.3%	45.5%	100.0%
Total	38	10	20	68
	55.9%	14.7%	29.4%	100.0%
	Cramer's V = 0.412, p = <0.001			

[a] = frequency, [b] = row percentage

For stair descent, the Cramer's V (0.380, $p=0.003$) revealed a strong association of membership of the individuals grouped for the *shallow* staircase with those grouped for the *steep* staircase (Table 4.4). Group 1 for the *steep* staircase contained predominantly individuals from group 2 for the *shallow* staircase (63.2%) (Table 4.4). Group 2 for the *steep* staircase contained predominantly individuals from group 3 for the *shallow* staircase (52.9%) (Table 4.4). Group 3 for the *steep* staircase contained predominantly individuals from group 1 for the *shallow* staircase (45.8%) (Table 4.4). Similar to group 2, group 4 contained predominantly individuals from group 3 for the *shallow* staircase (62.5%) (Table 4.4).

Table 4.4. Cross-tabulations of the groups identified on the shallow staircase with the groups identified on the steep staircase during stair descent. A Cramer's V is calculated to measure the degree of association between the groups.

Descent		***Shallow* staircase**			
		Group 1	Group 2	Group 3	Total
***Steep* staircase**					
	Group 1	1[a]	12	6	19
		5.3%[b]	63.2%	31.6%	100.0%
	Group 2	2	6	9	17
		11.8%	35.3%	52.9%	100.0%
	Group 3	11	9	4	24
		45.8%	37.5%	16.7%	100.0%
	Group 4	0	3	5	8
		0.0%	37.5%	62.5%	100.0%
	Total	14	30	24	68
		20.6%	44.1%	35.3%	100.0%
		Cramer's V = 0.380, p = 0.003			

[a] = frequency, [b] = row percentage

4.5 Discussion

In the present study, we used a multivariate approach to characterise the stair negotiation behaviour of older adults on two staircases with steps of different dimensions. For stair ascent, three groups were identified for both staircases. For stair descent, three groups were identified on the *shallow* staircase and four groups on the *steep* staircase. The groups differed from the overall mean by 1) showing only risky strategies, 2) only conservative strategies, or 3) a combination of risky and conservative strategies. Only a small number of older adults (11/68 for stair ascent; 8/68 for stair descent) altered their stair negotiation behaviour when exposed to the more challenging *steep* staircase. The majority of the older adults (57/68 for stair ascent; 60/68 for stair descent) maintained their individual stair negotiation behaviour irrespective of step dimensions.

A strong association of membership between groups on the *shallow* staircase and *steep* staircase was found for stair ascent (Cramer's V: 0.412, $p<0.001$) and descent (Cramer's V: 0.380, $p=0.003$). This indicates that the staircase with more challenging step dimensions had no effect on the grouping of individuals tested, i.e. individuals that were grouped together on the *shallow* staircase were also grouped together on the *steep* staircase.

For stair ascent, group 1 for the *steep* staircase consisted of 56.5% of the individuals of group 3 for the *shallow* staircase. Similar to group 3 for the *shallow* staircase, group 1 for the *steep* staircase displayed less PFLCS and higher cadence, which are risky strategies that could increase the risk for a slip or trip (M. S. Roys, 2001) (Figure 4.2). Additionally, group 1 for the *steep* staircase displayed higher RCOF and did not display a reduced foot clearance. Although, the increase in RCOF indicates an additional risky strategy (Hamel, Okita, Bus, et al., 2005), the individuals could have compensated for this by increasing their foot clearance (M. S. Roys, 2001; Templer, 1995). Group 2 for the *steep* staircase consisted of 82.4% of the individuals of group 1 for the *shallow* staircase. Similar to group 1 for the *shallow* staircase, group 2 for the *steep* staircase displayed higher PFLCS, which is a more conservative strategy (M. S. Roys, 2001) (Figure 4.2). Additionally, group 2 for the *steep* staircase displayed a reduced cadence. Although the difference in the GP of cadence between the two staircases is small (*shallow* GP=-0.44; *steep* GP=-0.59), this could indicate that individuals used a slightly more conservative strategy when the demand increased. Group 3 for the *steep* staircase consisted of 11 individuals who were spread over the three groups for the *shallow* staircase (group 1: 27.3%; group 2: 27.3 %; group 3: 45.5%). These individuals displayed no conservative strategies. Instead, they displayed only risky behaviours for five out of the eight parameters, such as less PFLCS and more variance in foot clearance, PFLCS, RCOF and cadence, increasing trip and slip risk (Hamel, Okita, Bus, et al., 2005;

Hausdorff et al., 2001; M. S. Roys, 2001) (Figure 4.2). This indicates that the increased demand resulted in a change to a more risky stepping behaviour. The findings in stair ascent indicate that the individuals of group 1 and group 2 maintained their stepping behaviour and the individuals of group 3 changed their stepping behaviour when the task demand increased.

For stair descent, group 1 for the *steep* staircase consisted of 63.2% of the individuals of group 2 for the *shallow* staircase. In contrast to group 2 for the *shallow* staircase, group 1 for the *steep* staircase did not display less RCOF, which is a conservative strategy (Christina & Cavanagh, 2002), but displayed less foot clearance and less variance in RCOF. The reduced foot clearance could increase trip risk and the reduced variance could indicate a more conservative strategy (Hamel, Okita, Higginson, et al., 2005; Hausdorff et al., 2001) (Figure 4.3). The more challenging step dimensions resulted in small changes in the stepping strategies (indicated by the GP that ranged from 0.51-0.77) to a slightly more risky strategy. Group 2 for the *steep* staircase consisted of 52.9% of individuals of group 3 for the *shallow* staircase. Similar to group 3 for the *shallow* staircase, group 2 for the *steep* staircase displayed higher mean and variance values in CoM angular acceleration, increasing the risk for a loss of CoM control (Buckley et al., 2013; Mian, Narici, et al., 2007) (Figure 4.3). However, the individuals of group 2 for the *steep* staircase did not display higher cadence, which could indicate that the individuals used a slightly more conservative behaviour when the demand increased. Group 3 for the *steep* staircase consisted of 45.8% of the individuals of group 1 for the *shallow* staircase. Similar to group 1 for the *shallow* staircase, group 3 for *steep* staircase displayed higher foot clearance, reduced cadence and lower mean and variance values for CoM angular acceleration, which are conservative strategies that could reduce trip or slip risk (Buckley et al., 2013; Hamel, Okita, Higginson, et al., 2005; Mian, Narici, et al., 2007) (Figure 4.3). In contrast, group 3 for the *steep* staircase did not display higher average and variance values of RCOF, which could indicate that individuals used a slightly more conservative strategy when the demand increased by decreasing the risk for a slip (Christina & Cavanagh, 2002). Group 4 for the *steep* staircase consisted of 8 individuals, with the majority of these individuals originating from group 3 for the *shallow* staircase (5/8). Group 4 for the *steep* staircase showed a more risky stepping behaviour compared to group 3 for the *shallow* staircase, by showing less PFLCS, a higher cadence and more variance in foot clearance, PFLCS and cadence, which could increase the risk for a trip or slip (Hausdorff et al., 2001; M. S. Roys, 2001) (Figure 4.3). Only one of these risky behaviours was similar to the behaviours adopted by group 3 for the *shallow* staircase, namely a higher cadence. This could indicate that the individuals of group 4 for the *steep* staircase altered their stepping behaviour to a more risky behaviour when the demand increased (Figure 4.3). The findings in stair descent indicate that the individuals of group 1-3 maintained their stepping behaviour and the individuals of group 4 changed their stepping behaviour when the task demand increased.

4.6 Conclusions

In conclusion, older adults adopted a range of stair negotiation behaviours, including the display of solely biomechanically risky strategies, solely biomechanically conservative strategies or a mix of biomechanically risky and conservative strategies. The comparison between staircases revealed that the majority of older adults maintained their overall biomechanical stepping profile, with only slight changes in terms of risk and safety characteristics when exposed to a more challenging staircase. This indicates that most of the older adults tested were identifiable based on their stepping behaviour irrespective of the step dimensions implemented. Importantly, the present findings also indicate that the underlying mechanism of a stair fall may remain the same irrespective of stair dimensions. In terms of safety, this could imply that when the stepping behaviour of an individual at risk for a stair fall is improved through targeted interventions, this individual would be safer on multiple step dimension configurations. At present, it is not possible to establish which of the behaviours for stair ascent and descent is truly safer or riskier, as it is imperative to link each group with a relevant metric of stair falls sustained over a follow-up period.

CHAPTER 5:

Prediction of stair falls in older people using a biomechanical profiling approach: A 12-month longitudinal study.

5.1 Abstract

Stair falls are a major health problem for older people, but at present there are no specific screening tools for stair fall prediction. Various general fall risk screening tests based on clinical and functional scores are available, but it remains unknown if such measurements can identify older individuals at risk for a stair fall specifically. In Chapter 3, we developed a stair-specific biomechanical approach which profiles individual stepping strategies, but its validity for predicting stair fall risk has not been tested as yet. The purpose of the present study was 1) to investigate whether stair fallers could be differentiated from non-fallers by mutual biomechanical risk factors or functional parameters and 2) to establish the biomechanical stepping profile at the greatest risk for a stair fall and identify the underlying functional parameters. Eighty-seven older adults (age: 72.1±5.2 y) ascended and descended a custom-built instrumented seven-step staircase and performed a range of clinical and functional tasks. K-means clustering was used to profile the overall stair negotiation behaviour of older adults for stair ascent and descent with six biomechanical outcome measures indicative of fall risk as input. Group profiles were calculated to examine differences between behaviours. Falls and events of balance perturbation (combined referred to as “hazardous events”) were monitored during a 12-month follow-up. A logistic regression analysis was executed to determine the underlying clinical and functional capabilities of each group. Cox regression analysis was executed to examine if the clinical and functional tests or biomechanical outcome measures could predict hazardous events. Kaplan-Meier survival curves and log-rank tests were obtained to identify the stepping strategy at greatest risk for a hazardous event. Clinical and functional tests did not predict hazardous events on stairs and the commonly used Fall Risk Assessment Tool (FRAT) classified only 1 out of 17 stair fallers as being at risk for a fall. Single biomechanical risk factors could also not predict hazardous events in both ascent and descent. Two particular stepping profiles identified by the

biomechanical profiling approach in stair ascent were linked with prospective falls. One stepping profile included solely conservative strategies (reduced risk for a slip and slow cadence), which were linked with visual acuity and hip flexion strength deficits and polypharmacy, and the other profile included solely risky strategies (increased risk for a slip and fast cadence), which were linked with a reduced medication intake. These findings highlight the potential of the stepping profiling method to predict stair fall risk in older adults against the limited predictability of functional and single parameter approaches currently used as screening tools. Future research should implement the stepping profiling method in more people in real life stair negotiation conditions, avoiding the constraints necessary to conduct biomechanical research in the lab.

5.2 Introduction

Identifying the individuals at risk for a fall is necessary in order to deliver effective fall prevention programs. At community level, there are currently many fall risk screening tools available. A systematic review of Gates et al. (2008) identified 29 different screening tests for predicting general fall risk among independently living older adults world-wide (Gates et al., 2008). In the UK, the Fall Risk Assessment Tool (FRAT) is most commonly used (NHS-UK, 2018). This screening tool is based on the identification of five risk factors: 1) general falls within the previous year, 2) more than four medications, 3) a diagnosis of stroke or Parkinson's disease, 4) self-reported balance problems, 5) inability to rise from a chair. Positive identification of any three of the five risk factors defines this person as at risk for a future fall and in need of referral to the falls service. Although the existing fall risk screening tests, including the FRAT, are not stair specific, they encompass parameters that are considered to be important for safe stair negotiation, such as balance, muscle strength and confidence levels (Jacobs, 2016; Startzell et al., 2000). 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 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 the risk for a fall by relying more on the handrails and/or negotiating the stairs in a step-by-step manner, as both these strategies allow a more effective balance control (King et al., 2018; Reeves et al., 2008b). However, generic fall screening methods do not encompass this individual adjustability in stepping technique and, thus, it is questionable whether they can identify older people at risk for stair falls specifically.

