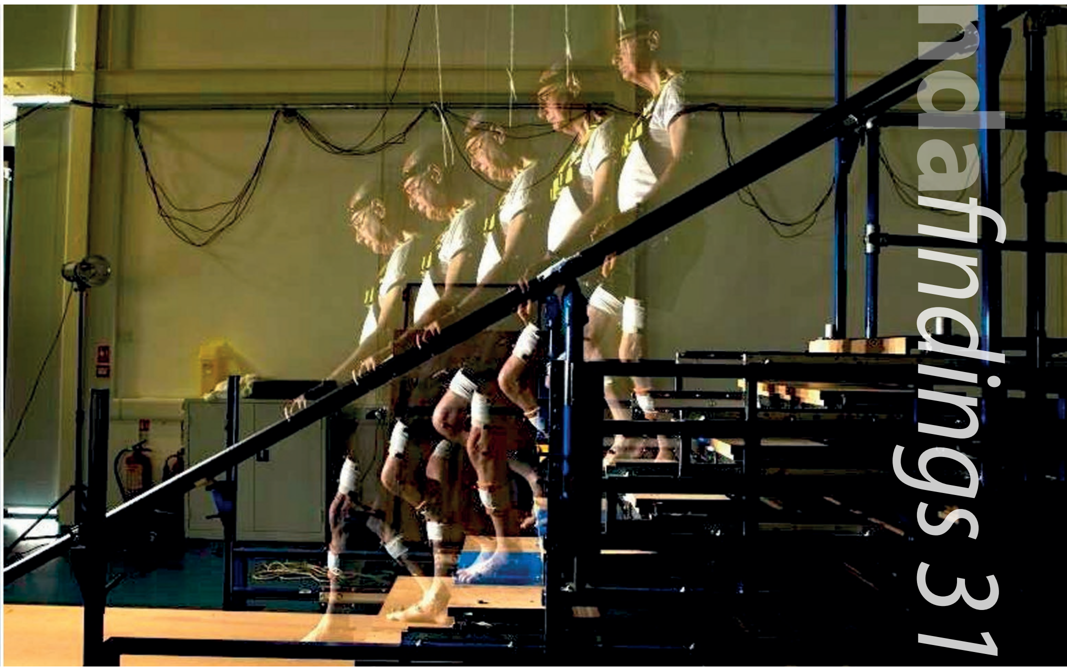
nda PROGRAMME

new dynamics of ageing

a cross-council research programme

Biomechanical and sensory constraints of step and stair negotiation in old age

Grant Holders: Costis Maganaris (PI), Liverpool John Moores University, UK & Vasilios Baltzopoulos, Brunel University, UK



Key findings

- Older adults descend stairs by relying more on their knee and ankle joint muscles than younger adults.
- Stair descent strategies reliant upon placing both feet on the same step result in a slower gait, with reduced lower-limb joint ranges of motion. The 'pause' that is created by this tandem double support means that the muscles surrounding the ankle and knee do not need to control the lowering of the entire body mass on to the next step; instead the leg is lowered to the next step.
- Placing two feet on each step during descent can be achieved by walking facing forwards or sideways. Both strategies can reduce the demands on the lower limb; however, the control over the centre of mass differs. Walking sideways results in an increased movement of the centre of mass into/towards the staircase during single limb stance, which is followed by a rapid acceleration down the staircase in the transition between stance and swing. Alternatively, walking forwards results in less centre of mass movement and a more constant, but lower acceleration down the staircase.
- Older adults produce reduced joint moments at the knee and ankle during descent of a staircase with a higher rise compared to younger adults. Their heel also passes further from the step that the opposite leg is standing on compared to younger adults.
- Older adults almost always make negotiation strategy changes when descending a short going staircase, while younger adults are less likely to do so. When descending a staircase with a shorter going, older adults stand on a single leg for longer than younger adults. Their centre of mass also moves slower than in younger adults.
- Resistance and stretching exercise training in older adults improves knee and ankle muscle strength, as well as ankle flexibility, but has little influence upon lower-limb joint motions during stair descent. The exercise training resulted in greater joint moment production at the ankle and hip, and less at the knee. By increasing step rise the opposite occurred, as greater knee joint moment was produced. It seems that training improvements in lower-limb maximum strength have allowed older adults to meet the demands of stair descent by redistributing moments across joints.
- Exercise training also resulted in greater forward leaning and sideways sway during stair descent. Older adults also demonstrated lower heel clearances. Yet, these adaptations were not present when step-rise was increased. These findings may reflect greater movement control and postural stability, and improved confidence during descent of staircases with a standard step-rise.

