

**The role of strategy selection, limb force capacity and limb positioning in  
successful trip recovery**

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2 **The role of strategy selection, limb force capacity and limb positioning in**

3 **successful trip recovery**

4

5 **Abstract**

6 *Background* Fall occurrence, mainly due to tripping, increases with age. There are two  
7 main strategies of trip recovery: elevating and lowering. Strategy selection depends on  
8 trip stimulus timing within the swing phase of walking, but the choice and ultimate  
9 success of a strategy selection may also depend on individual physical characteristics.

10 The aim of this study was to investigate: 1) recovery strategy choice by younger and  
11 older adults when perturbed in the ‘strategy overlap’ mid-swing phase, and 2) whether  
12 the interaction between recovery limb positioning and recovery limb force capacity  
13 determines recovery success in elevating strategy recoveries and accounts for strategy  
14 selection.

15 *Methods* A group of older (65-75 years) and a group of younger adults (20-35 years)  
16 completed a trip recovery protocol in a laboratory environment.

17 An inverted pendulum model was developed to investigate how walking speed,  
18 recovery limb positioning and recovery limb force interacted and influenced successful  
19 trip recovery when perturbed in different swing phases.

20 *Findings* Older adults always adopted a lowering strategy when perturbed in late mid-  
21 swing (60-80%), while younger adults also adopted elevating strategies. Simulations  
22 showed that, when perturbed later in swing, a larger recovery step and higher recovery  
23 limb force were required for successful recovery.

24 *Interpretation* We suggested that a combination of insufficient recovery limb strength,  
25 response time and movement speed make it difficult for older adults to achieve a large  
26 enough recovery step for a successful elevating strategy recovery when perturbed later  
27 in mid-swing.

28

29 **Keywords**

30 Balance; walking; lower limb; elderly; fall prevention

31

## 32 **1. Introduction**

33 Approximately one in three people aged over 65 fall at least once a year, mainly due to  
34 tripping (Tinetti et al. 1988). Most studies investigating biomechanical aspects of trip  
35 recovery have focussed on response time (Bogert van den et al. 2002; Ferber et al. 2002;  
36 Hsiao and Robinovitch 1999; Smeesters et al. 2001), lower limb strength (Pavol et al.  
37 2002; Pijnappels et al. 2008; Wojcik et al. 2001) and muscle activation (Burg van der  
38 et al. 2007; Pijnappels et al. 2005).

39 In early trip recovery (prior to recovery limb ground contact) the body's forward  
40 angular momentum will be reduced by the initial stance limb (Pijnappels et al. 2005),  
41 arm movement (Roos et al. 2008) and trunk stiffness (Burg van der et al. 2005), while  
42 in late trip recovery (during recovery limb ground contact) it is mainly reduced by the  
43 actions of the recovery limb and trunk stiffness. Pijnappels et al. (2005) demonstrated  
44 that younger adults were generally more capable than older adults to restrain the body's  
45 forward angular momentum using the initial support (trailing) limb prior to recovery  
46 limb contact. It is however unknown how recovery limb strength and positioning  
47 interact to influence recovery success.

48 The role of the recovery limb may depend on age and on the recovery strategy  
49 ('elevating' or 'lowering') employed (Eng et al. 1994). In an elevating strategy the  
50 obstructed limb is lifted over the obstacle and in a lowering strategy the obstructed limb  
51 is placed prior to the obstacle and the contralateral limb is lifted over the obstacle (Eng  
52 et al. 1994). Strategy selection depends on the timing of the trip stimulus within the  
53 swing phase of the walk (Schillings et al. 2000). Early swing perturbations result in  
54 elevating strategy recoveries (Schillings et al. 2000) as the centre of mass (CM) is

55 posterior to the centre of pressure (CP), leaving time to lift the obstructed limb over the  
56 obstacle. Late swing perturbations result in lowering strategy recoveries (Schillings et  
57 al. 2000) as the CM is already anterior to the CP and the swing foot is close to the  
58 ground; it is therefore easiest to immediately lower this foot to the ground and recover  
59 in subsequent steps. Around mid-swing there will be a ‘strategy overlap’ phase where  
60 strategy selection is mechanically not obvious.

61 Older adults more often adopt a lowering strategy recovery than younger adults (Pavol  
62 et al. 2001; Pijnappels et al. 2005), but it is not understood why. It could be that they  
63 are incapable of or unwilling to use an elevating strategy later in swing when this  
64 strategy may become more demanding.

