1 Exposure to unpredictable trips and slips while walking can improve balance
2 recovery responses with minimum predictive gait alterations
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18 **Abstract**

19 INTRODUCTION: This study aimed to determine if repeated exposure to unpredictable trips
20 and slips while walking can improve balance recovery responses when predictive gait
21 alterations (e.g. slowing down) are minimised.

22 METHODS: Ten young adults walked on a 10-m walkway that induced slips and trips in fixed
23 and random locations. Participants were exposed to a total of 12 slips, 12 trips and 6 non-
24 perturbed walks in three conditions: 1) right leg fixed location, 2) left leg fixed location and 3)
25 random leg and location. Kinematics during non-perturbed walks and previous and recovery
26 steps were analysed.

27 RESULTS: Throughout the three conditions, participants walked with similar gait speed, step
28 length and cadence($p>0.05$). Participants' extrapolated centre of mass (XCoM) was anteriorly
29 shifted immediately before slips at the fixed location ($p<0.01$), but this predictive gait alteration
30 did not transfer to random perturbation locations. Improved balance recovery from trips in the
31 random location was indicated by increased margin of stability and step length during recovery
32 steps ($p<0.05$). Changes in balance recovery from slips in the random location was shown by
33 reduced backward XCoM displacement and reduced slip speed during recovery steps ($p<0.05$).

34 CONCLUSIONS: Even in the absence of most predictive gait alterations, balance recovery
35 responses to trips and slips were improved through exposure to repeated unpredictable
36 perturbations. A common predictive gait alteration to lean forward immediately before a slip
37 was not useful when the perturbation location was unpredictable. Training balance recovery
38 with unpredictable perturbations may be beneficial to fall avoidance in everyday life.

39

40 Introduction

41 Falls in older people are a major cause of fractures, physical dependency, mortality and
 42 economic burden [1]. Perturbation training is an emerging paradigm that utilizes repeated
 43 exposure to sudden external perturbations, aimed at inducing locomotor adaptations and training
 44 balance recovery responses specifically required for fall avoidance [2, 3]. Theoretically,
 45 exposure to postural perturbations in a safe environment enables training of balance recovery
 46 responses that are critical for avoiding falls due to unexpected slips and trips in everyday life.

47 There is good evidence that both young and older adults can adapt their gait and
 48 improve their balance responses in response to repeated perturbations and substantially reduce
 49 falls in the laboratory within a few trials . However, if not regulated, participants tend to shorten
 50 their steps and shift their centre of mass [CoM]) to minimize the disturbing effects of the known
 51 upcoming perturbations [5, 11]. Although it has been reported that these predictive gait
 52 alterations are transferable across different conditions [11-13], many studies have used repeated
 53 perturbations at a consistent location which could make later trials highly predictable. Moreover,
 54 many studies used a single perturbation type (e.g. slips only) which could result in an over-
 55 adaptation and increased vulnerability to opposing perturbation types (e.g. trips). Therefore, it is
 56 questionable if such a gait strategy against predictable perturbations acquired in a laboratory
 57 setting is useful for situations where perturbations occur unexpectedly as in everyday life.

58 Moreover, although many studies have reported significant improvements in reactive
 59 balance control following repeated perturbations [5-7, 9, 14-16], a recent systematic review
 60 found that 80% of the included studies did not control for the effect of predictive gait alterations
 61 (e.g. including sufficient washout walks) [4]. Anticipation of upcoming perturbations and
 62 related changes in the approach walk (slower gait speed, shorter step lengths and anticipatory
 63 postural adjustments) can diminish the perturbation magnitude and therefore possibly

64 overestimate the improvements in reactive balance control reported [4]. Thus, the evaluation of
 65 balance recovery responses during walking has proved to be a significant challenge because
 66 unpredictability and magnitude of postural perturbations are difficult to maintain over repeated
 67 trials

68 To address the above issues, we developed a 10m perturbation walkway that can
 69 generate both trips and slips (i.e. opposing type perturbations) in varied locations while
 70 regulating step length, cadence and gait speed. This system, therefore, minimises predictive gait
 71 alterations during repeated perturbations, maintaining a greater level of unpredictability, as is in
 72 real life. The primary objective of this study was to test the hypothesis: Exposure to
 73 unpredictable perturbations can improve balance recovery responses in the absence of predictive
 74 gait alterations. In addition, to evaluate the importance of minimizing predictive gait alterations,
 75 we also tested following secondary hypothesis: Predictive gait alterations (e.g. shift of CoM)
 76 acquired through exposure to perturbations at a fixed condition would not transfer to conditions
 77 where both the type and location of perturbation were randomly presented and highly
 78 unpredictable. Findings from this study may contribute significantly to the design of effective
 79 exercise interventions using perturbations for fall prevention.