In brief

Falls, and fear of falling, are major factors affecting the mobility and quality of life of older people, and it is negotiating stairs in the home and public spaces where problems occur most frequently. In fact, the majority of falls associated with high mortality in older people occur on stairs, and two-thirds of these are during stair descent. With this project we investigated the biomechanical constraints of stair descent in an effort to find ways of improving the competence of older people when negotiating stairs and hence, minimise risk of falling. Our studies included: 1) investigating the biomechanical characteristics of different movement strategies in older people, 2) manipulating the dimensions of stairs, namely the step-rise and step-going, and 3) examining the effect of exercise training on the biomechanics of stair negotiation in older people. We found that stair descent, in general, is more demanding for older than younger people. Older people use a greater proportion of their available muscle strength and adopt certain movement strategies to better control the lowering of the body and avoid catching the heel, which can lead to a loss of balance, as the lead leg comes down to the step below. Staircases with high step-rises and short step-goings are particularly troublesome for older people as they impose demands closer to the functional capabilities in this population. Exercise training, however, can improve these functional capabilities and reduce the relative demands of stair descent in old age.

Summary

In the present research project, we manipulated three parameters to investigate their influence on the biomechanics of stair negotiation in older people: 1) strategy of descent movement, 2) dimensions of each step and 3) musculoskeletal functional capability by means of exercise training.

1. Strategy of descent movement. Descending a staircase with two feet on each step can be achieved in two ways; walking forwards (step-by-step) and sideways (side-step). Both strategies cause the individual to walk much slower as there is a 'pause' when both feet are in contact with the same step at the same time: tandem double stance. In a step-over-step strategy, the feet come in contact with alternate steps, resulting in split double stance. In this common approach our joints and muscles need to continuously control and absorb the lowering of body weight on each step. Therefore, there are two instances of necessary muscle action; firstly to absorb our body weight after first making contact with the step and secondly to control the lowering of the body weight prior to contact with the other leg on the subsequent step. This second instance is not necessary in step-by-step and side-step strategies. Both approaches are asymmetrical in the sense that one leg (the leading leg) acts to absorb the impact of the falling body weight after first making contact and the other leg (the trailing leg) acts to control the lowering of the body.

This second instance of muscle action also occurs in the transition between stance and swing and is a potentially dangerous aspect of stair descent. The body weight, which can be thought of acting through the centre of mass, is moving, accelerating and decelerating forwards down the staircase. The acceleration and deceleration of the centre of mass undulates both vertically and anteriorly in the step-over-step approach, which reflects the continuous and symmetrical nature of this approach. The side-step strategy results in the centre of mass moving towards the staircase during single limb stance i.e. the individual is leaning into the staircase. This is followed by a rapid acceleration of the centre of mass forwards (down the staircase) in the transition between stance and swing, which also corresponds to a large shift in the position of the centre of mass in relation to the centre of pressure on the step i.e. the body weight is quickly moving away from the base of support. In contrast, the step-by-step strategy results in very little vertical movement and a constant, but low-level, acceleration anteriorly with the centre of mass remaining close to the centre of pressure. Despite both strategies reducing the amount of muscle work needed during this transition period, the movement of the centre of mass differs. By the very nature of these strategies (facing forwards or sideways), the muscle groups required to control this movement would also be different. Both strategies require and rely upon the large flexors and extensors to absorb the falling body mass, however, there is an additional need for the abductor muscles in the side-step strategy, particularly in the transition between stance and swing.

The implications of these findings are that employing different stair descent strategies alters the demands on the muscles, joints and limbs of the individual. In cases where muscle strength, postural control and confidence in negotiating stairs are reduced, a slower approach that places two feet on each step offers a means to maintain the ability to descend stairs safely.