Fall risk detection using stair-specific biomechanical testing requires access to a gait lab and typically quantifies mean differences between subject groups for single biomechanical parameters indicative of risk for example, a reduced foot clearance with respect to the stair edge, which increases the chances of a trip (Hamel, Okita, Higginson, et al., 2005). 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. In Chapter 3, we established a novel multivariate approach that circumvents the limitations of the commonly used grouping approaches by profiling individual stepping strategies based on multiple parameters reflecting both risk and safety on stairs. It was found that older adults display various overall stair negotiation behaviours that consist of both risky and conservative strategies. However, the overall biomechanical stepping profile that is at a greater risk for a stair fall has not been established yet. In addition, it should be noted that access to specialised lab facilities and instrumented staircases, which is a requirement for identifying the stair-specific biomechanical features of each stepping profile, is a practical issue that would preclude the implementation of the profiling method as a fall predictive tool at community level. Therefore, easily quantifiable clinical and functional parameters that underpin the overall stepping profile of an individual should be identified and used in screening tools for stair fall risk detection in large-scale populations. However, at present we do not know which clinical and functional parameters are linked with a given stepping biomechanical profile.

To fill these important knowledge gaps towards the development of stair fall risk assessment tools at community level, we adopted a prospective study design to: 1) investigate whether participants who would go to experience stair falls over a 12-month follow up period could be differentiated by a mutual biomechanical risk factor or clinical and functional parameter, 2) establish the overall stepping profile linked with the greatest number of falls sustained and identify easily measurable clinical and functional parameters underpinning this stepping profile.

5.3 Methods

5.3.1 Participants

Eighty-seven older adults (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 used any other aid apart from the handrail to negotiate stairs were excluded. Written informed consent was obtained from all participants 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.

5.3.2 Staircase measurements

The measurements were taken on a custom-built instrumented seven-step staircase. This measurement set-up has been described in detail in Chapter 3. Briefly, kinematics were obtained using a 24 infrared camera system (120Hz, Vicon, Oxford Metrics, UK) and kinetics were obtained through four force platforms (1080Hz, 9260AA, Kistler AG, CH) embedded in the lower four steps (steps 1-4). The staircase configuration was set in agreement with the building regulations in the UK and represented a typical private staircase (British-Standards-Institute, 1984; Department-of-the-Environment-and-The-Welsh-Office, 1992), with the rise set at 20 cm and the run at 25 cm, resulting in a pitch of 38.7°. The steps of the staircase as well as the top landing and walkway were independent structures and handrails on both sides of the staircase were in place during all tests.

Trials were performed with participants clothed in tight fitting Lycra shorts and shirt and wearing their own comfortable shoes (no boots, heels or sandals). All participants were fitted in a five-point safety harness, which was attached to the overhead belay safety system. A trained member of the research team was attached to a rope on the floor and operated the rope of the belay system whilst making sure that there was no tension in the rope during the measurements. To allow familiarisation with the experimental setup and safety harness, participants performed up to five practice trials. After familiarisation, participants ascended and descended the staircase five times at their self-selected pace and manner (handrail use was allowed). The participants who used the handrails 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. In all trials, participants executed at least one step approaching the top of the stairs before stepping down and at least one step at the lower level away from the stairs.

5.3.3 Data analysis staircase measurements

The 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 14 mm; Appendix A). The segmental data were based on Dempster's regression equations (Dempster, 1955) and used geometrical volumes to represent each segment (Hanavan, 1964). 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 all kinetic and kinematic data were filtered using a low-pass fourth order Butterworth filter with a cut-off frequency of 6 Hz. The gait events were determined using force plate data.

The methods used to obtain the biomechanical outcome measures of the present study have been presented in detail in Chapter 3, therefore a brief description of the relevant outcome measures will be presented here. The outcome measures included: *1) Foot clearance.* This parameter reflects trip-induced fall risk, where a smaller foot clearance is associated with a greater fall risk. The foot clearance was calculated by projecting a virtual outline of the participant's shoe in the movement trials (see Chapter 3). The foot clearance was obtained for both ascent and descent during the swing phase over steps 1-5 when the virtual shoe outline of the leading limb passed the step edge. *2) Proportion of foot length in contact with stair (PFLCS).* This parameter reflects slip-induced fall risk due to foot positioning relative to the step edge, where a reduced length is associated with a greater fall risk. PFLCS was calculated using the virtual shoe outline introduced above 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 virtual shoe outline to the step edge. The PFLCS was calculated as a percentage using the following equation: PFLCS = (distance x / (distance x + distance y))*100%. *3) Required coefficient of friction (RCOF).* This parameter also reflects propensity for a slip between the shoe-surface interaction and a higher RCOF is associated with a greater fall risk. It 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 (Christina &

Cavanagh, 2002). 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.* Negotiating stairs fast may result in a fall as an increased speed could negatively modify the parameters above. 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).* This parameter reflects the ability to control the CoM against gravity as it descends and a higher acceleration is associated with a greater fall risk. 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 variances of these parameters* were calculated as the mean of the variance across the three trials for each of the analysed steps separately. Variance in itself is a risk factor for falls, as more variance can indicate a person's inability to maintain a steady/safe movement pattern (Hausdorff et al., 2001).

5.3.4 Clinical and functional tests

A range of clinical and functional tests were executed following the measurements on the staircase. Inclusion criteria for the proposed tests were their clinical relevance regarding fall risk based on current literature (Chapter 1) and feasibility at a community level. To account for the possible effect of fatigue caused by the staircase measurements, all participants were given a break (approximately 15 minutes) in which they received refreshments and the tests were started with the questionnaires that allowed the participants to be sat down and rest for another 30 minutes. None of the participants reported that fatigue had an influence on their performance on the clinical and functional tests.

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 (Powell & Myers, 1995), the Falls Efficacy Scale-International (FES-I), to assess concern about falling while completing activities of daily living (Yardley et al., 2005), the Montreal Cognitive Assessment (MoCA) to assess the cognitive functioning (Nasreddine et al., 2005) and the Nottingham extended Activities of Daily Living (NADL) index to assess the functional status (Nouri & Lincoln, 1987). The FRAT was executed to determine fall risk (NHS-UK, 2018).

Measures of vision were visual acuity and contrast sensitivity and these were obtained using the Freiburg Vision Test (FRACT) (Bach, 1996).

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 (K. O. Berg, Wood-Dauphinee, Williams, & Maki, 1992), and the Functional reach test, which provides information related to anticipatory balance control without a change in base of support while reaching forward (Duncan, Studenski, Chandler, & Prescott, 1992). 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 (Norkin & White, 2016).

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) (Andrews, Thomas, & Bohannon, 1996). The maximal torque was calculated and normalized for body mass (N·m/kg).

Functional fitness outcome measures were obtained by performing the six tests of the Fullerton Functional Fitness Test that were all included as a single outcome measures (Rikli & Jones, 1999): 1) Chair stand, to measure functional lower body strength; 2) Arm curl, to measure functional upper body strength; 3) 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 (Rikli & Jones, 1999).

5.3.5 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 performed using a fall calendar (Appendix B) by the principal researcher to register the occurrence, circumstances and self-perceived causes of falls and balance perturbations during both ascent and descent within this period. 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 and life events were recorded.

5.3.6 Statistical analysis

To examine differences in biomechanical stepping strategies between individuals, the multivariate method established in Chapter 3 was applied to the older adults who did not use handrails during the stair test. The older adults who were dependent on the handrails were excluded and grouped 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 k (i.e. number of clusters/groups) was determined through the SeCo framework that used a measure of separation and concordance, this method has previously been described in detail (Casana-Eslava et al., 2017; Chambers et al., 2013; Lisboa et al., 2013). To examine differences in the composition of each group, the group profiles (GP = ($Mean_{group}$ – $Mean_{overall}$) / $SD_{overall}$) were calculated for all outcome measures with a threshold set at 0.5. Furthermore, to determine the underlying clinical and functional capabilities of each group, including the handrail dependent group that was included as a separate group from this stage onwards, we carried out a logistic regression analysis using a forward stepwise procedure for each group separately with the clinical and functional tests as input. Presence in the specific group was used as the dependent variable for each group separately (0 = present within one of the other groups, 1 = present in the analysed group). The predictive power of each logistic model was evaluated by the area under the receiver operator characteristic curve (AUC) (Hanley & McNeil, 1982).

Stair falls and events of balance perturbation were combined for the fall prediction analysis and referred to as "hazardous events". Kaplan-Meier survival curves and log-rank tests were performed to identify the at risk biomechanical stepping strategy. The time to, and occurrence of, the first hazardous event within 12 months of follow-up were used as factors. Furthermore, a forward stepwise cox regression analysis was executed to examine if the clinical and functional tests could predict fall on stairs. In addition, a cox regression analysis was executed 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. The statistical methods used in the present study are explained in detail in Chapter 2. Statistical analyses were performed using SPSS (version 24, SPSS Inc., California, USA) and Matlab (R2018a, The Mathworks, Natick, USA). The significance level was set at $\alpha = 0.05$.

5.4. Results

5.4.1 Participants

The baseline procedure was completed by 87 older adults and the follow up by 82 older adults. Reported reasons for dropping out during the 12-month follow up 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.

5.4.2 Hazardous events

During the 12-month follow-up period, 17 out of the 87 older adults reported at least one fall (19.5%). Additionally, 12 older adults had an event of balance perturbation on the stairs (13.8%). For stair ascent, 13 older adults (14.9%) reported at least one fall and 8 other older adults (9.2%) had an event of balance perturbation. These combined were predominantly caused by a trip (90.4%) and approximately a fifth resulted in minor injuries, such as cuts and bruises (Table 5.1; Appendix C). 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. 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%) (Table 5.1). Four hazardous events resulted in injuries (50.0%), with one stair fall resulting in two fractures in the foot, requiring hospital admission (Table 5.1).

Table 5.1. Summary including the number, circumstances and self-perceived causes of the hazardous events sustained by the older adults during the 12 month follow-up period.

	Stair ascent	Stair descent	Overall
Number of fallers	13	4	17
Balance perturbations	8	4	12
Cause			
- Trip	19	3	22
- Loss of CoM control	1	2	3
- Missed step	1	2	3
- Slip	0	1	1
Location			
- Home	13	4	17
- Public building	8	4	12
- Outside	5	3	8
- Inside	16	5	21
Injuries			
- Yes (hospital admission)	4 (0)	4 (1)	8 (1)
- No	17	4	21

5.4.3 Stair ascent stepping strategies

The stability and separation of the specified values of k, displayed in the SeCo map (Figure 5.3A), revealed that k=3 was the optimal number of groups for stair ascent (group 1: 37; group 2: 24; group 3: 11 older adults). The GP revealed that group 1 differed from the overall mean by displaying higher PFLCS (GP = 0.66) and a lower cadence (GP = -0.60) (Table 5.2). Group 2 differed from the overall mean by displaying less PFLCS (GP = -0.71), higher RCOF (GP = 0.57) and higher cadence (GP = 0.78) (Table 5.2). Group 3 differed from the overall mean by displaying more variance in foot clearance (GP = 1.44), less PFLCS (GP = -0.67), more variance in PFLCS (GP = 0.66), more variance in RCOF (GP = 1.10) and more variance in cadence (GP = 1.72) (Table 5.2). Group 4 included the handrail dependent participants (N = 15). The participants in group 4 differed from the other groups in their overall stepping strategy by depending fully on the handrails when ascending the stairs.

