Analysis of lower limb movement to determine the effect of manipulating the appearance of stairs to improve safety: a linked series of laboratory-based, repeated measures studies

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Scientific summary

Analysis of gait kinematics

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Background

Falls are very common in elderly people, with at least one-third of those over 65 years of age falling at least once a year, and half of those aged 80 + years falling at least once per year. They are a major cause of morbidity and mortality, with about one-quarter of falls leading to injury and falls being the leading cause of accidental death in elderly people. Falls on steps and stairs are particularly common in those with visual impairment, as vision plays a major part in successful gait over stairs, particularly on the first and last steps of a staircase.

Objectives

In this series of laboratory-based studies, we investigated whether or not modifications to the appearance of steps and stairs could help make them safer for older people to negotiate. Descending steps is particularly dangerous for elderly people, and we assessed the usefulness of a step edge highlighter in providing safer gait during stair descent. As it is not uncommon for 'edge' highlighters to be positioned away from the step edge, we also assessed the effect of the position of a step edge highlighter relative to the step edge.

A safety precaution that has been used when vision is impaired during stair ascent is to increase foot clearance to avoid tripping. In another series of experiments, we investigated the usefulness of several versions of the horizontal–vertical (H–V) illusion to make the perceived appearance of steps look taller so that participants might increase foot clearance of the step edge to provide safer stair negotiation.

Methods

A series of studies using a repeated measures, laboratory-based design, investigating gait control and safety in independently mobile older people. We determined gait parameters that are important for safe stepping in stair ascent and descent, measured using three-dimensional lower limb segmental kinematic data, particularly toe clearance during stair ascent and heel clearance during stair descent. We assessed the effect on these gait measures of a tread edge highlighter in a variety of offsets from the stair edge during step descent.

In experiment 1, 16 fit and healthy older participants [mean age 71 years, standard deviation (SD) 7 years] descended a three-step stairway under four conditions: (1) a plain surface; (2) with 5.5-cm-wide, high-contrast edge highlighters abutting the length of the step edges; (3) with 5.5-cm-wide, high-contrast edge highlighters set back 1 cm from the step edge (away1); or (4) with the edge highlighter set back 3 cm from the step edge (away3).

In experiment 2, eight young adults (mean age 24 years, SD 4 years) wearing a simulation of visual impairment due to cataract descended the three-step stairway under the same conditions as described above.

In experiment 3, 15 fit and healthy older participants (mean age 70 years, SD 7 years) descended from either a 16.5-cm raised surface (similar to a kerb) or a 19.5-cm raised surface (similar to stepping down from a bus or train) under the same four conditions of edge highlighter.

We also attempted to provide safer stair ascent using a H–V illusion on the step riser and tread to make the steps look taller and to make the participants lift their feet slightly higher than normal. The horizontal line(s) component of the illusion was placed on the step tread and the vertical lines component was placed on the step riser.

Experiment 4 included two psychophysical experiments in which an image of the three-step stairway was produced on a computer screen and several versions of the illusion were superimposed onto the image so as to assess the optimum parameters for the illusion affect. Seven participants, with a mean age of 37 years (SD 14 years), made judgements about the perceived height of the staircase steps, as the frequency of vertical black and white lines (this also altered their relative thickness) was varied on the step riser (4, 8, 12, 16 and 20 cycles of black and white stripes per step; the horizontal line was either a 5.5-cm-wide or an 11-cm-wide stripe abutting the tread edge). In a second psychophysical experiment, four participants (aged 24, 28, 52 and 55 years) made judgements about the perceived height of the staircase steps as the horizontal line width and position were varied (line absent; 5.5-cm-wide line abutting the edge; 11-cm-wide line abutting the edge or 5.5-cm-wide line placed 5.5 cm away from the step edge) and the vertical line component was standardised at 16 cycles per step.

In experiment 5, 11 fit and healthy older participants (mean age 70 years, SD 7 years) were asked to ascend a 16.5-cm raised surface similar to a kerb under five different conditions in which the appearance of the surface was varied to include a plain surface, a surface with a 5.5-cm edge highlighter on the tread edge or a surface with one of three versions of a H–V illusion (in all three cases this included a horizontal line consisting of a 5.5-cm edge highlighter on the tread edge; in addition, the step riser included vertical stripes of a periodicity of 4, 12 or 20 cycles per step).

In experiment 6, 14 fit and healthy older participants (mean age 69 years, SD 7 years) ascended a three-step stairway under four conditions: with just a step edge highlighter of 5.5-cm width along the tread edge of each step; or with an optimised H–V visual illusion (5.5-cm-wide, horizontal, high-contrast lines abutting the tread edge plus vertical lines of a periodicity of 12 cycles per step on the step riser) on (1) the bottom or first stairway step, (2) the top or last stairway step and (3) both the top and bottom stairway steps.

The main outcome measures were horizontal heel clearance during descent and vertical toe clearance during ascent (of the raised surface or stairway). Heel and toe clearances < 5 mm were also considered, as were heel scuffs and toe hits/catches.

Results

In experiment 1, there was a significant effect of highlighter condition on horizontal heel clearance ($p < 0.001$) over the initial step edge, with clearance values smaller for away3 than for plain, abutting or away1 (post hoc; all p-values < 0.002).