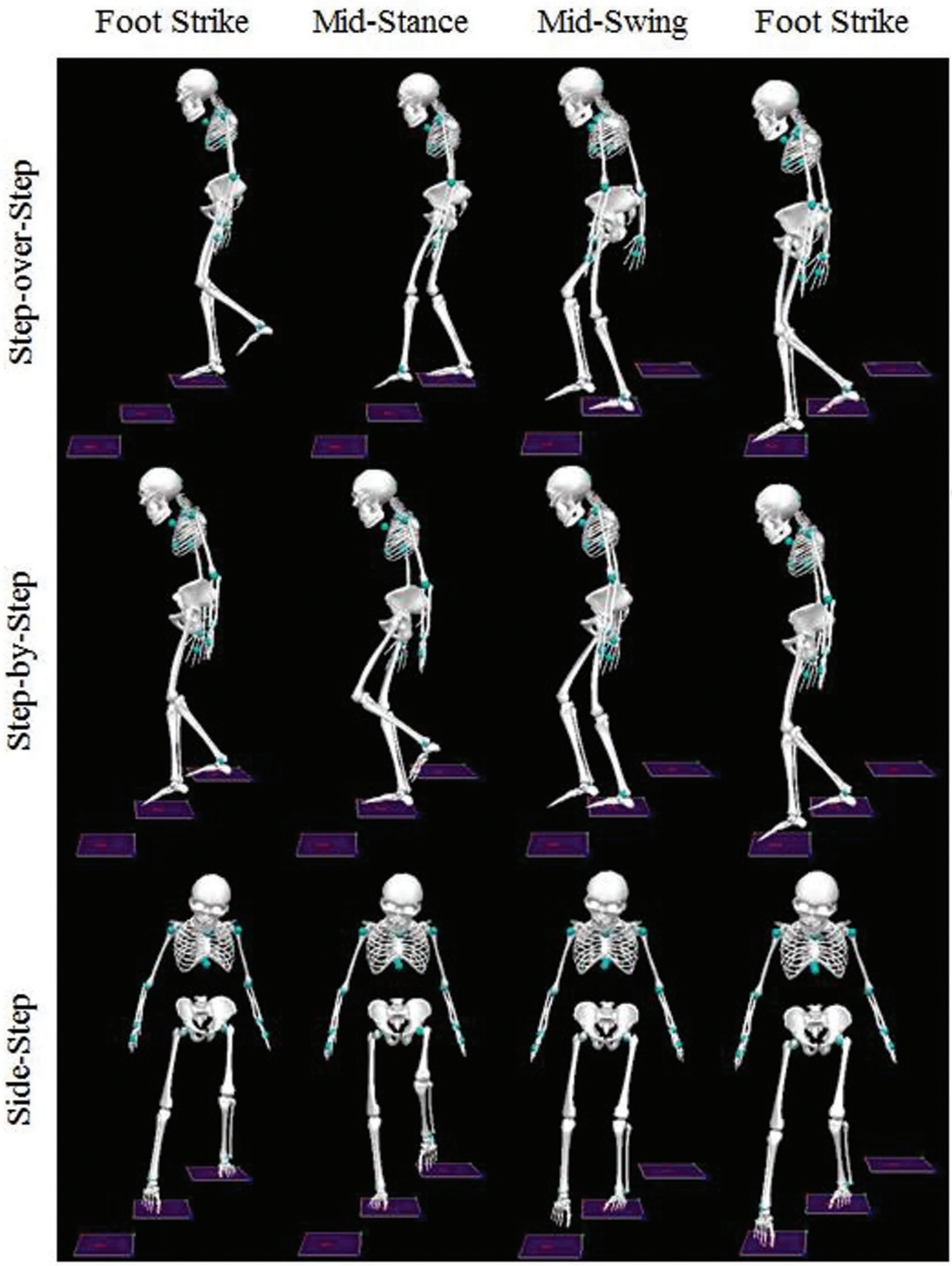


Figure 1. Example images from the start of a gait cycle, at mid-stance, mid-swing and at the end of the gait cycle for three descent strategies: step-over-step (top), stepby-step (middle) and side-step (bottom). In the side-step strategy, the shifting of body weight between limbs from mid-stance to mid-swing results in the centre of mass shifting, relative to the base of support, from leaning towards the staircase to leaning down the staircase.