65 Therefore, the aim of this study was to investigate: 1) the recovery strategies used by  
66 younger and older adults when perturbed in the ‘strategy overlap’ mid-swing phase and  
67 the success of these; and 2) whether the interaction between recovery limb positioning  
68 and recovery limb force capacity determines recovery success in elevating strategy  
69 recoveries and accounts for selection of strategy. Aim 1 was investigated using an  
70 experimental approach, while aim 2 was investigated using a simple modelling  
71 approach. The angular motion resulting from a trip can be simplified and modelled as  
72 pendular movement. Van den Bogert et al. (2002) demonstrated, with an inverted  
73 pendulum model, that reduced response time was more important for successful trip  
74 recovery than lower walking speed. Another inverted pendulum model, by Hsiao and  
75 Robinovitch (1999), showed that an interaction between step length, leg strength and  
76 step contact time determined the range of possible perturbations that could be recovered  
77 from in static lean-release experiments.

78 We hypothesised that the shift to using lowering instead of elevating strategy recoveries  
79 occurs earlier for older than for younger adults. Our second hypothesis was that

80 recovery limb positioning at ground contact influences the muscle force required for  
81 successful trip recovery and that appropriate recovery limb positioning becomes  
82 essential in situations close to the limits of successful recovery. Our final hypothesis  
83 was that a higher recovery limb force capacity (defined as the maximum force which  
84 can be developed in the limb) allows for recovery in more challenging trip situations,  
85 such as in response to later perturbations, larger perturbations and with non-optimal  
86 recovery limb placement.

87

## 88 **2. Methods**

### 89 **2.1 Trip recovery experiment**

90 **Protocol** The experimental methods were similar to those described previously (Roos  
91 et al. 2008). Briefly, following sample size calculations to allow detection of significant  
92 differences in kinematic measures (e.g. step length), female participants were recruited  
93 from the local community into a ‘younger’ group aged 20 to 35 years (n=8) and an  
94 ‘older’ group aged 65 to 75 years (n=7) via poster advertisements and personal contacts.  
95 To exclude gender effects only female participants were used. The local NHS (National  
96 Health Service UK) research ethics committee approved the experimental procedures  
97 (04/Q2001/169 and 05/Q2001/214) and written informed consent was obtained from  
98 all participants. Characteristics for the participants are described in Table 1. All  
99 participants were recreationally active and healthy, with no BMI (Body Mass Index)  
100 above 28, no use of medication that may cause dizziness, no history of repetitive falling  
101 and no fear of falling (assessed via the SAFFE questionnaire (Lachman et al. 1998)).  
102 Trips were induced in random walking trials, by a custom-built device, at varying time  
103 points of the swing phase. The participants were secured in a safety harness to prevent  
104 impact with the ground. Kinematic data were collected with a CODA CX1 system

105 (Charnwood Dynamics Ltd., United Kingdom) at 200 Hz.

106

107 **Data analysis** Kinematic data were processed as described in (Roos et al. 2008). The  
108 percentage of the swing phase at which trips were induced ( $\%_{\text{swing}}$ ) was expressed in  
109 relation to the average swing duration of all walking trials.  $\%_{\text{swing}}$  was calculated by  
110 dividing the swing time prior to the perturbation by this average swing duration.

111 To investigate recovery limb positioning, the recovery step length (RSL) was  
112 calculated. This was calculated as the anterior-posterior distance between the ankle  
113 coordinates of the obstructed foot at contact with the tripping device and the ankle  
114 coordinates of the recovery leg at contact with the force plate, expressed normalised to  
115 leg length.

116 Peak horizontal and vertical ground reaction forces (GRF) during ground contact of the  
117 recovery limb were calculated to give an indication of the maximum force in the  
118 recovery limb.

119 For statistical analyses, differences between groups were assessed using independent t-  
120 tests and relationships between mechanical variables were assessed with Pearson  
121 product-moment correlations. Statistical significance was accepted at the  $P \leq 0.05$  level.

122

## 123 **2.2 Trip recovery inverted pendulum simulation model**

124 **Model structure** To understand how recovery limb positioning and force capacity  
125 influence trip recovery success, a two-dimensional simulation model was developed  
126 and its outcomes were compared with experimental results. An inverted pendulum  
127 model with similarities to the model by Hsiao and Robinovitch (1999) was used, but it  
128 differed from the previous model in that it simulated trip recovery, not balance recovery  
129 from static lean-release, and thus it had an initial walking velocity.