Table 5.2. Group profiles (GP) of the biomechanical outcome measures assessed for the three groups for stair ascent. 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	RCOF	Var. RCOF	Cadence	Var. Cadence
Group 1	0.06	-0.21	**0.66**	-0.29	-0.38	-0.11	**-0.60**	-0.30
Group 2	-0.06	-0.34	**-0.71**	0.15	**0.57**	-0.33	**0.78**	-0.32
Group 3	-0.08	**1.44**	**-0.67**	**0.66**	0.04	**1.10**	0.31	**1.72**

Notes: *Var*: variance; *PFLCS*: proportion of foot contact length in contact with stairs; *RCOF:* required coefficient of friction.

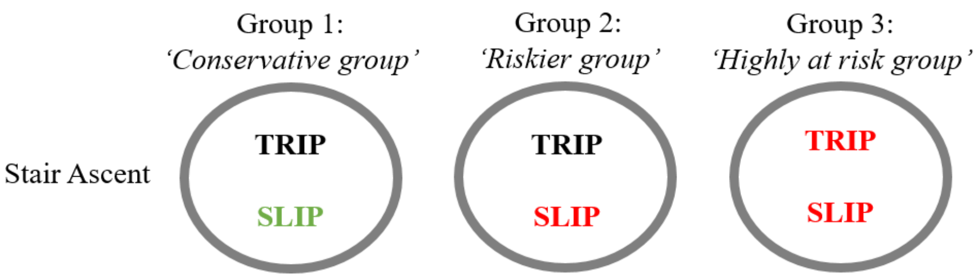

Figure 5.1. A simplified overview of the group profiles obtained for stair ascent, with the underlying mechanisms of a potential fall coloured in terms of the risks identified (red = riskier strategy; green = more conservative strategy; black = not particularly risky or conservative strategy).

The logistic model of group 1 during stair ascent (χ^2 = 34.01; p < 0.001) revealed that the presence of an older adult in this group could be predicted by visual acuity (OR = 0.128, 95% CI = 0.016–0.991, p = 0.049), hip flexion strength (OR = 0.002, 95% CI = 0.000–0.107, p = 0.002), passive knee flexion RoM (OR = 1.116, 95% CI = 1.021–1.219, p =

0.015), BBS (OR = 2.387, 95% CI = 1.466–3.886, $p < 0.001$) and number of medications (OR = 1.515, 95% CI = 1.087–2.110, $p = 0.014$; Table 5.3). This resulted in a high prediction accuracy showed by the area under the ROC curve (AUC) of close to 1.0 (AUC = 0.822, $p < 0.001$). The logistic model of group 2 ($\chi^2 = 14.86$; $p < 0.001$) revealed that membership of this group could be predicted using the number of medications (OR = 0.551; 95% CI = 0.379–0.803; $p = 0.002$), resulting in a high prediction accuracy (AUC = 0.748, $p < 0.001$; Table 5.3). The logistic model for group 3 ($\chi^2 = 18.51$; $p < 0.001$) revealed that membership of this group could be predicted using hip flexion strength (OR = 239.874; 95% CI = 4.503–12777.112; $p = 0.007$), the functional reach test (OR = 1.145; 95% CI = 1.008–1.302; $p = 0.037$) and the back scratch test (OR = 0.920; 95% CI = 0.852–0.992; $p = 0.031$), resulting in a high prediction accuracy (AUC = 0.853, $p < 0.001$; Table 5.3). The logistic model for group 4, ($\chi^2 = 71.71$; $p < 0.001$) revealed that membership of this group could be predicted with 100% accuracy (Nagelkerke $R^2 = 1.0$) by passive knee flexion RoM, active hip flexion RoM and the BBS, resulting in a very high prediction accuracy (AUC = 0.990, $p < 0.001$; Table 5.3).

Table 5.3. The significant ($p < 0.05$) clinical and functional outcome measures that were included in the logistic model of each group and could predict the presence of an individual in the specific group for stair ascent and descent. The parameters were coloured to indicate if the direction in which the group differed from the other groups was positive or negative in terms of safety (red = differed in negative direction; green = differed in positive direction).

	Parameter 1	Parameter 2	Parameter 3	Parameter 4	Parameter 5
Ascent					
Group 1	Visual Acuity	Hip flex. strength	Pas. knee flex. ROM	BBS	Medication intake
Group 2	Medication intake	-	-	-	-
Group 3	Hip flex. strength	Functional reach	Back scratch	-	-
Group 4 (HR)	Pas. Knee flex. ROM	Act. Hip flex. ROM	BBS	-	-
Descent					
Group 1	Hip flex. Strength	-	-	-	-
Group 2	Visual Acuity	2-min step test	-	-	-
Group 3	Act. dorsi flex. ROM	Back scratch	ABC questionnaire	-	-
Group 4	-	-	-	-	-
Group 5 (HR)	Pas. Knee flex. ROM	Act. Hip flex. ROM	BBS	-	-

Notes: *flex.:* flexion; *pas.:* passive; *ROM:* range of motion; *BBS:* Berg balance score; *act.:* active; *ABC:* activities-specific balance; *HR:* handrail dependent.

5.4.4 Stair descent stepping strategies

For stair descent, the SeCo map (Figure 5.3B) revealed that k=4 was the optimal number of groups (group 1: 8; group 2: 21; group 3: 17; group 4: 26 older adults). The GP revealed that group 1 differed from the overall mean by displaying more variance in foot clearance (GP = 0.52), less PFLCS (GP = -0.62), more variance in PFLCS (GP = 1.95), less RCOF (GP = -0.91), higher cadence (GP = 1.03) and more variance in cadence (GP = 1.66) (Table 5.4). Group 2 differed from the overall by displaying less foot clearance (GP = -0.73) (Table 5.4). Group 3 differed from the overall mean by displaying a higher CoM angular acceleration (GP = 1.25) and more variance in CoM angular acceleration (GP = 1.41) (Table 5.4). Group 4 differed from the overall mean by displaying a higher foot clearance (GP = 0.78), lower CoM angular acceleration (GP = -0.54), less variance in CoM angular acceleration (GP = -0.54) and lower cadence (GP = -0.79) (Table 5.4).

Group 5 included the handrail dependent participants (N = 15). The participants in group 5 differed from the other groups in their overall stepping strategy by depending fully on the handrails when descending the stairs.

Table 5.4. Group profiles (GP) of the biomechanical outcome measures assessed for the four groups 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
Group 1	-0.44	**0.52**	**-0.62**	**1.95**	0.13	-0.44	**-0.91**	-0.28	**1.03**	**1.66**
Group 2	**-0.73**	-0.47	-0.10	-0.18	-0.39	-0.30	-0.08	-0.40	0.40	-0.22
Group 3	-0.09	-0.25	0.02	-0.30	**1.25**	**1.41**	0.00	-0.05	0.23	0.07
Group 4	**0.78**	0.38	0.26	-0.25	**-0.54**	**-0.54**	0.35	0.44	**-0.79**	-0.38

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

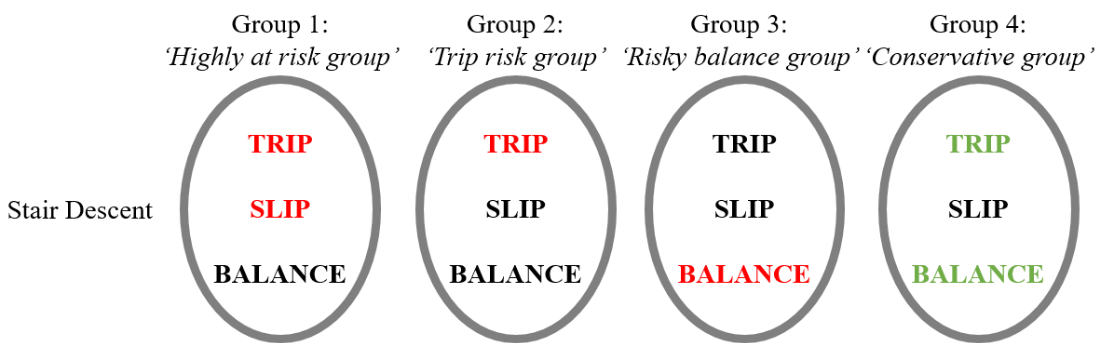

Figure 5.2. A simplified overview of the group profiles obtained for stair descent, with the underlying mechanisms of a potential fall coloured in terms of the risks identified (red = riskier strategy; green = more conservative strategy; black = not particularly risky or conservative strategy).

The logistic model for group 1 ($\chi^2 = 10.50$; $p = 0.001$) revealed that the presence of an older adult in this group could be predicted by hip flexion strength (OR = 330.320, 95% CI = 6.896–15822.421, $p = 0.003$), resulting in a high prediction accuracy (AUC = 0.854, $p = 0.001$; Table 5.3). The logistic regression executed for group 2 ($\chi^2 = 17.56$; $p < 0.001$)

revealed that membership of this group could be predicted by visual acuity (OR = 6.648; 95% CI = 0.976–45.298; p = 0.053) and the 2 min step test (OR = 1.026; 95% CI = 1.010–1.042; p = 0.002), resulting in a high prediction accuracy (AUC = 0.801, p < 0.001; 5able 4.3). The logistic model for group 3 (χ^2 = 20.06; p < 0.001) revealed that membership of this group could be predicted by active dorsi-flexion RoM (OR = 1.202; 95% CI = 1.034–1.397; p = 0.017), the back scratch test (OR = 0.935; 95% CI = 0.881–0.992; p = 0.026) and the ABC scale (OR = 1.275; 95% CI = 0.998–1.630; p = 0.052), resulting in a high prediction accuracy (AUC = 0.830, p < 0.001; Table 5.3). None of the clinical and functional outcome measures could predict the presence of an older adult in group 4. Similar to the handrail-dependent group of stair ascent, the logistic model for group 5 (χ^2 = 71.71; p < 0.001) revealed that membership of this group could be predicted with 100% accuracy (Nagelkerke R^2 = 1.0) by passive knee flexion RoM, active hip flexion RoM and the BBS, resulting in a very high prediction accuracy (AUC = 0.990, p < 0.001; Table 5.3).

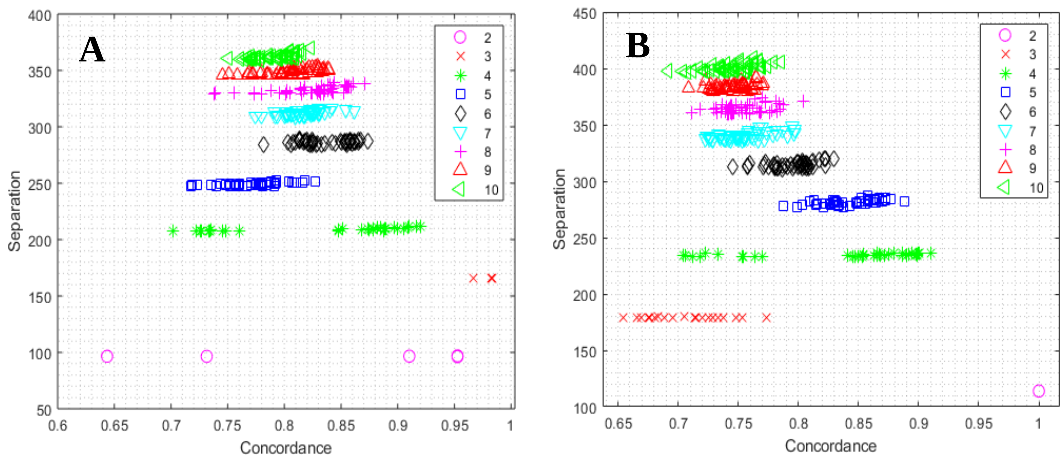

Figure 5.3. Separation-Concordance map for the biomechanical outcome measures for stair ascent (A) and descent (B), highlighting the top 10% (of 500 initialisations of the k-means algorithm) with the ΔSSQ displayed on the y-axis and the internal median Cramérs' V on the x-axis for each value of k (2-10).