80

81 **Methods**

82 **Participants**

83 Eleven healthy adults aged 20-40 years provided written informed consent prior to
 84 participating in this study. Inclusion criteria were: aged between 20-40 years, living
 85 independently, and able to stand or walk for 20 minutes unassisted. Exclusion criteria were
 86 diagnosis of osteoporosis or neurological impairment that restrict activities of daily living (none

was excluded). The study protocol was approved by the University of New South Wales Human Research Ethics Committee (HC16227).

Apparatus

The trip and slip perturbation system was built into a 10m walkway consisting of wooden decking with stepping tiles atop (Fig 1). A slip was induced by a movable tile on two hidden low-friction rails with linear bearings that could slide forward up to 70cm upon foot contact. The slipping tile was locked or unlocked as appropriate using a concealed wedge. A trip was induced using a 14cm height tripping board that could spring up from the walkway. The trip board comprised two wooden walkway boards (14cm combined height) – a trip height consistent with previous studies that used 11cm to 15cm high obstacles [16-19]. A trained tester triggered the tripping board with a wireless controller at mid-swing of the gait cycle [17]. The tripping board and slipping tile were not visually detectable and could be moved to any location along the walkway. The participants faced away from the walkway before each trial so that the positioning of the hazards could not be seen.

Fig 1. The trip and slip perturbation system used for this study. A slip was induced by a movable tile on two hidden low-friction rails with linear bearings that could be unlocked to slide up to 70cm upon foot contact. A trip was induced using a 14cm height tripping board that could be triggered to spring up from the walkway. The tripping board and slipping tile were not visually detectable and could be moved to any location along the walkway. Black and white vinyl stepping tiles were placed on the walkway to reproduce individual's step length and a metronome was set to the individual's cadence.

111

112 **Experimental protocol**

113 Initially, participants walked at usual pace for 3 lengths of a 5.7m (active area: 4.8m)
114 electronic walkway (GAITRite ® mat, v4.0, 2010 CIR Systems, USA) to calculate average step
115 length and cadence. A one-meter approach was provided so that participants were walking at
116 their normal pace when on the walkway. Participants were also instructed to continue walking
117 for one meter beyond the walkway to ensure that the walking pace was kept consistent
118 throughout the task. Using this information, black and white vinyl stepping tiles were placed on
119 the perturbation walkway to regulate each individual’s usual step length and a metronome was
120 set to regulate their usual cadence (Fig 1).

121 Participants were secured with a ceiling-mounted full body harness to avoid contact
122 with the ground if they fell following a perturbation. All participants were exposed to slips and
123 trips in 3 sessions of different conditions (Table 1). In each session, 4 slips, 4 trips and 2 non-
124 perturbed walk (catch) trials were administered. To minimize predictive gait alterations, slips
125 and trips were mixed in each condition. In condition 1, the hazards were placed on the right side
126 of the walkway at a fixed middle location. In condition 2 the hazards were placed on the left
127 side of the walkway at a fixed middle location. In condition 3, the hazards were placed either on
128 the right or left side of the walkway and at variable locations (near, middle or far) (pseudo
129 random order and locations). For all conditions (including when a condition changed),
130 participants were instructed that they “may experience a hazard when walking on this walkway”
131 but not told how, when and where a slip or a trip would occur. They were further instructed to
132 “walk normally in time with the metronome stepping on middle of the black and white tiles”.