130 The trip recovery model was developed in Simmechanics (Matlab 2007a, The  
 131 Mathworks). It consisted of a rigid segment (representing the upper body and initial  
 132 stance limb) with a body mass ( $m_{body}$ ) and height ( $h_{body}$ ). The body CM was placed  
 133 halfway along the length of the rigid segment. A rotational spring (stiffness  $K_{rot}$ ) at the  
 134 base of this segment simulated the reduction of the body's forward angular momentum  
 135 by the initial stance limb. A massless segment with a linear spring (stiffness  $K_{lin}$ ) was  
 136 attached to the body segment with a fixed hinge joint (hip) at leg length height (Figure  
 137 1). This spring simulated the reduction of the body's forward angular momentum by  
 138 the recovery limb during the first recovery step. A larger  $K_{lin}$  stiffness represented a  
 139 larger recovery limb force capacity (i.e. capable of generating a large force in the  
 140 recovery limb). Body positioning was defined by the body inclination angle ( $\theta$ ) and the  
 141 angle of the swing limb relative to the body ( $\alpha$ ) (Figure 1).

142 The impulse from the trip force was ignored as it was relatively small in the trip  
 143 recovery experiments (it did not exceed 43 N). Based on the assumptions of inverted  
 144 pendulum motion, it was assumed that at a trip the linear momentum of walking would  
 145 be directly translated into angular momentum. The initial angular velocity of the body  
 146 CM ( $\omega_0$ ) was therefore directly calculated from the walking speed ( $v_{walk}$ ):

147 *Equation 1*     
$$\omega_0 = \frac{360 * v_{walk}}{\pi * h_{body}}$$

148 The model consisted of a pre-contact and a contact phase sub-routine. The pre-contact  
 149 routine (which simulated the action of the initial stance limb) ended when the recovery  
 150 limb contacted the ground or if successful recovery was achieved through the initial  
 151 stance limb alone. The contact sub-routine was initiated with the end-points of the pre-  
 152 contact routine. The stop conditions for the contact routine were if either successful  
 153 recovery or a fall occurred. Successful recovery was achieved when the angular



154 momentum was reversed ( $\omega < 0^\circ/\text{s}$ ) and a fall occurred when  $\theta > 90^\circ$ . The exact critical  $\theta$   
155 value for when a fall would occur did not need to be defined as when this angle was  
156 exceeded the body would continue to fall and rotate forward to eventually exceed  $90^\circ$ .

157 The natural length of the linear spring ( $L_{\text{leg\_contact}}$ ) was assumed to be shorter than the  
158 leg length since the recovery limb is not fully extended at ground contact. It was set to  
159 0.98 times the leg length (agreeing with the average knee angle at recovery limb contact  
160 for elevating strategy experimental trials:  $159^\circ \pm 11^\circ$ ).

161 Outcome variables were values indicating whether successful recovery was possible  
162 and the maximum force at the linear spring during the contact phase ( $F_{\text{max}}$ ).  $F_{\text{max}}$  was  
163 calculated by multiplying the recovery limb displacement by its stiffness  $K_{\text{lin}}$  and  
164 storing its maximum value.

165

166 **Parameter estimation** The parameters  $K_{\text{lin}}$  and  $K_{\text{rot}}$  were estimated with the ‘response  
167 optimization’ toolbox of Simulink.  $K_{\text{rot}}$  was estimated within the pre-contact routine  
168 and  $K_{\text{lin}}$  within the contact routine, both matching experimental data for  $\theta$  and  $\omega$  as  
169 closely as possible. The experimental body inclination angle was calculated,  
170 throughout trials, as the angle of the line through the ankle and CM with a line  
171 perpendicular to the ground. These experimental data were obtained from elevating  
172 strategy trials without a flight phase for which a full body marker data set was available  
173 (five trials in total).

174

175 **Simulations** A Matlab routine linking the sub-routines was used to run multiple  
176 simulations varying  $\%_{\text{swing}}$  and  $v_{\text{walk}}$ . The dimensions of the inverted pendulum model  
177 were  $h_{\text{body}} = 1.70$  m,  $m_{\text{body}} = 61.0$  kg, leg length = 0.88 m. These were average values  
178 of the subjects whose trials were used in the parameter estimation. The average

179 estimated value for  $K_{rot}$  was used (1850 Nm/rad).  $K_{lin}$  was varied between 5000 N/m  
180 and 25000 N/m, as estimated values from experimental data were between 4966 N/m  
181 and 30559 N/m. To represent trips from early to late swing,  $\%_{swing}$  was varied between  
182 30% (where  $\theta_0 = -8^\circ$ ) and 90% (where  $\theta_0 = 16^\circ$ ).  $\alpha$  was varied between 0 and  $90^\circ$ .  $v_{walk}$   
183 was varied between 0.25 and 1.5 m/s. The range of initial values for  $\alpha$  and  $v_{walk}$  were  
184 larger than those of the experimental values to achieve a wider range of trip perturbation  
185 and recovery scenarios in the simulations.