2. Step dimensions. Stair descent requires the joints of the lower limb (hip, knee and ankle) to support body mass against gravity. During descent of a high rise staircase (305mm step-rise compared to a standard step-rise of 174mm; step-going 280mm in both cases), older adults have lower movements at the knee and ankle than younger adults. This could be the result of older adults employing different biomechanical strategies to compensate for reduced knee and ankle muscle strength. Older adults could reduce the movements at the knee and ankle by maintaining a more upright posture to keep the centre of mass closer to the centre of pressure (the point where the foot is in contact with the step). In this study, analysis of the separation between the centre of mass and the centre of pressure highlighted small variations between younger and older adults, but not sufficient to account for the joint movement differences found. An alternative strategy would be to offload the lower limbs. This could be achieved by supporting some of the body mass with the upper limbs. There was a tendency for both younger and older adults to use the handrails during the task; although it was not universally adopted as a strategy, older adults were more likely to do so. The handrails were not instrumented, so it is not possible to determine if the older adults used the handrails for support while the younger adults placed less reliance on them. However, given that no differences were found in the other parameters measured, this seems the likely conclusion.

Older adults may be aware of their limitations and take measures to safely negotiate high rise staircases. One source of hazard would be making contact with the step edge with the foot. Our study shows that older adults have a larger gap between the heel and the edge of the step the opposite foot is standing on and the heel as it moves from a higher to lower step than younger adults. This could be a conscious decision to cope with the high demand task.

The implications of these findings are that older adults may be capable of negotiating staircases with high rise, by making compensations. However, this is still more hazardous than descending a staircase with a lower rise and could still pose a risk to older adults if handrails are not in place to allow the upper limbs to support body weight and unload the lower limb muscles.

During descent of a short going staircase (175mm step-going compared to a standard step-going of 275 mm; step-rise 175mm in both cases), older adults have a longer single support time than younger adults. This means that they spend more time supported on one leg as the moving leg swings from one step to the next. This may be a hazardous situation for a population with weaker muscles than younger adults. This strategy likely limits the area to place the foot on in the short going staircase. The risk of misplacing the foot on the narrow step could be more of a hazard than the maintaining single leg stance for a little longer. This would suggest that older adults perform this task in a more tentative manner than younger adults. This theory is re-enforced by the results found in the analysis of the acceleration of the centre of mass. Older adults have much lower accelerations in the backwards-forwards and vertical directions compared to younger adults, which also suggests slower variations in these movements.

During the difficult task of descending the short going staircase, both younger and older adults used different negotiation strategies to perform the task safely. The strategies observed were to use the handrails and to rotate the feet or the whole body to make it easier to place the front part of the foot on the step. However, one third of the younger adults used no strategy changes while all of the older adults used at least one negotiation strategy change.

The implications of these findings are that older adults are capable of negotiating short going staircases. However, they have to make changes to their strategy. The increased single support time places them in a hazardous single leg support stance while supporting their body mass on a flexed lower limb for longer periods of time. This could have muscle fatigue implications, which could limit them to shorter staircases. As is the case for the high rise staircases, older adults may rely on handrails capable of giving them support.

Figure 2. Foot positioning during descent in a staircase with 175 mm rise and 310 mm going (top), and in a staircase with 220 mm rise and 220 mm going (middle and bottom). In the 170 mm-rise and 310 mm-going configuration descent the feet look forward and there is enough room to place the ball of the lead foot within the step (top). In the 220 mm-rise and 220 mm-going configuration, if the feet are placed forward, the ball of the lead foot is placed outside the edge of the step, which can reduce balance and result in a fall. Sideways placement of the feet (bottom) circumvents this problem.