133

134 **Table 1. The study protocol.**

<p><i>Condition 1: Right leg / fixed location (4 slips and 4 trips)</i></p> <p>F1, <u>N1</u>, <u>S1_m</u>, <u>T1_m</u>, F2, <u>N2</u>, S2_m, T2_m, S3_m, T3_m, <u>S4_m</u>, <u>T4_m</u></p>
<p><i>Condition 2: Left leg / fixed location (4 slips and 4 trips)</i></p> <p><u>S5_m</u>, <u>T5_m</u>, <u>N3</u>, S6_m, T6_m, S7_m, <u>N4</u>, T7_m, <u>S8_m</u>, <u>T8_m</u></p>
<p><i>Condition 3: Random leg / random location (4 slips and 4 trips)</i></p> <p><u>S9_{f/R}</u>, <u>T9_{n/R}</u>, T10_{f/R}, <u>N5</u>, S10_{m/L}, S11_{n/R}, <u>N6</u>, T11_{m/L}, <u>S12_{f/R}</u>, <u>T12_{n/R}</u></p>

135 F: free walk (no regulation), N: non-perturbed walk (regulated to usual gait pace), L: left leg, R:
136 right leg, S: slip, T: trip. Locations of the hazards on the walkway (n: near, m: middle, f: far).
137 Gait speed (step length and cadence) was regulated using stepping tiles and metronome adjusted
138 to the participant's usual gait. All participants underwent the same protocol. The bolded letters
139 signify the trials used to in statistical analyses. The purpose and analyses of the F1 and F2 are
140 described in S2 Appendix.

141

142

143 **Measurements**

144 An 8-camera Vicon Bonita motion capture system (Vicon Motion Systems Ltd., Oxford,
145 UK) sampling at 100 Hz was used to collect kinematic data. Thirty four 14-mm diameter
146 reflective markers were attached to the head, trunk, upper and lower limbs according to the
147 Vicon Plug-in-Gait model marker set with a single sacral marker [20]. To avoid loss of
148 important information in for the study purpose (i.e. smoothing out the spikes due to sudden trips
149 and slips), we did not filter the kinematic data. Instead, the quality of the kinematic data and

150 absence of noise in both individual markers and model outputs have been visually confirmed
151 prior to commencement of statistical analyses. Centre of mass (CoM) position was calculated
152 using the Vicon Nexus 1.8.3 full body Plug-in-Gait model. The kinematic variables were
153 calculated from the 3D marker trajectories using custom software developed in MATLAB
154 R2010a (The MathWorks, Inc., Massachusetts, USA).

155

156 **Falls and kinematic parameters**

157 A fall was defined by a harness supported load >30% of a participant's body weight
158 [21]. To examine predictive gait alteration and balance recovery response, the following
159 kinematic parameters were calculated during the step before and after perturbation-onset. As a
160 primary outcome, margin of stability (MoS), a measure of dynamic stability [22], was
161 calculated at step touchdown. The MoS is the anterior-posterior distance (cm) between the
162 closest edge of the base of support (BoS) and the velocity- corrected (extrapolated) sagittal
163 plane centre of mass (XCoM) position . XCoM was calculated as the position of (the vertical
164 projection of) the CoM plus its velocity times a factor $\sqrt{l/g}$ (l = leg length and g = acceleration
165 of gravity) on the basis of a simple inverted pendulum model [22]. The post-perturbation step
166 MoS was the primary outcome to examine improved balance recovery response. To quantify the
167 magnitude of the balance perturbation caused by the trip/slip, XCoM displacement (cm), the
168 distance between XCoM and the ankle joint of the supporting limb was calculated at the frame
169 prior to touchdown of the leading foot. Step length (cm) relative to the previous step was
170 calculated from foot markers. The XCoM displacement and step length which determine the
171 MoS (i.e. the CoM and BoS states) were two secondary outcomes. In addition, average slip
172 speed (cm/s) was calculated as balance recovery response from slips. The slip initiation (foot
173 strike to the slipping tile) and the slip end (foot lift off from the slipping tile) were visually

determined in the Vicon 3D workspace. As measures of predictive gait alterations (i.e. after-effect), during no-perturbation trials, gait speed (m/s), cadence (step/min), step length (cm), toe height (cm) at mid-swing and foot-contact angle relative to the ground (deg) were also calculated and averaged across 4 steps.

Strategies for balance recovery

Recovery strategies from a trip were classified as (1) lowering strategy: the obstructed limb was quickly lowered to the ground before the obstacle, (2) elevating-contact strategy: the obstructed limb cleared the obstacle after obstacle-contact, and (3) elevating-cross strategy: the foot crossed over the obstacle without contact [23, 24]. Strategies for recovery from a slip were classified as (1) backward and (2) forward stepping when the first recovery foot landed posterior or anterior to the slipping foot, respectively [5, 9].