186

187 **Sensitivity analysis** A sensitivity analysis was conducted to investigate whether the  
188 maximum force ( $F_{max}$ ) required to recover successfully was more sensitive to variations  
189 in  $\alpha$  or to variations in  $v_{walk}$ .  $\alpha$  and  $v_{walk}$  were varied one standard deviation ( $9^\circ$  and  
190 0.2 m/s) from a mid-range value ( $\alpha = 35^\circ$  and  $v_{walk} = 0.75$  m/s) and their  $F_{max}$  values  
191 were compared to that for the mid-range value.  $\alpha$  was increased by one standard  
192 deviation from the mid-range value as this would increase the moment arm to reverse  
193 the body angular momentum and therefore reduce the required recovery effort.  $v_{walk}$   
194 was decreased by one standard deviation from the mid-range value as a slower walking  
195 speed would result in a smaller body angular momentum after the trip perturbation and  
196 would therefore also reduce the required recovery effort.

197

### 198 **3. Results**

#### 199 **3.1 Experimental results**

200 The percentage of swing at which the trip perturbation occurred ( $\%_{swing}$ ) was calculated  
201 for 61 trip trials for the younger adults (with 59% elevating strategies) and for 89 trials  
202 for the older adults (with 20% elevating strategies). Perturbations occurred at random  
203 percentages of swing and the average percentage of swing at which trips occurred was

204 not significantly different between younger and older adults (57% (SD 19%) and 71%  
205 (SD 23%) respectively) although a tendency for older adults to receive perturbations  
206 later in the swing phase was observed.

207 Both younger and older adults always used an elevating strategy when perturbed in  
208 early swing (<40%), always a lowering strategy when perturbed in late swing (>80%),  
209 and elevating as well as lowering strategies when perturbed in early mid-swing (40-  
210 60%) (Figure 2). Responses to perturbations in late mid-swing (60-80%) differed  
211 between younger and older adults; older adults always adopted a lowering strategy,  
212 while younger adults also adopted elevating strategies (Figure 2).

213 Trials in which a fall occurred (>30% of body weight supported by the safety harness,  
214 n = 11, 4 from older group, 7 from younger group) were analysed purely to describe the  
215 %<sub>swing</sub> of the perturbation. None of the falls occurred in response to early swing  
216 perturbations, one in response to an early mid-swing perturbation, seven in response to  
217 late mid-swing perturbations and three in response to late swing perturbations.

218 Older adults showed a significantly ( $p < 0.01$ ) smaller recovery step length (RSL) than  
219 younger adults during elevating strategies (0.61 and 0.81 LL respectively, table 2).

220 Younger adults showed a positive correlation ( $r = 0.727$ ,  $p < 0.001$ ) between RSL and  
221 %<sub>swing</sub> during elevating strategy recoveries, meaning they took larger recovery steps  
222 when perturbed later in swing. This correlation was not present in the older adults ( $r =$   
223  $0.040$ ,  $p = 0.887$ ). Maximum horizontal and vertical GRF were not correlated with  
224 walking speed or RSL for elevating strategy recoveries of younger and older adults.

225

### 226 **3.2 Simulation results**

227 Simulation results for variations in  $\alpha$  and  $v_{\text{walk}}$  are shown in surface plots (Figure 3). An  
228 increased  $v_{\text{walk}}$  resulted in unsuccessful recovery for small  $\alpha$  values. For the medium  $\alpha$

229 values, where successful recovery was possible, an increased  $v_{\text{walk}}$  resulted in an  
230 increased  $F_{\text{max}}$  required for successful recovery. For large  $\alpha$  values, successful recovery  
231 was possible before the recovery limb contacted the ground ( $F_{\text{max}} = 0$  N). As the  
232 recovery limb was placed more forward there was more time available in the pre-  
233 contact phase to reduce the forward angular momentum of the body. An increased  
234 recovery limb force capacity ( $K_{\text{lin}}$ ) allowed successful recoveries for progressively  
235 smaller  $\alpha$  values.