5.4.5 Prediction of hazardous events

Overall, there was a constant risk for a hazardous event during stair ascent and descent, as indicated by the Kaplan-Meier survival curves (Figure 5.4 A, B). For stair ascent, hazardous events could not be predicted by any of the clinical or functional tests as no significant stepwise Cox-regression model could be obtained, i.e. none of the clinical or functional tasks significantly improved the prediction. Similar to stair ascent, none of the clinical or functional tasks could predict hazardous events in stair descent, as the obtained stepwise Cox-regression model ($\chi 2 = 22.922$; $p = 0.003$) included eight non-significant functional 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 (1-6) could also not predict hazardous events, as the obtained cox-regression models with the biomechanical parameters as inputs were non-significant for stair ascent ($\chi^2 = 7.925$; $p = 0.441$) and descent ($\chi^2 = 10.070$; $p = 0.434$).

Table 5.5. The number, circumstances and self-perceived causes of the hazardous events for the four groups during stair ascent, with group 4 representing the handrail dependent group (HR dep.).

	Group 1	**Group 2**	**Group 3**	**Group 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

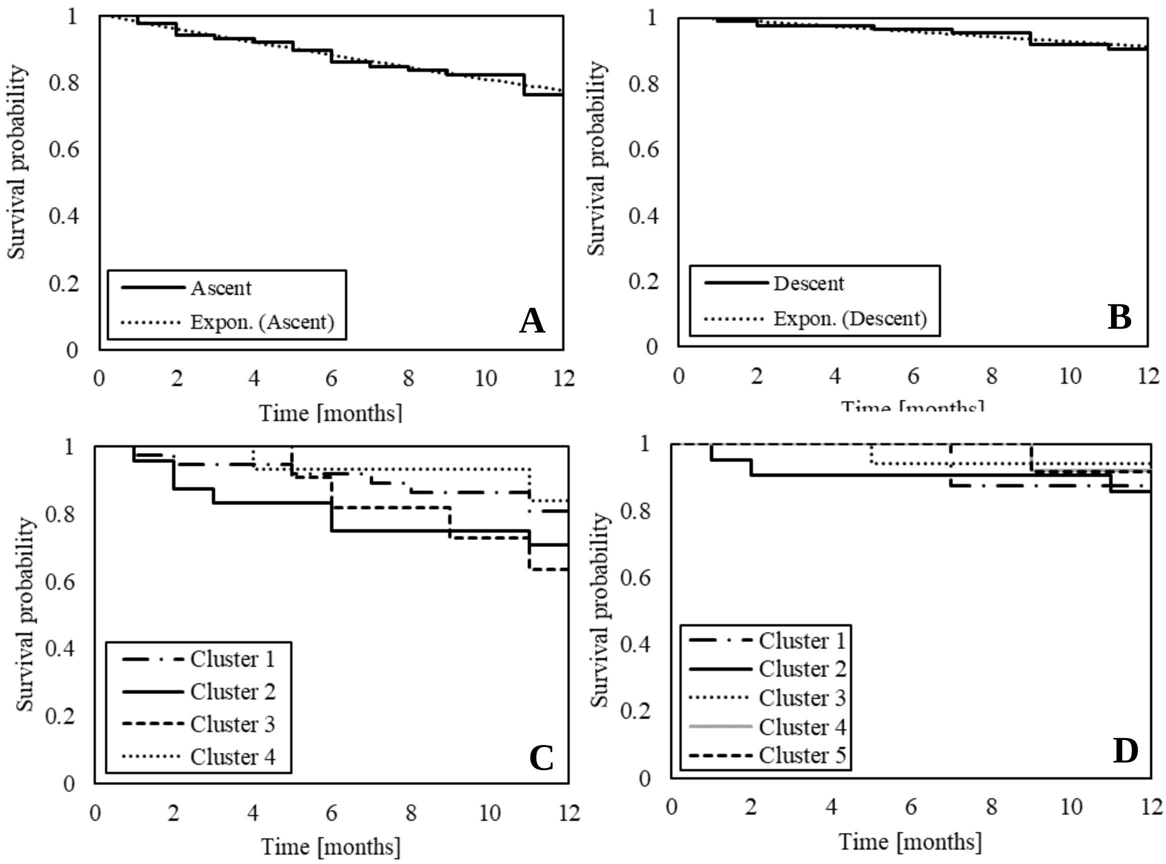

Figure 5.4. Kaplan–Meier survival curves for sustaining a hazardous event during the 12-month follow-up for stair ascent (A), stair descent (B), the groups identified for stair ascent (C) and the groups identified for stair descent (D).

For both stair ascent and descent, hazardous events were spread over the groups based on biomechanical parameters identified by the multivariate approach (Table 5.5, 5.6). The stepping strategy (i.e. group) 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: $\chi^2 = 2.324$; $p = 0.508$) or descent (log rank test: $\chi^2 = 1.100$; $p = 0.894$) (Figure 5.4 C, D). However, it is evident that groups 1 and 2 during stair ascent (Figure 5.4C) display an exponential distribution, indicating that the hazard, which is the probability of a hazardous event (Bewick, Cheek, & Ball, 2004), does not change with time ($h(t) = \lambda$). This is confirmed by plotting the hazard rate over time for these groups (Figure 5.5A), which indicates that the hazardous events are directly related to the stair-negating strategy of these groups (Hess & Levin, 2014). For stair descent, group 2 appeared to display an exponential distribution, indicating a constant hazard (Figure 5.4D). However, the hazard rate of this group was low compared to the hazard rate of group 1 and group 2 in stair ascent (Figure 5.5A) and did not differ from group 4 and group 5 in descent, which also showed a tendency for an exponential distribution (Figure 5.5B). Therefore, it is not possible to relate the hazardous events directly related to stair-negating strategy of group 2 (Hess & Levin, 2014).

Table 5.6. The number, circumstances and self-perceived causes of the hazardous events for the five groups during stair descent, with group 5 representing the handrail dependent group (HR dep.).

	Group 1	**Group 2**	**Group 3**	**Group 4**	**Group 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 control	0	0	0	1	1	2
- Missed step	0	2	0	0	0	2
- Slip	0	1	0	0	0	1
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

5.5 Discussion

In the present study, we adopted a 12-month prospective design to study stair fall risk in older people. Specifically, we sought to establish 1) the predictability of stair fall risk from practical clinical and functional outcome measures and 2) the overall stepping profile, which accounts for various risky and conservative biomechanical strategies, at risk for a hazardous event on stairs. Hazardous events in ascent or descent could not be predicted using the clinical and functional outcome measures, or any of the existing screening tools that are currently used to characterise overall fall risk at community level.

In contrast, the multivariate method revealed that two out of the four overall stepping strategies identified during stair ascent 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 clinical and functional parameters that can be used in community-level screening tools for stair fall risk detection could be identified for most stepping strategies for both stair ascent and descent.

5.5.1 Biomechanical stepping strategies and the underlying clinical and functional capabilities

The multivariate biomechanical approach identified three groups for stair ascent. Group 1 displayed a higher PFLCS and a lower cadence, which are both conservative strategies. The higher PFLCS reduces the risk for a slip and the lower cadence reduces the risk for both a slip and trip (M. S. Roys, 2001). Therefore, this group will be referred as the 'conservative group' (Figure 5.1). This overall 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 (Table 5.3). The reduced visual acuity, strength and polypharmacy could possibly outweigh the improved balance and knee RoM and, therefore, explain why individuals in group 1 adopted a more conservative stepping strategy. Group 2 adopted a more risky strategy by displaying a lower PFLCS, a higher RCOF and higher cadence. The lower PFLCS and higher RCOF increase the risk for a slip and the higher cadence increases the risk for both a slip and a trip (Hamel, Okita, Bus, et al., 2005; M. S. Roys, 2001). Therefore, this group will be referred as the 'riskier group' (Figure 5.1). This overall more risky strategy is linked to a reduced medication intake (Table 5.3), which indicates a better overall fitness that could potentially offset some of the risky strategies adopted by the individuals of group 2 (Campbell, Borrie, &

Spears, 1989). Group 3 displayed a lower PFLCS and more variance in foot clearance, PFLCS, RCOF and cadence, which all increase the risk for a stair fall. The lower PFLCS increases the risk for a slip and more variance can indicate a person's inability to maintain a steady/safe movement pattern (Hausdorff et al., 2001). Therefore, this group will be referred as the 'highly at risk group' (Figure 5.1). This overall riskier strategy was linked to a higher hip flexion strength, increased functional reach and reduced back scratch performance (Table 5.3). The higher strength and improved balance could outweigh the reduced upper body flexibility and, therefore, allow the older adults to adopt a riskier overall stepping strategy. Group 4 was fully dependent on the handrails when ascending the stairs and therefore displayed an overall conservative stepping strategy. This strategy was linked to a reduced active RoM at the hip joint, a reduced passive RoM at the knee joint and poorer performance on the BBS (Table 5.3). This suggests that for group 4, the handrails were necessary to improve stability and mitigate the negative effect of reduced RoM on stair ascending ability.

For stair descent, the multivariate biomechanical approach identified four groups. Group 1 displayed greater variance values for foot clearance, PFLCS and cadence. These indicate that the individual has a limited ability to maintain a steady movement pattern (Hausdorff et al., 2001) increasing the risk for a trip and slip. Furthermore, group 1 displayed less PFLCS, increasing the risk for a slip (M. S. Roys, 2001), and a greater mean cadence, increasing the risk for a trip, slip or loss of CoM control (Simoneau, Cavanagh, Ulbrecht, Leibowitz, & Tyrrell, 1991). However, these riskier strategies were accompanied by a smaller RCOF, which is a more conservative strategy that could mitigate the risk for a slip (Christina & Cavanagh, 2002). Therefore, this group will be referred as the 'highly at risk group' (Figure 5.2). This overall riskier strategy was linked to a greater hip flexion strength (Table 5.3), which could potentially offset some of the risky strategies adopted by the individuals in group 1. Group 2 was at an increased for a trip due to a smaller foot clearance (Hamel, Okita, Bus, et al., 2005). Therefore, this group will be referred as the ‘trip risk group’ (Figure 5.2). This more risky stepping strategy was linked to an improved visual acuity and more steps on the 2-minute stepping task (Table 5.3). The improved visual functioning and higher fitness levels could potentially offset the risky strategies adopted by the individuals in group 2. Group 3 displayed a greater peak and variance in CoM angular acceleration, which both increase the risk for a loss of CoM control when stepping down (Buckley et al., 2013; Mian, Narici, et al., 2007; Mian, Thom, et al., 2007; Templer, 1995). Therefore, this group will be referred as the ‘risky balance group’ (Figure 5.2). This riskier stepping strategy was linked to a greater active dorsal flexion RoM, higher values on the ABC scale and a reduced performance on the back scratch test (Table 5.3). The increased RoM and higher confidence levels could offset the increased risk for a stair fall. Group 4 displayed solely conservative strategies, such as a higher foot clearance, a lower cadence, and a lower peak and variance in CoM angular acceleration (Buckley et al., 2013; Hamel, Okita, Bus, et al., 2005; Mian, Narici, et al., 2007). Therefore, this group will be referred as the ‘conservative group’ (Figure 5.2).This more conservative stepping strategy could not be linked to any of the clinical and functional tests (Table 5.3), which could potentially explain why individuals in group 4 selected a more conservative overall stepping strategy. Group 5 displayed an overall conservative stepping strategy, as handrails were used throughout when descending stairs. 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.