Statistical analysis

To test our hypotheses, the regulated non-perturbed walks (N1-N6), the first and last slip (S1, S4, S5, S8, S9 and S12) and first and last trip (T1, T4, T5, T8, T9 and T12) trials in each condition were used in the following planned analyses. Predictive gait alteration was first assessed by examining whether changes existed in gait parameters during regulated non-perturbed walk trials (N1 vs N2), and secondly, change in previous-step kinematics during slip/trip trials at the fixed hazard locations (S1 vs S4 and T1 vs T4). If significant changes (i.e. predictive gait alterations) were observed, transfer between limbs and locations was assessed by investigating whether the changes persisted when a condition was changed without notice (inter-limb transfer: N1 vs N3, S1 vs S5 and T1 vs T5, inter-location transfer: N1 vs N5, S1 vs

197 S9 and T1 vs T9). To confirm the absence of predictive gait alterations at the end of condition 3,
 198 kinematics between the first and last non-perturbed walks (N1 vs N6), and previous-step
 199 kinematics between the first and last trials for slips (S1 vs S12) and trips (T1 vs T12) were
 200 compared. Improvements in balance recovery responses were assessed by examining whether
 201 changes existed in recovery-step kinematics at the completion of the condition using random
 202 hazard locations (S1 vs S12 and T1 vs T12). Paired *t*-tests were applied for the above
 203 comparisons. Changes in the balance recovery strategy (i.e. effects of trial number on the
 204 proportion of strategies) were examined by applying the generalized linear mixed model
 205 (multinomial or binomial logistic regression) for slip and trip trials separately. IBM SPSS
 206 Statistics version 24 (IBM Corp., New York, USA) was used for the analyses. $P < 0.05$ was
 207 considered statistically significant.

208

209 **Results**

210 **Demographics, gait characteristics and dropout**

211 Ten participants (5 female and 5 male) completed the protocol and were included in the
 212 analyses. The demographics and usual gait characteristics of the participants (mean $\pm$ standard
 213 deviation) were as follows: age 29.1 ± 5.6 years, height 176.4 ± 11.2 cm, weight 70.4 ± 14.8 kg,
 214 cadence 110.3 ± 7.6 step/min, step length 74.3 ± 8.2 cm and gait speed 137.3 ± 18.6 cm/s. The
 215 dominant leg was right for 9 participants.

216

217 Falls

218 One participant (10%) fell at S1 and 2 participants (20%) fell at S5 (i.e. recorded $\geq 30\%$
219 body weight on the harness following the slip). No participants fell in any of the trip trials.

220

221 Gait patterns during no-perturbation trials

222 Throughout the regulated non-perturbed trials (N1 vs N2 and N1 vs N6), participants
223 walked with similar gait speed, step length, cadence and foot-contact angle ($p > 0.05$) (Fig 2). A
224 significant increase of toe height was observed during the first condition (N1 vs N2, $p = 0.009$).
225 This increased toe height were maintained from right and left legs (N1 to N3, $p = 0.001$) and
226 from fixed to random locations (N1 to N5, $p = 0.003$).

227

228 **Fig 2. Gait parameters during non-perturbed walk trials (N1 to N6, n=10) interspersed**
229 **within slip and trip trials throughout the protocol.** The dots and error bars are means and
230 standard errors, respectively. * $p < 0.05$, ** $p < 0.01$, n.s. $p > 0.05$

231

232 Kinematics during slip trials

233 During the first condition (right leg, fixed location), significant changes to previous step
234 kinematics included a greater anterior XCoM displacement (S1 vs S4, $p = 0.009$) and reduced
235 MoS (S1 vs S4, $p = 0.002$) suggesting predictive gait alteration (Fig 3). Although, these changes
236 were maintained from right to left legs (S1 vs S5, $p < 0.004$), they did not maintain in random
237 hazard location (S1 vs S9, $p > 0.096$). At the end of the random condition, there were no

238 significant changes in previous step kinematics (S1 vs S12, $p > 0.05$) indicating the absence of
239 predictive gait alterations against slips.

240 During a recovery step, significantly less posterior XCoM displacement were observed
241 for the last slip, compared to the first (S1 vs S12, $p < 0.05$) suggesting improvements in balance
242 recovery responses (Fig 3). No significant changes in MoS and step length were seen across
243 conditions (S1 vs S12, $p > 0.05$). Slip speed also significantly decreased from S1 (135.8 ± 10.4
244 cm/s) to S12 (82.8 ± 25.9 cm/s, $p = 0.005$).