236 When perturbed later in swing a higher  $F_{\text{max}}$  was required to recover successfully.  
237 Perturbations in mid-swing (50%) resulted in successful recoveries for small  $\alpha$  values  
238 combined with small  $v_{\text{walk}}$  values, while later in swing (70% and 90%) these resulted in  
239 unsuccessful recoveries. When a perturbation occurred at 70% of swing, the maximum  
240 force required to recover successfully ( $F_{\text{max}}$ ) was more sensitive to an increase of the  
241 recovery step length ( $\alpha$ ) than to a decrease of the walking speed ( $v_{\text{walk}}$ ) for all recovery  
242 limb force capacity values ( $K_{\text{lin}}$ ) (Table 3). Later in swing ( $\%_{\text{swing}} = 90\%$ )  $F_{\text{max}}$  was also  
243 more sensitive to an increase of recovery step length ( $\alpha$ ) than to a decrease of the  
244 walking speed ( $v_{\text{walk}}$ ) for a recovery limb force capacity value ( $K_{\text{lin}}$ ) of 5000 N/m.  
245 However for the higher recovery limb force capacity values ( $K_{\text{lin}} = 15000$  and 25000  
246 N/m)  $F_{\text{max}}$  was more sensitive to a decrease in walking speed ( $v_{\text{walk}}$ ) than to an increase  
247 in recovery step length ( $\alpha$ ).

248

#### 249 **4. Discussion**

250 This study sought to determine whether trip recovery strategy selection differed  
251 between younger and older adults, particularly in the mid-swing phase, and to establish  
252 the interaction between recovery limb positioning and recovery limb force capacity in  
253 determining recovery success. We found that older adults made the transition to

254 lowering strategies earlier in the swing phase, and that recovery success following late  
255 swing perturbations was influenced by the ability to position the recovery limb and the  
256 maximum force capability of the limb.

257

258 Older participants less often adopted an elevating strategy than younger participants  
259 (20% vs. 59% of trials), in agreement with previous studies (Pavol et al. 2001;  
260 Pijnappels et al. 2005), which may have been partly due to the fact that the older adults  
261 received more trips later in swing (Figure 2) and had a slightly reduced walking speed  
262 prior to trip (1.11 LL/s for older adults versus 1.22 LL/s for younger adults). However,  
263 irrespective of differences in walking speed which should make both types of recovery  
264 strategy easier due to less forward angular momentum, our findings show that different  
265 strategies were employed in late mid-swing (60-80%), where younger adults adopted  
266 either an elevating or a lowering strategy, while older adults adopted a lowering strategy  
267 recovery only (except for one instance) (Figure 2). This confirms our first hypothesis  
268 that the shift from adopting a lowering strategy instead of an elevating strategy recovery  
269 is made earlier for older (% swing  $\approx$  60%) than for younger adults (% swing  $\approx$  80%). We  
270 also found that most falls occurred in responses to perturbations in late-mid or late  
271 swing, although the number of falls induced was too few to confirm this speculation.  
272 Our experiments were designed to cause tripping and not falling, so we can therefore  
273 only show a possible tendency for more falls to occur when perturbed later in swing,  
274 and future research will have to show whether this tendency is significant. Nevertheless,  
275 based on these findings, we suggest the late mid-swing phase to be a more challenging  
276 phase for older adults, as they did not use an elevating strategy recovery in this phase,  
277 which we propose to be a more effective strategy for full recovery in initial steps  
278 following a perturbation.

279

280 The proposition that an elevating strategy would be more effective but more difficult  
281 than a lowering strategy recovery when individuals are perturbed later in swing is based  
282 largely on the tenet that for an elevating strategy: (1) there is more time available to  
283 counteract the forward angular momentum by the initial stance limb, as described by  
284 (Pijnappels et al. 2004), and (2) the recovery limb is lifted over the obstacle and placed  
285 more anterior relative to the body CM, providing a larger moment arm to reduce the  
286 body's forward angular momentum (Pijnappels et al. 2004). It will however become  
287 more difficult to elevate the swing limb over the obstacle when perturbed later in swing,  
288 as the body CM moves more anterior relative to the CP. Our simulations confirmed that  
289 an elevating strategy recovery becomes more difficult later in swing, as larger forces  
290 were required in the recovery limb and successful recovery was not always possible  
291 with smaller recovery steps. The experimental data of the younger adults also showed  
292 a larger recovery step size when perturbed later in swing, as RSL was positively  
293 correlated with %<sub>swing</sub>; this relationship was not evident in the older adults group. When  
294 perturbed later in swing, the swing leg is already placed more forward relative to the  
295 CM, there is however less time available for optimal recovery limb placement. A larger  
296 step would provide a larger moment arm to reduce the angular momentum due to a trip.  
297 We therefore expect that the larger recovery steps younger adults took when perturbed  
298 later in swing would be beneficial to them to continue using an elevating strategy but  
299 would require increased movement speed.