In experiment 2, there was a significant effect of highlighter condition on horizontal heel clearance over the initial step edge ($p = 0.002$), with clearance values being smaller for away3 compared with abutting (post hoc; p-value $= 0.001$). There was a significant effect of highlighter condition on horizontal heel clearance within-subject variability ($p = 0.003$), which was increased in the plain condition compared with abutting ($p = 0.022$), away1 ($p = 0.024$) or away3 ($p = 0.003$). Horizontal heel clearances were < 5 mm in 8% (plain), 10% (away3), 3% (away1) and 0% (abutting) of cases, and heel scuffs occurred in 15% (plain), 10% (away3), 5% (away1) and 2.5% (abutting) of cases.

In experiment 3, there was a significant effect of highlighter condition on horizontal heel clearance ($p < 0.001$), which was smaller for away3 than for plain ($p < 0.001$), abutting ($p < 0.001$) or away1 ($p < 0.001$).

In the psychophysical experiments (experiments 4a and 4b), all observers showed significant overestimations of the true height of the staircase step (19 cm) and, for all but one observer, the magnitude of this overestimation increased with spatial frequency (i.e. the H–V effect was greater as the periodic black and white gratings became thinner). Several of the observers were veridical in height judgement at the lowest spatial frequency (they judged the height of the step correctly when the black and white gratings were relatively thick), but overestimation of height increased rapidly with spatial frequency (as the gratings became more frequent and thinner). The magnitude of this illusory percept was substantial, with overestimations approaching 25% for some observers. The width of the nosing appeared to have little effect. The most significant overestimation of riser height (up to 20%) occurred for the abutting nosing condition, although the absence of a nosing or the presence of a gap between step edge and the nosing reduced (but did not eliminate) the illusion.

In experiment 5, vertical toe clearance was significantly increased by the H–V illusions ($p < 0.0001$). There was an increase in vertical toe clearance for each H–V illusion in comparison to plain and abutting (post hoc; $p < 0.0007$ and $p < 0.004$ respectively). There were no statistically significant differences between each H–V illusion, ($p > 0.05$), although between-subject variability was slightly reduced for the 12 cycles per step spatial frequency illusion (SD 1.9 cm) in comparison with the four cycles per step spatial frequency illusion (SD 2.5 cm) and the 20 cycles per step spatial frequency illusion (SD 2.4 cm).

In experiment 6, vertical toe clearances varied with the four different appearances of the staircase steps over the bottom ($p < 0.0001$) and top steps ($p < 0.0001$) but were the same for the middle step ($p = 0.71$). For the bottom step, vertical toe clearance was increased when the illusion was placed on the bottom step only ($p < 0.0001$) or on both the top and bottom step (p-value < 0.0001), but was similar to the plain control ($p = 0.063$) when on the top step only. For the top step, vertical toe clearance was increased when the illusion was placed on the top step only ($p < 0.0001$) or on both the top and bottom step ($p < 0.0001$), but was similar to the plain control ($p = 0.92$) when on the bottom step only.

Conclusions

We found that the position of the edge highlighter was important and that highlighters set 3 cm back, as is not uncommon when friction strips are used on stairways, increased the number of very low heel clearances (< 5 mm) and heel scuffs. We also found that with simulated visual impairment, adding a high-contrast, 5.5-cm highlighter along the tread edge reduced the number of very low heel clearances (< 5 mm) and heel scuffs. The results suggest that using a 5.5-cm, high-contrast, horizontal tread edge highlighter may be a useful modification to help avoid heel scuffs and falls during stair descent. The results also highlight the importance of the edge highlighter's location, which should be abutting or very close to the tread edge. Building recommendations suggest that a tread edge highlighter can be positioned 'near' to the tread edge. This seems too open to interpretation, and within 1 cm seems preferable.

Experiments 1–5 determined the optimum parameters for the H–V illusion used in experiment 6: a horizontal, 5.5-cm, high-contrast strip abutting the tread edge (used in stair descent as a tread edge highlighter) plus a series of vertical stripes of spatial frequency of 12 cycles per step. In experiment 6, these were added to the bottom and top step of a three-step stairway, as most falls on stairs occur on the first and last steps. The optimised illusion was found to increase vertical toe clearance significantly, without causing an increase in variability and/or a change in balance or stability when negotiating the stairway. The results also suggest that using this optimised H–V illusion superimposed onto steps/stair risers may be a useful modification on a raised walkway (e.g. kerbs) and/or the first and last steps of stairways to help avoid trips and falls during walkway/stair ascent.

Although the results of these studies are very encouraging, to determine whether or not the illusions actually prevent falls on stairs, an assessment of falls rate on stairways with and without the edge highlighter and the H–V illusion would need to be performed.

As falls are multifactorial and interventions therefore need to be multifactorial, other vision-related interventions should be considered:

1. Although it has been shown that providing distance single-vision spectacles to active long-term multifocal wearers for outdoor use reduces fall rate, compliance with this intervention was poor and a low addition multifocal lens could provide a useful option. This would probably provide much better vision for safe gait and stair negotiation, but still provide sufficiently good short-term reading when outdoors to improve compliance.
2. A randomised controlled trial (RCT) hypothesising that improved refractive correction would reduce falls surprisingly found the opposite result: large changes in refractive correction actually increased falls. It has been suggested that this was attributable to relatively large changes in refractive correction causing adaptation problems for older people. This study led to suggestions that clinicians should be conservative in their prescribing and only make relatively small changes in refractive correction. Work is needed to determine whether or not partial correction of large changes in refractive correction improve falls rates, and a RCT to assess such an approach seems the obvious next step.

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