245
246 **Fig 3. Changes in previous- and recovery-step kinematics during slip trials (n=10).** Margin
247 of stability (MoS) was the distance between an extrapolated (i.e. velocity-corrected) centre of
248 mass (XCoM) to the closest base of support limit at foot touch down. XCoM displacement was
249 the distance between the XCoM to the ankle joint of the supporting limb in the sagittal plane.
250 The dots and error bars are means and standard errors, respectively. The arrows indicate the
251 possible directions relating to better stability. S: slip. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, n.s.
252 $p > 0.05$

253

254 Kinematics during trip trials

255 During a step prior to a trip, MoS, XCoM displacement and step length showed no
256 significant changes during all conditions indicating no predictive gait changes (T1 vs T4 and T1
257 vs T12, $p > 0.05$) (Fig 4).

258 During a recovery step, there was a significant increase in MoS, XCoM displacement
259 and step length between the first and last trip (T1 vs T12, $p < 0.05$) suggesting improved
260 reactions to trips (Fig 4).

261

262 **Balance recovery strategy**

263 Fig 5 shows stepping strategies taken to recover balance following slips and trips.
 264 Backward stepping was most prevalent at the first slip (S1: 90%), which declined to 50% at S8
 265 and increased to 100% at S9 (first slip at random location) and decreased again to 50% at S12.
 266 These changes in the proportion of strategies for balance recovery from slips were not
 267 significant ($p>0.05$). However, there was a significant change in the proportion of strategies for
 268 balance recovery from trips ($p<0.01$). As shown in Fig 5, the lowering-contact strategy was
 269 most prevalent at the first trip (T1: 90%), decreasing to 10% at T12. In turn, the proportions of
 270 the elevating-contact strategy (T1: 0% to T12: 50%) and elevating-cross strategy (T1: 10% to
 271 T12: 40%) increased across the trials.

272

273 **Fig 5. Strategies for balance recovery after slips (A) and trips (B) (n=10).** S: slip, T: trip.
 274 Changes in proportions of balance recovery strategies used were examined by applying the
 275 generalized linear mixed model (multinomial or binomial logistic regression). A significant
 276 effect of trials was observed in the trip trials ($p<0.01$). This indicate that the proportions of the
 277 lowering strategy in response to trips decreased (T1: 90% to T12: 10%) and the elevating-
 278 contact (T1: 0% to T12: 50%) and elevating-cross (T1: 10% to T12: 40%) strategies increased.
 279 There was no significant effect of trials in the proportion of strategies during the slip trials.

280

281

282 **Discussion**

283 This study aimed to examine balance recovery responses to repeated trips and slips
284 while minimising predictive gait alterations. By repeatedly delivering trips and slips using a
285 walkway with stepping tiles and a metronome, we could successfully regulate gait speed, step
286 length, cadence and examine changes in reactive balance control. At the completion of training,
287 MoS after a trip was significantly increased indicating improved balance recovery responses to
288 unpredictable trip hazards. However, it was less clear if the training improved balance recovery
289 responses from slips.

290

291 **Predictive gait alterations and transfer**

292 Previous studies have shown the most common predictive gait alteration (or
293 feedforward adaptation) to repeated slips is an anterior shift of the CoM; a strategy employed to
294 counteract the effect of backward trunk rotation [5, 9, 15, 25]. In this study, we observed an
295 anterior shift of XCoM (additional analysis confirmed significantly forward CoM position but
296 not velocity) even though trips (a perturbation that propels the CoM forward) were interspersed
297 with slips. Although this shift of CoM transferred from one leg to the other when the slip
298 location was fixed, it did not transfer to slips given at random locations. These findings can
299 explain previous studies that have found training effects are transferrable from a movable
300 platform to a slippery floor [11], short to long slips [12], and from one leg to the other [13] i.e.
301 situations where hazard locations are sufficiently alike to allow the same predictive CoM
302 control strategy. However, our findings showing this anterior shift of CoM strategy did not
303 transfer to unpredictable slip hazard locations when slips and trips were interspersed, suggest it
304 is also unlikely to generalize to unpredictable hazards encountered in everyday life.