300

301 During elevating strategy recoveries, older adults took smaller recovery steps (mean  
302 RSL = 0.61 LL) than younger adults (mean RSL = 0.81 LL). The simulations showed  
303 that a smaller  $\alpha$  (corresponding to a smaller recovery step) required a larger  $F_{\max}$  to

304 successfully recover from a trip, and successful recovery was not possible for the very  
305 small  $\alpha$  values (Figure 3). This supports our suggestion that a larger recovery step later  
306 in swing by younger adults is beneficial to them to continue using an elevating strategy  
307 when perturbed later in swing, as larger recovery steps require a smaller  $F_{\max}$ . This  
308 suggests that it is a combination of recovery limb force capacity and recovery limb  
309 placement (influenced by reduction of the body forward angular momentum by the  
310 initial stance limb, response time and recovery limb movement velocity) that limit  
311 successful recovery in older adults. It confirms the second hypothesis that recovery  
312 limb positioning influences the force required to recover from a trip and that appropriate  
313 recovery limb positioning is essential for successful recovery in situations close to the  
314 limits of recovery. This agrees with simulations by Hsiao and Robinovitch (1999) which  
315 showed recovery success from lean-release to be dependent on a coupling between step  
316 length, step execution time and leg strength.

317

318 To confirm the third hypothesis, the simulation results showed that a larger recovery  
319 limb force capacity ( $K_{\text{lin}}$ ) allowed successful recovery in more challenging situations,  
320 in response to later perturbations, larger perturbations (increased walking speed) and  
321 recoveries using smaller  $\alpha$  values (Figure 3). Within the model, for perturbations in late  
322 mid-swing with a recovery limb force capacity ( $K_{\text{lin}}$ ) of 5000 N/m, the maximum force  
323 in the recovery limb required to recover successfully from a trip ( $F_{\max}$ ) was more  
324 sensitive to variations in recovery step length ( $\alpha$ ) than to variations in walking speed  
325 ( $v_{\text{walk}}$ ) (Figure 3 and Table 3). As recovery step length is influenced by response time,  
326 these results agree with findings by van den Bogert et al. (2002) that response time was  
327 more important for successful lowering strategy recoveries than walking speed.  
328 However, we found that for perturbations in late mid-swing in simulations with higher

329 force capacity ( $K_{lin} = 15000$  and  $25000$  N/m), the maximum force in the recovery limb  
330 required to recover successfully from a trip ( $F_{max}$ ) was not as sensitive to variations in  
331 recovery step length ( $\alpha$ ) and became more sensitive to variations in  $v_{walk}$  (Figure 3 and  
332 Table 3). Recovery success is often limited in older adults, as they generally have a  
333 smaller recovery limb force capacity (and therefore cannot generate as high values of  
334  $F_{max}$ ) and a reduced recovery limb movement speed (and therefore cannot achieve the  
335 highest  $\alpha$  values). Our simulations imply that older adults would benefit most from a  
336 faster response time and increased limb movement speed in order to achieve a  
337 sufficiently large recovery step length. When perturbed later in swing, an increased step  
338 length does not substantially improve recovery success of elevating strategy recoveries  
339 and lowering strategy recoveries would be more beneficial. On the other hand, younger  
340 adults who are inherently stronger may be more influenced by walking speed than  
341 response time with regards to their trip recovery success.

342

343 The experimental data of the younger adults agreed better with the simulation outcomes  
344 than those of the older adults. This was mainly due to the fact that the experimental  
345 parameters of the older adults showed no correlation with  $\%_{swing}$ , which was most likely  
346 due to older adults not adopting elevating strategy recoveries in response to  
347 perturbations in late mid-swing. Also the range of recovery step length (younger: 0.48  
348 to 1.12 LL versus older: 0.42 to 0.80 LL) and maximum vertical GRF (younger: 947 to  
349 2326 N versus older: 768 to 1422 N) was greater in younger than in older adults. This  
350 supports the suggestion that older adults were limited in recovery limb force and  
351 movement speed and response time to create a larger recovery step and could therefore  
352 not adopt an elevating strategy recovery when perturbed later in swing.

353



354 When interpreting the simulation modelling outcomes it has to be kept in mind that the  
355 model is a simplification of reality. The simulations predict only trends of trip recovery  
356 behaviour. The benefit of using a simulation modelling approach was that it allowed  
357 investigating a wide range of trip perturbations and recovery scenarios. To investigate  
358 specific physical requirements for successful trip recovery on an individual basis a more  
359 sophisticated simulation model of trip recovery would be required, and this is part of  
360 our ongoing work.