3. Exercise training. Compared to the younger participants, the older adults used higher strength reserves of the lower limbs when descending stairs. This was clear for most staircase configurations and may indicate that older adults operate closer to their muscle strength limits than the young adults. An implication of this is that the older participants would have less strength reserve to cope with unanticipated events, such as foot misplacement or slipping, and therefore potentially more prone to falling. However, training improvements in maximal lower-limb strength, and ankle flexibility, resulted in older adults becoming more reliant on the ankle and hip joints to descend stairs. This was particularly apparent at a point of high demand, when the individual was bearing weight on a single leg. It seems that exercise training allowed our older adults to adopt staircase-specific strategies to safely lower themselves, supported by a single leg, to the step below. It is not surprising that training did not influence the range of motion of lower-limb joints, as these were mainly constrained by step-rise, and therefore staircase design.

Exercise training also resulted in greater forwards and sideways movement of the centre of mass, relative to their base of support, when descending stairs in the older adults. Again, improvements in maximal strength and flexibility, particularly at the ankle, may have enhanced joint stability, and therefore confidence walking downstairs. How this relates to an age-related inability to adapt to disturbances in balance is uncertain and warrants further investigating. With improved lower-limb strength and movement control, older individuals would be more confident to let their body mass deviate from their base of support. Furthermore, this 'movement freedom' and confidence may explain why training resulted in the foot being positioned closer to the step edge during stair descent. The implications of these findings are that the exercise training programme undertaken allowed the older participants to meet the demands of stair descent by distributing joint movements (particularly at the ankle, which deteriorates substantially with ageing) to control body movement in a safe and controlled manner. However, by increasing step-rise and task demand, it appears older adults do not benefit from some of these training adaptations; increased rise steps may be too challenging even for training adaptations to overcome.

Background

Although regulations are in place to provide staircases that are safe to use, many older buildings have staircases that do not conform to these regulations. Such staircases could have a high rise and/or a short going. These geometric characteristics make a task that older adults find difficult, even more challenging. Given that many fatal falls occur on staircases and that these non-conforming staircases could be in place for many years to come, it is important to understand the difficulties facing older adults when confronted with non-standard staircases, what strategies they use to negotiate such staircases and what can be done to make the task less hazardous for them.

Lower-limb musculoskeletal function is known to deteriorate with ageing. Alongside changes in postural stability and control, these typically lead to poorer functional mobility. For older adults negotiating stairs this is restrictive, particularly between buildings where staircase design and subsequent demands vary. However, exercise training may be important to allow the older individuals to meet these demands when walking downstairs. For example, training studies using exercise classes and resistance exercises for older adults have shown improvements in i) lower-limb strength, ii) mobility performance, and iii) time taken to negotiate stairs. Stretching training may also improve joint flexibility, and subsequently gait biomechanics when walking.

Using exercise training to maintain muscle function in old age is domestically important for independent living and quality of life, yet occupationally important for an ageing work force. Despite advances in the understanding of exercise adaptations in older adults, training studies combining lower-limb resistance and stretching exercises to improve stair negotiation performance in the old have been lacking.

Methods

Biomechanical measurements

Measurements were taken from nineteen old (69-83 yr) and twenty young (23-38 yr) adults descending a staircase with adjustable step rise and step going (Figure 1). A higher rise and a shorter going were configurations presented in two more demanding staircase designs; each was negotiated on separate visits before, and for older adults, after 16 weeks of exercise training. Trials were performed barefoot. Kinematic and kinetic parameters were measured via step-embedded force platforms and a motion-capture system (Vicon Motion Systems, Oxford, UK). These acquisition methods allowed assessment of lower-limb joint (ankle, knee and hip; Figure 2) angles and movements, foot clearances (defined as the distance between the heel and the step edge, for lead and trail limbs) and centre of mass motion during stair descent.