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

5.5.2 Prediction of hazardous events

Seventeen older adults (19.5%) sustained at least one fall, not considering the balance perturbations, within the 12-month follow-up period (Table 5.1). Previous studies report that stair falls account for approximately 20% of all falls suffered by older adults every year (Jacobs, 2016; Svanström, 1974; Tinetti et al., 1988), with approximately 33% of older adults falling every year (Lord et al., 1993; Rapp et al., 2014). Based on these figures, we would expect only six stair fallers in our study, but we had almost three times as many (Table 5.1). Although, the literature reports more falls during stair descent (Svanström, 1974; Tiedemann et al., 2007), in the present study 76% of stair falls occurred during stair ascent. This could be explained by the fact that the studies in the literature assessed the number of falls through hospital statistics and since falls sustained during stair descent are more injurious (Table 5.1), it is expected that these result in a higher number of hospital admissions compared to falls sustained during stair ascent.

For both stair ascent and descent, hazardous events could not be predicted based on the clinical and functional parameters measured or any of the existing screening tools, as shown by the cox-regression models. This could be partially explained by adjustments that the older individuals made to their overall stair negotiation behaviour based on their functional capacities. For example, it is intuitive to assume that the participants with the poorest performance in the functional tasks would be at the greatest risk for a stair fall. However, by depending fully on the handrails, these individuals adopted the most conservative strategy overall. 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. However, by using the handrails only one of the six older adults at risk for a fall in this group went on to actually experience a stair fall, resulting in a very low sensitivity (0.17) of the FRAT to predict stair fall risk (Appendix D). From the total of 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 fall risk screening approaches that are based exclusively on clinical and functional scores are not specific enough to detect older adults at risk for a fall on stairs, as such scores cannot account for adjustments in the stair negotiation technique that an individual can make to minimise the risk for a hazardous event, for example by the use of the handrails. Equally important, individual biomechanical parameters specific to the stair negotiation task could also not predict hazardous events for either stair ascent or descent, which supports the use of a multivariate profiling approach.

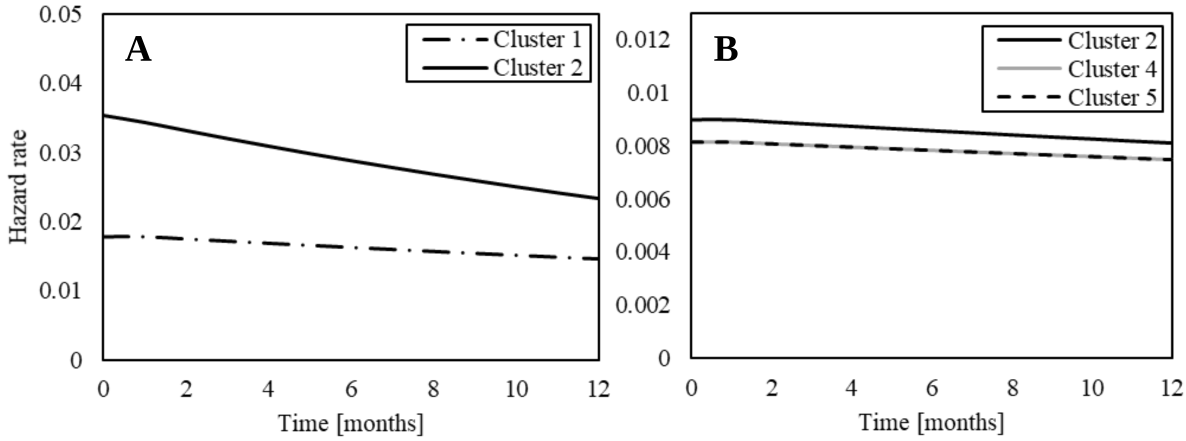

Figure 5.5. The hazard rate (-) for a hazardous event of group 1 and 2 for stair ascent (A) and group 2, 4 and 5 for stair descent (B).

An overall stepping profile that was particularly at risk for a hazardous event during stair ascent could not be identified. However, in the survival curves it is evident that group 1 (the ‘conservative group’) and group 2 (the ‘riskier group’) display an exponential distribution for fall risk (Figure 5.4C), which results in a constant hazard rate (Figure 5.5A). This finding indicates that the overall stepping strategy of group 1 and group 2 can be directly linked to the hazardous event sustained. These findings suggest that compared to the other groups, the displayed conservative strategy in group 1 does not outweigh the reduced functional capabilities, which include reduced visual acuity and less hip flexion strength, and a high medication intake (Table 5.3). For group 2, the findings suggest that having a lower medication intake compared to the other groups, does not allow adopting a riskier overall stepping strategy. The higher hazard rate for group 1 compared to group 2 could potentially be explained by the joint biomechanical outcome measures (PFLCS and cadence) and medication intake that differentiate these groups from the others. Similar to stair ascent, an overall stepping strategy (group) that was particularly at risk for a hazardous event during stair descent could not be identified. In the survival curves for stair descent it is evident that group 2 (the 'trip risk group'), which displays a riskier overall stepping strategy, shows an exponential distribution for fall risk (Figure 5.4D). However, the hazard rate of group 2 (Figure 5.5B) was low compared to the hazard rate of the groups in stair ascent (Figure 5.5A). In addition, the hazard rate of group 2 did not differ from groups 4 and 5 in descent, which displayed more conservative strategies and showed a tendency for an exponential distribution (Figure 5.5B). The above findings suggest that, for stair ascent, the multivariate profiling approach has the ability to link the hazardous events documented in the two groups (group 1 and group 2) to their overall stepping behaviour. The hazardous events in the other groups (group 3 and group 4) could not be related to their overall stepping strategies, and could be caused, for example, by a change in stepping behaviour or functional capabilities of the older adults, although this cannot be confirmed at present. Based on the present findings, individuals in group 1 would reduce their risk for a stair fall by improving visual acuity (e.g. by wearing glasses that correct for the reduced visual acuity) and hip flexor muscle strength. To offset the negative effect of polypharmacy, adopting conservative strategies such as reducing the cadence or placing a greater proportion of the foot on the step might also reduce the stair fall risk. Older adults in group 2 had no functional deficits present compared to the rest of the 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, similar to the individuals with the diminished functional capabilities (Reeves et al., 2008b). Adequate functional capabilities were also evident in groups 1-4 for stair descent, which might explain the low number of hazardous events sustained. Adopting more conservative stepping behaviours similar to the individuals with the diminished functional capabilities might further reduce the risk for a fall during stair descent. The older adults of group 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 (Gavin et al., 2019) and by a step-by-step manner, which decreases the demand of the task in terms of joint loading (King et al., 2018).

The implicit assumption in the present analysis is that the overall stepping strategies of the older adults profiled in controlled lab conditions (e.g. constraints included that participants negotiated the stairs in step-over-step manner without using the handrail) is representative of their stepping behaviour in real life. Clearly, however, these constraints do not apply when negotiating stairs daily and there are multiple factors that could have an influence on the overall stepping strategy. In Chapter 4, we have shown that the overall stepping profile of an older person is not modified when negotiating stairs with different step dimensions than those examined here, but there are several factors that could have an influence, such as environmental factors (e.g. lighting and stair surface (Hamel, Okita, Higginson, et al., 2005; Tisserand, 1985)), individual factors (e.g. less attention for the stepping task due to dual tasking (Vallabhajosula, Tan, Mukherjee, Davidson, & Stergiou, 2015)), or other factors (e.g. number of people on the stairs (Lam & Cheung, 2000)). Simulating in the lab all the external conditions that may modify the biomechanical stepping profile of an individual is technically 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 on the step, cadence and CoM trajectories (González, Hayashibe, & Fraisse, 2012; Selvaraj et al., 2018; Shany, Redmond, Narayanan, & Lovell, 2011). Using stair-specific biomechanical parameters measured in real life conditions together with a higher sample size (i.e. increasing the number of hazardous events) in real life stair negotiation conditions could improve the predictive power of the multivariate approach and avoids the constraints necessary to conduct biomechanical research in the lab. Once the stepping profile at the highest risk is identified in real life conditions, the underlying easy quantifiable clinical and functional parameters should be identified and implemented in screening tools to identify people at risk for a fall on stairs.

5.6 Conclusion

In conclusion, for the first time the individual stepping strategies of older adults were profiled for stair ascent and descent and linked with fall risk in a longitudinal study. Clinical and functional tests 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. To improve the predictability of the stepping profiling approach, it is suggested that biomechanical input data are collected in real life conditions, avoiding the constraints of controlled lab settings necessary for biomechanical research.

CHAPTER 6:
General discussion

6.1 Purpose

The overall purpose of the present thesis was to develop a novel multivariate approach that has the ability to identify older adults at risk for a fall on stairs at community level. This would allow the design and implementation of targeted interventions for improving stair safety in older people.

6.2 Summary of experimental findings

1) A novel multivariate approach for profiling individual stair-negotiating behaviour was established (Chapter 3). This approach circumvented the limitations of single-parameter comparisons between predetermined subject groups and profiled the individual stair-negotiating behaviour based on multiple biomechanical parameters reflecting both risk and safety on stairs. In contrast to the age effects seen by the single-parameter comparisons, the multivariate approach revealed that younger adults, older fallers and older non-fallers were spread over the identified stepping behaviours, as they did not present a similar particularly risky or conservative overall behaviour that would group them in the same group. Furthermore, the identified stepping behaviours were found to be a combination of biomechanically risky and safer components.

2) The multivariate approach was applied in Chapter 4 to investigate whether older adults maintained their stair-negotiating behaviour when the step dimensions had been changed to represent more challenging or easier step dimensions that could be encountered in domestic and public buildings in daily life. It was found that the majority of the older adults maintained their stair-negotiating behaviour, for both ascent and descent, irrespective of step dimensions. This indicates that manipulating the demand of the task within the range of step dimensions studied would not affect the underpinning mechanism of a potential stair fall.

3) In Chapter 5, the validity of the multivariate approach to predict stair fall risk was tested and compared to the predictive power of single biomechanical factors, and single clinical and functional parameters. Single biomechanical risk factors could not predict stair falls and balance perturbations on stairs in both ascent and descent. Clinical and functional tests also did not predict stair falls and balance perturbations on stairs, and the commonly used Fall Risk Assessment Tool (FRAT) classified only 1 out of 17 stair fallers as being at risk for a fall. Two particular stepping strategies identified by the multivariate biomechanical profiling approach in stair ascent were linked with prospective falls and the underlying clinical and functional parameters of the stepping strategies could be identified. These findings highlight the potential of the stepping profiling method to predict stair fall risk in older adults against the limited predictability of functional and single-parameter approaches currently used as screening tools.

6.3 Clinical relevance

6.3.1 Limitations of single-parameter comparisons

Using the conventional single-parameter grouping approaches, the measurements in Chapter 3, showed that that older adults would be considered 'safer' on stairs as they differed from the younger adults by predominantly displaying more conservative strategies and only one riskier strategy. However, based on the group means it cannot be established whether the older individuals who adopted the riskier strategy were the same individuals who adopted more conservative strategies for the other parameters. The multivariate approach circumvented this limitation by grouping individuals based on multiple risky and conservative stepping strategies. It was found that age and fall history was in fact not a factor that assigned older adults or younger adults in the same group and that the stair-negotiating behaviour of individuals was indeed based on a mix of biomechanically riskier and safer strategies.