361

## 362 **5. Conclusions**

363 Older adults were unable or unwilling to use an elevating strategy when perturbed  
364 during late mid-swing (60-80%), while younger adults adopted either an elevating or a  
365 lowering strategy. Simulations with an inverted pendulum model, supported by  
366 experimental data, showed that a combination of recovery limb positioning and  
367 recovery limb strength limited the use of an elevating strategy in this late mid-swing  
368 phase in older adults. We suggested this phase may be more challenging for older adults  
369 than for younger adults. Some studies have shown that slip and trip recovery responses  
370 may be improved by training (Bieryla et al. 2007; Pavol et al. 2004). The results of this  
371 study suggest that trip training should focus on both speed and strength aspects and  
372 practice responses to perturbations in this challenging late mid-swing phase.

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## Captions to illustrations

### figure 1

Structure of the inverted pendulum trip recovery model, with  $\theta$  the body angle relative to the vertical,  $\alpha$  the angle of the recovery limb relative to the body,  $K_{rot}$  the rotational spring stiffness, and  $K_{lin}$  the linear spring stiffness.

### figure 2

The use of elevating and lowering strategy recoveries by younger (Y) and older (O) adults in response to perturbations in certain phases of swing of a walk (%<sub>swing</sub>).

### figure 3

$F_{max}$  surface plots from simulations with the trip recovery pendulum model, with the recovery limb angle ( $\alpha$ ) on the horizontal axis,  $v_{walk}$  on the vertical axis and  $F_{max}$  on the surface. White areas on the surface plots indicate where trip recovery was unsuccessful (a fall resulted).  $F_{max}$  was 0 N when successful recovery was achieved within the pre-contact sub-routine prior to recovery limb ground contact.  $K_{lin}$  increases from the top to the bottom row, where figures a-c are for a  $K_{lin}$  of 5000 N/m, figures d-f for a  $K_{lin}$  of 15000 N/m and figures g-i for a  $K_{lin}$  of 25000 N/m. The time of perturbation (%<sub>swing</sub>) increases from the left to the right column, where figures a, d and g represent perturbations at 30% of swing, b, e and h represent perturbations at 70% of swing and c, f and i represent perturbations at 90% of swing. The red crosses are at  $\alpha=35^\circ$  and  $v_{walk}=0.75$  m/s with red arrows indicating an increased  $\alpha$  by one standard deviation (A, C, E, G, K and M) and a decreased  $v_{walk}$  by one standard deviation (B, D, F, H, L and N).

**Table 1**

Characteristics of the younger and the older participant group with mean values and standard deviations.

	Age (years)	Body mass (kg)	Height (m)	Lower limb length (m)
Younger	26.1 (3.5)	63.2 (8.4)	1.67 (0.04)	0.89 (8.4)
Older	70.0 (2.5)	64.2 (4.8)	1.66 (0.06)	0.87 (0.02)

**Table 2**

Mean recovery step lengths (RSL) for elevating and lowering strategies of younger and older adults with standard deviations. Significant differences to younger subjects ( $p < 0.001$ ) are indicated with \*. No significant differences were found in RSL between elevating and lowering strategies.

		RSL (LL)
Younger	Elevating	0.81 (0.23)
	Lowering	0.82 (0.24)
Older	Elevating	0.61 (0.11)*
	Lowering	0.67 (0.27)*

**Table 3**

The sensitivity of  $F_{\max}$  (the maximum force in the recovery limb required to recover successfully from a trip) to changes in  $\alpha$  and  $v_{\text{walk}}$ .  $F_{\max}$  was 0 N when successful recovery was achieved before the recovery limb contacted the ground. The letters and numbers in brackets after the  $F_{\max}$  values correspond to the letters and numbers of the data points in figure 3.

% swing	$K_{\text{lin}}$ (N/m)	$F_{\max}$ (N)		
		mid-range value	$\alpha + 9^\circ$	$v_{\text{walk}} - 0.2$ m/s
70%	5000	1234 (1)	0 (A)	1176 (B)
	15000	1260 (2)	0 (C)	1141 (D)
	25000	1413 (3)	0 (E)	1253 (F)
90%	5000	1393 (4)	1235 (G)	1345 (H)
	15000	1554 (5)	1531 (I)	1469 (J)
	25000	1799 (6)	1802 (K)	1688 (L)