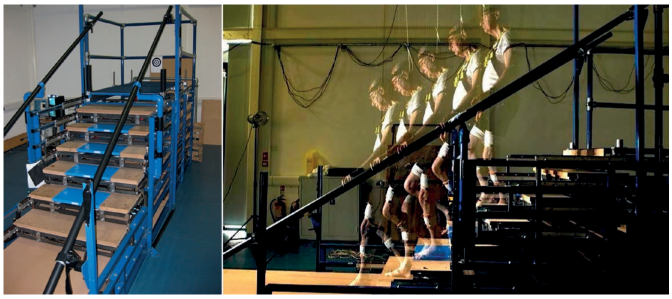


Figure 3. Experimental staircase

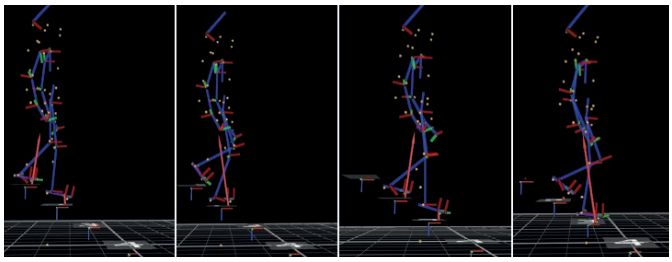


Figure 4. Motion-capture imaging during stair descent.

Stair descent strategies

The older adults descended the staircase using three different negotiation strategies: 1) a traditional step-over-step strategy where one foot is placed on each step, 2) a step-by-step strategy where both feet are placed on each step and the individual faces forwards, and 3) a side-step strategy where both feet are placed on each step the individual faces sideways. These three strategies were assessed during stair descent at a standard step-rise (170mm) and a higher step-rise (220mm). The step-going was 280 mm in both cases.

Exercise training

Older adults performed small group, training sessions involving supervised resistance and stretching exercises for the lower-limb twice a week, for 16 weeks. Resistance exercises were conducted on leg-press, knee extension and calf-press machines, each involving three sets of ~8 repetitions at 75 to 80% three-repetition maximum. Also at the ankle, maximal calf-press exercises (three sets of 10-12 maximal efforts) were included to improve plantarflexor rate of force development, and static stretches (three sets of 45 s) were included to improve ankle range of motion. Lower-limb maximal strength was measured on a dynamometer (Cybex NORM, New York) before and after training.

Conclusions

Older participants descended stairs using a greater proportion of lower-limb maximal strength, when compared to younger adults. This was consistent across different step-rises, and suggests that the older adults operate closer to their strength limits than the younger individuals. This may have implications for fall risk.

Alternate stair negotiation strategies place different demands on the muscles and joints at different stages of stair descent. Physical activity interventions need to consider these demands to ensure that appropriate exercises are implemented.

Older adults find it difficult to negotiate staircases with high step-rises or short step-goings. The former configuration challenges muscle strength, and the second, postural stability. Self-selected compensatory strategies adopted included unloading the lower limbs by using the handrail and turning sideways to better control the lowering of the body and lead leg and place the foot more safely within the step below.

Exercise training resulted in older participants distributing joint movements across the ankle and hip, as opposed to solely loading the knee joint. These may demonstrate a neuromuscular strategy allowing the older adults to meet the high demands of stair descent.

Training also influenced postural stability; greater forward leaning and sideways sway may reflect the improved muscle strength and confidence when walking downstairs.

The additional demand of increasing step-rise seemed to negate training improvements shown for standard stairs. Effective handrails need to be in place to improve safety in such circumstances.

Contact details:
Costis Maganaris, PhD
Professor of Musculoskeletal Biomechanics
Research Institute for Sports and Exercise Sciences
Liverpool John Moores University
Tom Reilly Building
Byrom Street
Liverpool L3 3AF
Email: c.maganaris@ljmu.ac.uk

Published by the NDA Research Programme
Department of Sociological Studies
University of Sheffield
Elmfield
Northumberland Road
Sheffield
S10 2TU
www.newdynamics.group.shef.ac.uk
Email: nda@sheffield.ac.uk

Contributors:
I. Di Giulio, University College London, UK DA. Jones, E. Kingdon & N. Reeves,
Manchester Metropolitan University, UK G. Spyropoulos, University of Thessaly, Greece J. Gavin, A Ewen,
GS. King & T. Underdown, Liverpool John Moores University, UK M. Roys,
Building Research Establishment, Watford, UK

Acknowledgement:
The investigators are thankful to the OPRG member Mary Sinfield.

Design | Print | www.sheffield.ac.uk/cics/printanddesign | July 2014