6.3.2 Stepping behaviour & step dimensions

The measurements in Chapter 4 showed that the majority of older adults maintained their stepping behaviour when negotiating a *steep* staircase vs a *shallow* staircase (dimensions and pitch highlighted in Figure 6.1). This finding implies that older adults would maintain their stepping behaviour irrespective of the step dimensions of the staircase encountered daily (range of dimensions highlighted as yellow shaded area in Figure 6.1). Furthermore, the findings indicate that the underlying mechanism of a stair fall may remain the same irrespective of stair dimensions. In terms of safety, this would imply that when the stepping behaviour of an individual at risk for a stair fall is improved through targeted interventions, this individual would be safer on multiple step dimension configurations that could be encountered daily.

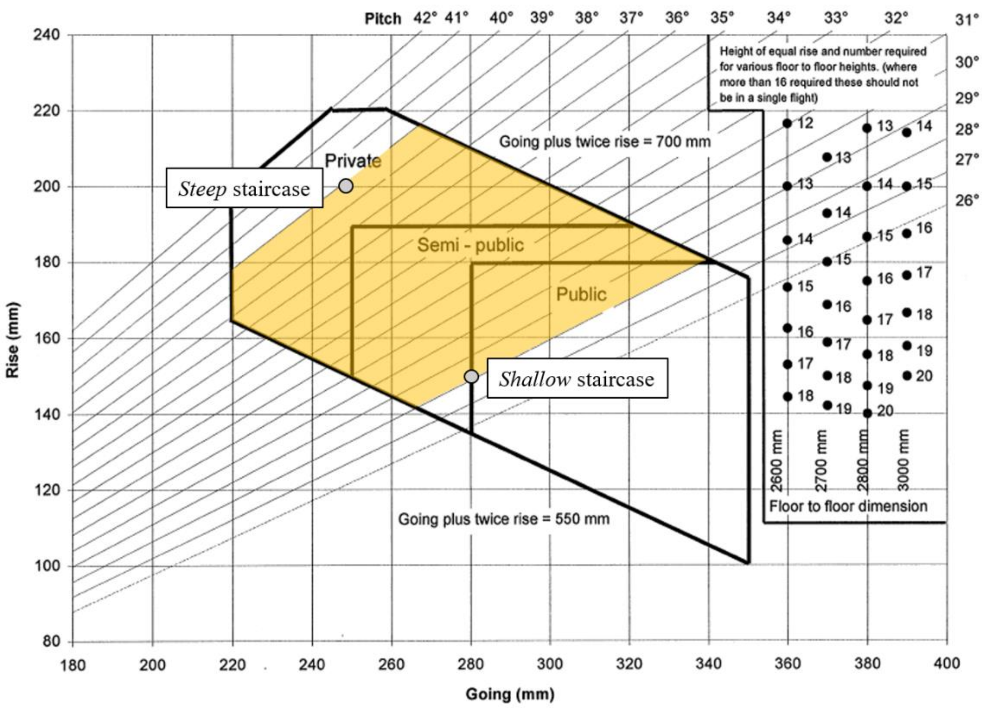

Figure 6.1. The shallow and steep staircases used in the present study and the range of step dimensions in between the tested step dimensions (yellow shaded area) highlighted on a figure that illustrates the range of acceptable step dimensions (figure adopted from Roys, 2001).

6.3.3 Stepping strategies & clinical and functional capabilities

The findings of Chapter 5 indicate that for the majority of the identified biomechanical stepping profiles in stair ascent and descent, clinical and functional parameters underlying these profiles that can easily be measured could be identified. The applicability of these measurements in large-scale populations without the need of a specialized gait lab opens new possibilities for stair fall risk detection and prevention at community level.

Furthermore, the findings of Chapter 5 indicate that the older adults adjusted their stepping behaviour according to their functional capabilities. For example, older adults with better functional and clinical scores could 'afford' to adopt a riskier overall stepping behaviour. Likewise, the older adults with the poorest performance on the clinical and functional tests adopted the most conservative overall stepping behaviour by depending fully on the handrails. Based on these findings, older adults with a poor performance on clinical and functional tests should be advised by their health professional or the fall prevention service to adopt a more conservative stepping behaviour, for example, use the handrails and walk slower on stairs, in addition to taking measures to improve the functional deficit present, for example, by targeted exercise training (Gavin et al., 2019).

6.3.4 Stair falls

A range of studies exists that have monitored falls prospectively. Although a small number of these prospective studies have included the option 'stairs' as a fall location, stairs are typically categorized together with 'steps' and falls for stair ascent and descent are not separated. Moreover, when stairs are given as a fall location no separate analysis is executed to detect stair fall risk (W. P. Berg, Alessio, Mills, & Tong, 1997; Maki et al., 1994; Muir et al., 2010b; Svanström, 1974). Chapter 5 is the first prospective study that has monitored falls and balance perturbations specifically on stairs. A total of seventeen older adults (19.5%) sustained at least one actual fall on stairs, and twelve additional older adults sustained balance perturbations on stairs, within the 12-month follow-up period. Based on previous reports, we would expect only six stair fallers in our study, but we had almost three times as many (seventeen fallers). In addition, although the literature reports more falls during stair descent (Svanström, 1974; Tiedemann et al., 2007), in the present study 72% of 'hazardous events' (falls and balance perturbations combined) occurred during stair ascent. This could be explained by the fact that some of these studies assessed the number of falls through hospital statistics and since falls sustained during stair descent are more injurious it is expected that these result in a higher number of hospital admissions compared to falls sustained during stair ascent (Svanström, 1974). Indeed, although less hazardous events occurred for stair descent in the 12-month follow-up period, stair descent was found to be the most dangerous aspect of stair negotiation with 50% of falls resulting in injury (with 1 fall resulting in hospital admission) compared to 19% of falls resulting in injury during stair ascent. Overall, these findings indicate that falls on stairs are more common, especially during stair ascent, than is indicated in the literature, once more highlighting the importance to identify older adults at risk for a fall on stairs.

6.3.5 Stair fall prediction

6.3.5.1 Prediction using clinical and functional scores

Although existing fall risk screening tests encompass parameters that are considered to be important for safe stair negotiation, such as balance, muscle strength and confidence levels (Jacobs, 2016; Startzell et al., 2000), none of the functional and clinical parameters could predict a hazardous event for stair ascent or stair descent (Chapter 5). Although, it is intuitive to assume that the participants with the poorest performance in the functional tasks would be at the greatest risk for a stair fall, by depending fully on the handrails, these individuals adopted the most conservative behaviour overall and sustained the smallest number of falls, i.e. they were the “safest” group – not the riskier group. As highlighted above (section 5.3.3), this indicates that the handrail-depended older adults remained safe on stairs by adopting stepping strategies in line with their individual functional capabilities. This modification in stair-negotiating technique may explain why general fall screening tools are not specific enough to detect older adults at risk for a fall on stairs (Gates et al., 2008). Indeed, from the six older adults identified at risk by the FRAT, commonly used to identify a general fall risk in the UK, only one older adult sustained a stair fall, resulting in a very low sensitivity (0.17) for accurate prediction. Moreover, from the seventeen older adults who did sustain a stair fall, sixteen were classified as not being at risk by the FRAT. These findings indicate that stair negotiation is a complex skill, adjustable to individual deficits. Generic fall screening methods do not encompass this adjustability in stepping technique and should not be implemented for the prevention of stair falling as they have very limited predictive power.

6.3.5.2 Stair fall prediction using single biomechanical parameters

Similar to the clinical and functional parameters, none of the biomechanical parameters, indicative of risk and directly related to the stair negotiation task, predicted hazardous events during either stair ascent or descent (Chapter 5). This finding shows that there was no single parameter or combination of parameters that could differentiate stair fallers from non-fallers and highlights the limited predictive power of biomechanical approaches typically used in the literature, reinforcing the notion that falls are a multifactorial problem and more holistic approaches are needed to assess fall risk (Gillespie et al., 2012). Therefore, it is suggested that studies aiming to identify biomechanical fall risk on stairs use multivariate approaches for profiling the overall stepping behaviour of the individual.

6.3.5.3 Stair fall prediction using the present multivariate profiling approach

In contrast to the functional and clinical, and biomechanical single-parameter approaches, the novel multifactorial approach developed showed potential in stair ascent to predict stair fall risk in older adults. Stair fall occurrence could be directly linked to the stepping behaviour in two groups of older adults. One group displayed an overall more conservative stepping strategy which was linked with a lower visual acuity, lower hip flexion strength and polypharmacy. The other group displayed a more risky stepping strategy by having a lower portion of the foot in contact with the stair, a higher required coefficient of friction and higher cadence. This riskier overall strategy was not linked to any functional deficits. Therefore, specific advice could be provided in the future to prevent future stair falls in older individuals with similar deficits. Specifically, the first group should improve their visual acuity (e.g. by wearing glasses that correct for the impaired visual acuity) and hip flexor muscle strength, and the other group should adopt a more conservative strategy by reducing their cadence and increasing the proportion of the foot length in contact with the step to minimize the risk for future stair falls. For the remaining older adults, no functional deficits could be identified and their stepping strategy could not be linked directly to stair falls, therefore, to minimise stair fall risk in older adults with a similar stepping profile, adopting even more conservative strategies, for example, using the handrails would be advisable as this allows additional control of dynamic postural stability and reduces lower limb requirements for providing frontal plane stability (Reeves et al., 2008b). The same was the case for stair descent, namely no single stepping profile or functional deficits could be linked to stair fall risk. Therefore, to minimise stair descent fall risk in older adults with a similar stepping profile, adopting even more conservative strategies would be advisable, for example, using the handrails which allows a more effective balance control (Reeves et al., 2008b), descending the stairs in a step-by-step manner or adopting a side-ways foot placement, which both decrease the overall stair descent demand in terms of joint loading (King et al., 2018).

6.4 Future recommendations

6.4.1 Implementation of profiling method in real life

As highlighted in Chapter 5, future research should implement the stepping profiling method in more people in real life stair negotiation conditions, avoiding the constraints necessary to conduct biomechanical research in the lab. A way to achieve this is to collect relevant data using sensors, such as accelerometers, gyroscopes and pressure sensors. It has been shown that accelerometers can determine a range of spatiotemporal gait parameters and give insight in the control of the CoM, which is indicator for the risk of a loss of CoM control during stair descent. Furthermore, it has been found that clearance of the foot to the step edge, which indicates trip risk, can be obtained using a distance sensor attached to the shoe (Selvaraj et al., 2018). The risk for a slip could be determined by measuring the foot angle relative to the step edge using a IMU sensor (Selvaraj et al., 2018). Alternatively, marker-less motion capture can be explored to measure biomechanical parameters indicative of stair fall risk. These biomechanical parameters could be used as input in the multivariate profiling tool, thus allowing the identification of risky stepping strategies in real life situations and circumventing the assumptions made when establishing the stepping behaviour in the lab.