305 An anterior shift of the CoM may pose a risk to gait stability because it is related to
306 reduced pre-slip MoS (Pearson's correlation coefficient $r=-0.98$) indicating a greater

307 vulnerability to trips. Bhatt et al. also found predictive gait alteration to repeated slips leads to
 308 greater forward trunk rotation when a trip is unexpectedly encountered, and the forward shift of
 309 CoM position acquired during slip training dissipates after mixed slip and trip training [24].
 310 Therefore, while predictive control of the CoM can reduce perturbation impacts and may assist
 311 initial learning of balance recovery skills, mixed training appears to minimize poor responses to
 312 novel perturbations with opposite CoM displacements.

313 Increased toe clearance has previously been reported as a predictive gait alteration to
 314 repeated trip and/or slip exposures [16, 24]. We found elevated toe height (+3 cm) during gait
 315 transferred from right to left legs and from fixed to random hazard locations and also assisted
 316 obstacle clearance in later trials (i.e. employment of elevating strategies). Elevated toe clearance
 317 may therefore be a predictive strategy that generalizes to safe negation of unpredictable
 318 perturbations encountered in everyday life.

319

320 **Balance recovery responses from slips**

321 Our regulated gait protocol precluded most predictive gait alterations previously
 322 reported (i.e. shorter step length [14, 24], flat-foot landing [5, 14], anterior shift of CoM [5, 9,
 323 15, 25]. With these regulation, our results show participants reduced slip speed and post-slip
 324 XCoM displacement likely due to improvements in balance recovery responses. It is possible
 325 that slip speed was decreased by reduced muscle activation onset, quicker peak activation times
 326 [26] and co-activation of the lower-extremity muscles [26]. If improvements in the sensorimotor
 327 system can be obtained through repeated exposure to unpredictable perturbations, it would
 328 likely be generalizable in daily life situations where individuals cannot predict all fall hazards
 329 but need immediate and appropriate responses.

330 Previous studies have reported a 90-100% reduction of backward balance loss from the
 331 1st slip to the 5th trial in response to repeated slips in young adults [5, 9]. In contrast, backward
 332 stepping in our study (akin to backward balance loss) reduced by only 40% in the first 8 slips
 333 (S1-S8), likely because the interspersed slips and trips did not allow large predictive alterations
 334 to occur. Moreover, all participants (100%) took a backward step when a slip was encountered
 335 at the new location (S9). These backward steps were most likely related to the negative
 336 recovery-step XCoM displacement and step length observed during S9. Unlike predictive gait
 337 alterations, that occur quickly when the type and location of hazard have been revealed,
 338 improvement in balance recovery responses (that possibly involve motor skill learning and
 339 improved muscle activation) probably occur more gradually and require longer-term and higher-
 340 dose training than the current protocol.

341

342 **Balance recovery responses from trips**

343 We found improved balance recovery responses from trips as indicated by increases in
 344 recovery-step MoS during recovery. Following repeated exposure to trips, participants were
 345 more likely to clear the obstacle, rather than lower the obstructed limb immediately to the floor.
 346 This change in strategy likely contributes to improved stability because the lowering strategy
 347 (terminating the step before the obstacle) causes a greater gait disruption and is unlikely to assist
 348 in arresting the forward momentum of the COM (instability). The improved strategy type and
 349 stability (MoS) observed was possibly due to improved use of hip-flexor muscles and improved
 350 support limb push-off, as we have seen these to be important for successful trip recovery in
 351 previous studies [17, 18]. Pijnappels et al. reported balance recovery from a trip requires support
 352 limb power to propel the CoM upwards and provide time and space for an adequate recovery
 353 step to arrest the angular momentum of the COM [17, 18]. Faster initiation of the recovery step
 354 [27] may also constitute a crucial component of successful balance recovery.

355

356 **Study limitations**

357 We acknowledge certain limitations of this study. First, although the protocol aimed at
 358 precluding predictive gait alterations and was successful in keeping most gait parameters similar
 359 to normal gait, participants walked with an elevated toe clearance throughout the trials and this
 360 would have contributed to the improved reactions to trips observed. Second, the manual control
 361 of the switch to trigger the trip hazard yielded some variability in timing, such that the trip
 362 would not have always been encountered at precisely mid-swing. Third, the use of a metronome
 363 and stepping tiles were necessary to maintain the normal gait speed and ensure consistent
 364 perturbations, they may also have diminished the natural variability during gait and increased
 365 the attentional demands of gait. Fourth, our study did not examine retention effects, which
 366 require further investigation to appreciate the utility of perturbation training for fall prevention
 367 in daily life. Fifth, our small study sample did not allow correction for multiple comparisons
 368 (e.g. Bonferroni), therefore, may be subjected increased type one error. Finally, the
 369 generalizability of the study findings to older adults needs to be examined in future studies.