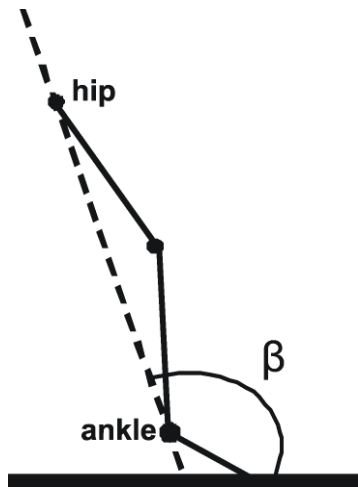


Figure 1

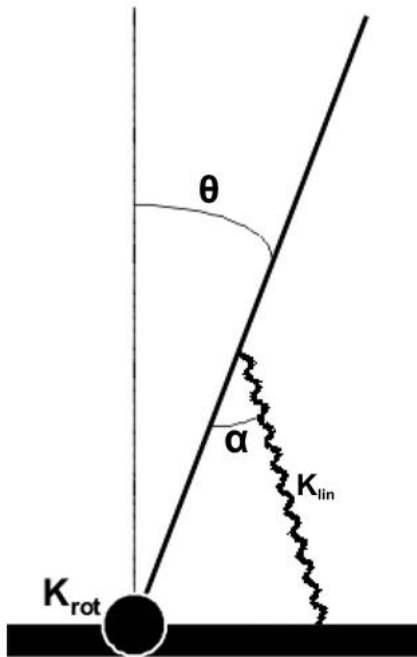


Figure 2



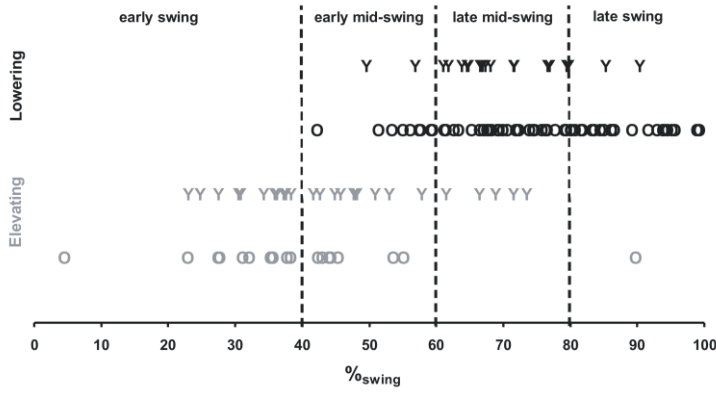


Figure 3

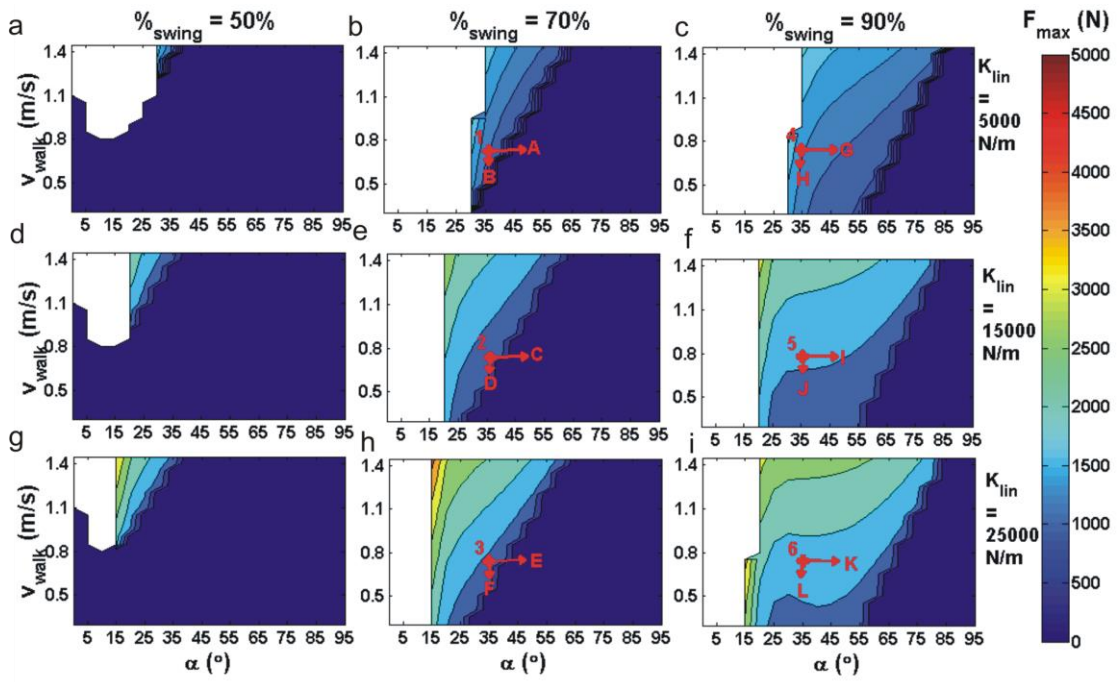


Figure 4