6.4.2 Stair fall monitoring in larger studies

The present research work encompasses the first prospective study that has monitored falls on stairs specifically. The prediction of stair falls could be improved by grouping the hazardous events based on the underlying mechanism that caused the event (e.g. trip, slip or loss of balance) or environmental circumstances of the fall (e.g. the step dimensions, the surface material of the steps and whether the fall occurred at home or in the public) and link these separately to the identified stepping strategies (Edwards, Dulai, & Rahman, 2019). Although, the underlying mechanisms of the stair falls were recorded in the present thesis, the number of hazardous events for each mechanism were insufficient to group them based on the underlying mechanisms for further analysis. Therefore, it is recommended that larger cohort studies related to ageing, such as the Canadian longitudinal study on ageing and the Irish longitudinal study of ageing (Stinchcombe, Kuran, & Powell, 2014; Whelan & Savva, 2013), which already assess falls on stairs, obtain more detail regarding the falls on stairs. This more detailed approach could potentially link the direct mechanism that caused the stair fall to a certain stepping behaviour. In addition, this information could be used to inform fall prevention approaches targeting the built environment, improving the built environment design characteristics can lower the risk of falls and fall-related injuries (Nemire et al., 2016; Verma et al., 2016).

6.4.3 Enhancement of awareness

One other important factor that could facilitate the prevention of falls in older adults is enhancing the awareness of the consequences of stair falls. During the 12-month follow-up period people reported that talking about stair falls with the research team made them more aware. Importantly, a high number of falls were experienced by the more active and healthy older adults. These older adults often believe that falls prevention information and measures are relevant to ‘other’ older people, typically older and more frail, and therefore at greater risk for a fall (Yardley, Donovan-Hall, Francis, & Todd, 2006). Therefore, it is recommended to also make the more active and fit older adults aware that they are at an increased risk for a stair fall even though they might still feel healthy and active, as this could potentially prevent some future stair falls.

6.4.4 Reactive balance control training

Combined resistance and stretching training has recently been shown to improve balance control during stair descent in older adults (Gavin et al., 2019). A functional capability important for postural recovery following a perturbation is the reactive balance control, i.e. the ability to quickly react following an event leading to a loss of balance. More specifically, a poor reactive balance control has been linked to an increased risk for a general fall (Aviles et al., 2019; Gerards, McCrum, Mansfield, & Meijer, 2017) and it was found that reactive balance control measures could be used to predict fall risk for a general fall (Mansfield et al., 2015). Reactive balance control may also be important for the prevention of stair falls, for instance to recover a safe stance by quickly adjusting foot position following a trip during stair ascent. Presently, the impact of the ability to control balance reactively on stair fall risk has not been assessed. Therefore, it is recommended that future research looks into this possibility, particularly, as it has been shown that reactive balance control in older individuals can be improved through perturbation-based balance training at community level (Gerards et al., 2017).

6.5 Conclusion

In the present thesis, a novel multivariate method to profile individual stair-negotiating behaviour has been developed, which circumvented the limitations of single-parameter comparisons between predetermined groups using mean values. This multivariate method was than applied to an older population to detect stair fall risk. It was found that the biomechanical stepping behaviour of older adults could be profiled and the specific stepping profile adopted was maintained irrespective of step dimensions, indicating that the mechanism of a fall is not altered by step dimensions in the range of values experienced daily. In contrast to the limited predictability of functional and single-parameter biomechanical approaches currently used as screening tools, the multivariate stepping profiling method showed potential to predict fall risk during stair ascent in older adults. Future research should implement the stepping profiling method in more people in real life stair negotiation conditions to improve the prediction of the stepping profiling method, so that targeted interventions for improving stair safety in older individuals can be developed.

Appendices

Appendix A: Marker placement

The full-body kinematic data collected in the present thesis 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 14 mm). The attachment locations of segment defining and segment tracking markers are clarified in this appendix (Figure A.1). Markers for segment definition were attached to the calcaneus, lateral/medial calcaneus, first and fifth metatarsus head, lateral/medial malleolus, second cuneiform, proximal phalange halux, lateral/medial femoral condyle, anterior/posterior iliac spine, iliac crest, acromion, anterior/posterior head, lateral/medial epicondyle of the humerus, styloid process of the radius and ulna, third metacarpal head (all left and right), sacral crest, cervical vertebrae 7, thoracic vertebrae 10, clavicular notch and xiphoid process of the sternum. In addition, marker clusters for segment tracking were attached to the lateral sides of the shanks and thighs (four markers per cluster), on the second and third metatarsal (three markers per cluster) and single markers were attached on the forearms, upper arms, above the auricular points, right scapula.

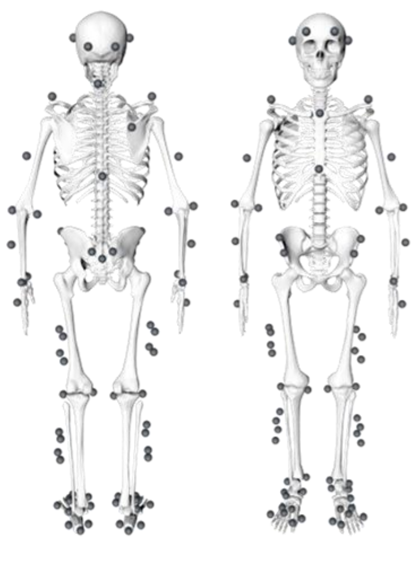

Figure A.1. Front and back view of the attachment locations of the 76 reflective markers.

Appendix B: Fall monitoring

Subsequent to the baseline measurements the participants were followed for 12 months, in which the participants were contacted monthly via phone calls or email by the principal researcher to register the occurrence, circumstances and self-perceived causes of stair falls and balance perturbations during both ascent and descent. The participants who preferred email contact received the fall diary on the pages below via email. Every day the participants were asked to highlight whether they had a stair fall (or balance perturbation) or not on the front page of the diary (see page 102). In case the participants experienced a fall they were asked to write down more information concerning this event (e.g. how did you fall, during which activity and if you had any injuries as a result) on the reverse of the diary (see page 103). How to write down this additional information was explained when the participants received their first falls diary immediately after the final testing session.

Fall Diary

Participant ID: Month: March Year: 2018

MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY	SATURDAY	SUNDAY
			1 Fall/trip ☐ No Fall ☐	**2** Fall/trip ☐ No Fall ☐	**3** Fall/trip ☐ No Fall ☐	**4** Fall/trip ☐ No Fall ☐
5 Fall/trip ☐ No Fall ☐	**6** Fall/trip ☐ No Fall ☐	**7** Fall/trip ☐ No Fall ☐	**8** Fall/trip ☐ No Fall ☐	**9** Fall/trip ☐ No Fall ☐	**10** Fall/trip ☐ No Fall ☐	**11** Fall/trip ☐ No Fall ☐
12 Fall/trip ☐ No Fall ☐	**13** Fall/trip ☐ No Fall ☐	**14** Fall/trip ☐ No Fall ☐	**15** Fall/trip ☐ No Fall ☐	**16** Fall/trip ☐ No Fall ☐	**17** Fall/trip ☐ No Fall ☐	**18** Fall/trip ☐ No Fall ☐
19 Fall/trip ☐ No Fall ☐	**20** Fall/trip ☐ No Fall ☐	**21** Fall/trip ☐ No Fall ☐	**22** Fall/trip ☐ No Fall ☐	**23** Fall/trip ☐ No Fall ☐	**24** Fall/trip ☐ No Fall ☐	**25** Fall/trip ☐ No Fall ☐
26 Fall/trip ☐ No Fall ☐	**27** Fall/trip ☐ No Fall ☐	**28** Fall/trip ☐ No Fall ☐	**29** Fall/trip ☐ No Fall ☐	**30** Fall/trip ☐ No Fall ☐	**31** Fall/trip ☐ No Fall ☐	

Fall Diary

Participant ID: Month: **March** Year: **2018**

Date	How did you fall?	What activity caused the fall?	Did you suffer any injuries?
1.			
2.			
3.			
4.			
5.			
6.			
7.			
8.			

Please select out of the options given below the appropriate number representing the cause, activity and injury, and place this number in table.

How did you fall?
1. I tripped
2. I slipped
3. I lost my balance
4. My legs gave way
5. I felt faint
6. I felt giddy/dizzy
7. I am not sure

What activity caused the fall?

Standing
1. Bending
2. Reaching
3. Washing
4. Dressing
5. Other

Executing a movement or transfer

6. Walking
7. Turning
8. Taking a single step
9. Negotiating stairs
10. Carrying an object
11. Transfer to/from sitting
12. Transfer to/from bed
13. Transfer to/from the toilet
14. Other

Did you suffer any injuries form the fall?
1. Bruises
2. Cuts/grazes
3. Broken wrist
4. Broken hip
5. Broken ribs
6. Back pain
7. No injuries
8. Other

Appendix C: Fall overview

In the present appendix the cause, location, type of injury and other relevant info of each hazardous event is presented for stair ascent (Table C.1) and descent (Table C.2).

Table C.1. Detailed overview of the hazardous events suffered during stair ascent.

ID	**Fall**	**Cause**	**Location**	**Injuries**	**Extra info**
004_PS	1.	Trip	Public staircase	None	Caught with hands, rushing, possibly fatigued
	2.	Trip	Public staircase	None	Caught with hands
009_JF	1.	Trip	Public staircase (outside building)	None	Caught with hands
011_AL	1	Trip	Home staircase	None	Rushing + wearing slippers
014_JJ	1	Missed step	Home staircase	None	Caught with hands
019_LS	1	Trip	Home staircase	None	Able to recover quickly with hands
020_JT	1.	Trip	Home staircase	None	Able to recover quickly with hands
025_AC	1	Trip	Home staircase (garden)	Scratched arm	Fell sideways against a wall
	2	Trip	Home staircase (garden)	Cuts + bruises + sprained wrist	Fell forward and caught with hands
029_CW	1	Trip	Home staircase	None	Grabbed handrail
	2	Trip	Home staircase	None	Rushing a bit
040_JM	1	Trip	Home staircase	Bruised shin	Able to recover quickly with hands
044_HC	1	Trip	Home staircase	None	Rushing
	2	Trip	Home staircase	None	Actually running up stairs
059_BG	1	Trip	Home staircase	Bruised knee and toe	Fell whilst lifting a suitcase
	1	Trip	Home staircase	None	Able to recover quickly
063_MB	1	Trip	Home staircase	None	Going up two at a time
065_BM	1	Trip	Public staircase	None	Top step of stairs landed on knee
069_AH	1	Loss of balance	Public staircase	None	Stair in the train, suitcase dragged her forward
070_MB	1	Trip	Public staircase	None	Misjudged height of the step
072_JM	1	Trip	Home staircase (front of house)	None	Foot caught underneath the step
079_LC	1	Trip	Public staircase (outside holiday accommodation)	Cuts on front of leg	Caught foot on high steps
084_JB	1	Trip	Public staircase	None	Running up steps
089_DP	1	Trip	Public staircase	None	Looking sideways at picture
096_WH	1	Trip	Home staircase (garden)	None	Landed on knee

Table C.2. Detailed overview of the hazardous events suffered during stair descent.

ID	Fall	Cause	Location	Injuries	Extra info
028_BB	1	Missed step	Public staircase	Hip bruised +pain	Misjudged bottom step fell on side
035_JM	1	Loss of balance	Home staircase (garden)	Broke two bones in foot	Went over right ankle
036_LS	1	Slipped	Home staircase	Bruised back	At night whilst holding handrail fell on back
	2	Slipped	Public staircase (outside)	Bruised back	Holding handrail fell on back
046_JD	1	Missed step	Public staircase	None	Missed the step and stumbled
057_KM	1	Tripped	Home staircase	None	Tripped over sports bag
059_BG	1	Tripped	Home staircase	None	Able to recover quickly with hands
084_JB	1	Tripped	Public staircase (outside)	Pulled Achilles	Misjudged thickness of the sole of his trainers
093_WC	1	Loss of balance	Public staircase	None	Knee gave way husband caught her

Appendix D: Performance on clinical and functional tests

Table D.1. Mean (± SD) values of the clinical and functional outcome measures assessed for the four groups during stair ascent, with group 4 representing the handrail dependent group (HR dep.).

		Group 1	**Group 2**	**Group 3**	**Group 4** (HR dep.)
Person-related factors	Age (yrs.)	71.5 ± 4.1	70.8 ± 3.7	71.5 ± 5.2	76.5 ± 7.7
	Body height (m)	1.64 ± 0.07	1.70 ± 0.09	1.75 ± 0.05	1.64 ± 0.08
	Body mass (kg)	65.7 ± 10.7	72.7 ± 15.4	81.1 ± 10.6	76.6 ± 18.8
	Number of medications	2.7 ± 1.8	1.3 ± 1.5	1.8 ± 1.6	5.2 ± 3.2
	Previous falls	0.35 ± 0.54	0.46 ± 0.59	0.45 ± 0.52	0.80 ± 1.08
Questionnaires	ABC scale	94.2 ± 7.8	98.0 ± 1.9	98.2 ± 2.2	77.9 ± 15.6
	FES-I scale	18.5 ± 2.8	17.5 ± 2.2	17.6 ± 1.6	22.7 ± 6.9
	MoCa	27.8 ± 2.1	28.0 ± 1.5	28.0 ± 1.3	24.9 ± 4.6
	NADL index	21.8 ± 0.4	22.0 ± 0.2	21.9 ± 0.3	19.3 ± 3.4
	FRAT (classified at risk)	1	0	0	5
Visual	Visual Acuity (dec. VA)	0.84 ± 0.25	0.97 ± 0.33	0.92 ± 0.34	0.76 ±0.39
	Contrast sensitivity (%)	1.6 ± 0.5	1.8 ± 1.3	1.7 ± 1.0	2.2 ± 1.1
Balance measurements	BBS	55.5 ± 1.0	55.7 ± 0.8	55.4 ± 1.3	51.0 ± 3.1
	Func. Reach (cm)	31.3 ± 5.2	33.5 ± 5.3	35.9 ± 6.6	23.6 ± 6.4
	Single leg stance	1.9 ± 2.5	1.2 ± 1.9	1.2 ± 1.5	8.87 ± 5.51
RoM (degrees)	Act. Hip flex.	121.1 ± 8.7	121.6 ± 8.0	121.2 ± 8.8	111.8 ± 9.8
	Act. Knee flex.	138.2 ± 6.3	138.0 ± 5.6	139.5 ± 5.4	128.4 ± 14.0
	Act. Ankle p. flex.	55.5 ± 11.1	56.4 ± 10.0	50.4 ± 9.4	49.1 ± 9.1
	Act. Ankle d. flex.	3.8 ± 5.1	4.3 ± 4.3	4.3 ± 6.3	0.3 ± 5.7
	Pas. Hip flex.	130.2 ± 9.2	131.4 ± 9.1	127.7 ± 8.7	128.3 ± 10.1
	Pas. Knee flex.	146.4 ± 5.7	145.7 ± 5.1	146.0 ± 5.6	134.6 ± 17.8
	Pas. Ankle p. flex.	61.6 ± 10.4	60.3 ± 11.1	56.3 ± 9.1	54.0 ± 8.8
	Pas. Ankle d. flex.	7.2 ± 6.9	8.3 ± 5.6	8.7 ± 5.9	3.1 ± 6.4
Muscle strength (Nm/kg)	Handgrip	0.37 ± 0.10	0.42 ± 0.09	0.45 ± 0.13	0.32 ± 0.10
	Hip flex.	0.42 ± 0.14	0.56 ± 0.19	0.64 ± 0.22	0.29 ± 0.13
	Hip Abduc.	0.84 ± 0.23	1.00 ± 0.27	0.06 ± 0.25	0.67 ± 0.21
	Knee flex.	0.57 ± 0.17	0.64 ± 0.20	0.71 ± 0.19	0.48 ± 0.15
	Knee ext.	0.90 ± 0.27	1.08 ± 0.28	1.18 ± 0.27	0.72 ± 0.25
Fullerton Functional Fitness Test	Chair stand (rep.)	15.3 ± 4.2	16.1 ± 2.6	15.7 ± 3.5	11.3 ± 3.1
	Arm curl (rep.)	21.2 ± 3.9	22.9 ± 4.1	23.8 ± 6.2	17.2 ± 4.4
	2-min step test (rep.)	211.2 ± 28.9	223.9 ± 42.1	224.7 ± 46.7	145.9 ± 42.7
	Chair sit and reach (cm)	0.9 ± 10.6	-0.4 ± 11.2	-5.8 ± 11.6	-8.5 ± 8.6
	Back scratch (cm)	-2.7 ± 8.7	-4.0 ± 11.9	-9.6 ± 11.6	-8.3 ± 14.0
	Timed up and go (sec)	7.3 ± 1.2	6.6 ± 1.0	6.2 ± 1.0	11.6 ± 2.9

Notes: *ABC:* activities-specific balance confidence scale; *FES:* fall efficacy scale; *MoCa:* Montreal cognitive assessment; *NADL:* Nottingham activities of daily living; *FRAT:* fall risk assessment tool; *BBS:* berg balance scale; *Act:* active; *Pas:* passive; *flex.:* flexion; e*xt:* extension; *p.:* plantar; *d.:* dorsal; *abduct:* abduction.

Table D.2. Mean (± SD) values of the clinical and functional outcome measures assessed for the five groups during stair descent, with group 5 representing the handrail dependent group (HR dep.).

		Group 1	**Group 2**	**Group 3**	**Group 4**	**Group 5** (HR dep.)
Person-related factors	Age (yrs)	72.5 ± 4.4	70.4 ± 3.6	70.4 ± 4.3	72.1 ± 4.2	76.5 ± 7.7
	Body height (m)	1.74 ± 0.04	1.68 ± 0.09	1.66 ± 0.07	1.67 ± 0.09	1.64 ± 0.08
	Body mass (kg)	79.1 ± 11.5	71.7 ± 13.1	68.5 ± 14.6	67.9 ± 13.1	76.6 ± 18.8
	Number of medications	1.8 ± 1.7	1.7 ± 1.5	2.0 ± 1.7	2.6 ± 2.0	5.2 ± 3.2
	Previous falls	0.6 ± 0.7	0.3 ± 0.5	0.3 ± 0.5	0.5 ± 0.58	0.8 ± 1.1
Questionnaires	ABC scale	98.3 ± 2.0	96.0 ± 8.2	98.1 ± 1.8	94.1 ± 6.2	77.9 ± 15.6
	FES-I scale	18.4 ± 3.4	17.4 ± 2.1	17.4 ± 1.2	19.0 ± 2.8	22.7 ± 6.9
	MoCa	27.1 ± 1.4	28.1 v 1.3	27.9 ± 1.7	27.9 ± 2.3	24.9 ± 4.6
	NADL index	22.0 ± 0.0	21.9 ± 0.3	21.8 ± 0.4	21.8 ± 0.4	19.3 ± 3.4
	FRAT (classified at risk)	0	0	0	1	5
Visual	Visual Acuity (dec. VA)	0.94 ± 0.41	1.0 ± 0.32	0.90 ± 0.24	0.80 ± 0.24	0.76 ± 0.39
	Contrast sensitivity (%)	1.9 ± 1.1	1.6 ± 0.5	1.5 ± 0.5	1.8 ± 1.3	2.2 ± 1.1
Balance measurements	BBS	55.5 ± 1.1	55.8 ± 0.6	55.5 ± 1.1	55.3 ± 1.1	51.0 ± 3.1
	Func. Reach (cm)	35.8 ± 4.0	34.4 ± 5.7	31.3 ± 5.7	31.4 ± 5.6	23.6 ± 6.4
	Single leg stance	0.88 ± 1.38	1.05 ± 1.44	0.76 ± 1.21	2.63 ± 2.92	8.87 ± 5.51
RoM (degrees)	Act. Hip flex.	122.2 ± 8.5	121.8 ± 6.8	121.7 ± 7.7	120.4 ± 10.1	111.8 ± 9.8
	Act. Knee flex.	136.4 ± 4.5	138.1 ± 5.2	139.9 ± 6.1	138.1 ± 6.6	128.4 ± 14.0
	Act. Ankle p. flex.	53.0 ± 7.4	55.2 ± 11.2	54.1 ± 9.9	56.0 ± 11.6	49.1 ± 9.1
	Act. Ankle d. flex.	2.1 ± 5.5	4.2 ± 3.9	6.1 ± 4.4	3.2 ± 5.7	0.3 ± 5.7
	Pas. Hip flex.	132.0 ± 8.4	130.6 ± 8.2	128.2 ± 7.9	130.6 ± 10.7	128.3 ± 10.1
	Pas. Knee flex.	143.8 ± 4.4	146.6 ± 4.5	146.3 ± 6.1	140.6 ± 29.3	134.6 ± 17.8
	Pas. Ankle p. flex.	56.9 ± 7.2	60.6 ± 11.7	58.0 ± 10.7	62.8 ± 9.9	54.0 ± 8.8
	Pas. Ankle d. flex.	6.6 ± 4.5	8.5 ± 5.5	9.7 ± 4.9	6.2 ± 7.8	3.1 ± 6.4
Muscle strength (Nm/kg)	Handgrip	0.46 ± 0.11	0.43 ± 0.11	0.40 ± 0.09	0.36 ± 0.09	0.32 ± 0.10
	Hip flex.	0.70 ± 0.18	0.50 ± 0.16	0.51 ± 0.22	0.43 ± 0.16	0.29 ± 0.13
	Hip Abduc.	1.10 ± 0.24	0.95 ± 0.29	0.96 ± 0.19	0.83 ± 0.26	0.67 ± 0.21
	Knee flex.	0.76 ± 0.17	0.62 ± 0.21	0.64 ± 0.15	0.55 ± 0.17	0.48 ± 0.15
	Knee ext.	1.24 ± 0.20	1.08 ± 0.33	0.98 ± 0.21	0.88 ± 0.28	0.72 ± 0.25
Fullerton Functional Fitness Test	Chair stand (rep.)	15.1 ± 1.7	16.5 ± 4.4	16.6 ± 2.9	14.5 ± 3.5	11.3 ± 3.1
	Arm curl (rep.)	23.6 ± 4.5	23.5 ± 4.6	22.4 ± 4.4	20.5 ± 4.0	17.2 ± 4.4
	2-min step test (rep.)	212.4 ± 46.2	238.0 ± 40.2	216.7 ± 31.4	203.0 ± 26.8	145.9 ± 42.7
	Chair sit and reach (cm)	0.3 ± 8.6	-0.6 ± 11.7	-0.4 ± 13.3	-0.5 ± 10.1	-8.5 ± 8.6
	Back scratch (cm)	-2.8 ± 10.6	-4.2 ± 10.0	-8.9 ± 13.2	-1.6 ± 8.0	-8.3 ± 14.0
	Timed up and go (sec)	6.5 ± 1.2	6.5 ± 1.1	7.0 ± 1.0	7.4 ± 1.2	11.6 ± 2.9

Notes: *ABC:* activities-specific balance confidence scale; *FES:* fall efficacy scale; *MoCa:* Montreal cognitive assessment; *NADL:* Nottingham activities of daily living; *FRAT:* fall risk assessment tool; *BBS:* berg balance scale; *Act:* active; *Pas:* passive; *flex.:* flexion; e*xt:* extension; *p.:* plantar; *d.:* dorsal; *abduct:* abduction.

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