370

371 **Conclusions**

372 Even in the absence of most predictive gait alterations, balance recovery responses to
 373 trips and to a lesser extent to slips were improved through exposure to repeated unpredictable
 374 perturbations. With the exception of elevated toe clearance, most predictive gait alterations to
 375 perturbations at a fixed location is likely not generalizable in daily life situations where
 376 perturbation type and location could not be predicted. A common predictive gait alteration to
 377 lean forward immediately before a slip was not useful when the perturbation location was
 378 unpredictable. The findings suggest that training of balance recovery responses to unpredictable

379 perturbations may be beneficial to fall avoidance in everyday life. Further studies are needed to
 380 examine retention, kinetic and physiological mechanisms, and generalizability of our findings to
 381 older adults at risk of falling.

382

383 **Acknowledgements**

384 We express our deep gratitude all the participants of this study.

385

386

387 **References**

- 388 1. Stevens JA, Corso PS, Finkelstein EA, Miller TR. The costs of fatal and non-fatal falls
 389 among older adults. *Inj Prev.* 2006;12(5):290-5. doi: 10.1136/ip.2005.011015. PubMed PMID:
 390 17018668; PubMed Central PMCID: PMCPMC2563445.
- 391 2. Okubo Y, Schoene D, Lord SR. Step training improves reaction time, gait and balance
 392 and reduces falls in older people: a systematic review and meta-analysis. *Br J Sports Med.* 2016.
- 393 3. Mansfield A, Wong JS, Bryce J, Knorr S, Patterson KK. Does perturbation-based
 394 balance training prevent falls? Systematic review and meta-analysis of preliminary randomized
 395 controlled trials. *Phys Ther.* 2015;95(5):700-9. doi: 10.2522/ptj.20140090. PubMed PMID:
 396 25524873.
- 397 4. Bohm S, Mademli L, Mersmann F, Arampatzis A. Predictive and Reactive Locomotor
 398 Adaptability in Healthy Elderly: A Systematic Review and Meta-Analysis. *Sports Med.*
 399 2015;45(12):1759-77. doi: 10.1007/s40279-015-0413-9. PubMed PMID: 26487633; PubMed
 400 Central PMCID: PMCPMC4656697.

- 401 5. Bhatt T, Wening JD, Pai YC. Adaptive control of gait stability in reducing slip-related
402 backward loss of balance. *Exp Brain Res*. 2006;170(1):61-73. doi: 10.1007/s00221-005-0189-5.
403 PubMed PMID: 16344930.
- 404 6. Bierbaum S, Peper A, Karamanidis K, Arampatzis A. Adaptational responses in
405 dynamic stability during disturbed walking in the elderly. *J Biomech*. 2010;43(12):2362-8. doi:
406 10.1016/j.jbiomech.2010.04.025. PubMed PMID: 20472240.
- 407 7. Bierbaum S, Peper A, Karamanidis K, Arampatzis A. Adaptive feedback potential in
408 dynamic stability during disturbed walking in the elderly. *J Biomech*. 2011;44(10):1921-6. doi:
409 10.1016/j.jbiomech.2011.04.027. PubMed PMID: 21555126.
- 410 8. Chambers AJ, Cham R. Slip-related muscle activation patterns in the stance leg during
411 walking. *Gait Posture*. 2007;25(4):565-72. doi: 10.1016/j.gaitpost.2006.06.007. PubMed PMID:
412 16876417.
- 413 9. Pai YC, Bhatt T, Wang E, Espy D, Pavol MJ. Inoculation against falls: rapid adaptation
414 by young and older adults to slips during daily activities. *Arch Phys Med Rehabil*.
415 2010;91(3):452-9. doi: 10.1016/j.apmr.2009.10.032. PubMed PMID: 20298839; PubMed
416 Central PMCID: PMC2842602.
- 417 10. Marigold DS, Patla AE. Strategies for dynamic stability during locomotion on a
418 slippery surface: effects of prior experience and knowledge. *J Neurophysiol*. 2002;88(1):339-53.
419 doi: 10.1152/jn.00691.2001. PubMed PMID: 12091559.
- 420 11. Bhatt T, Pai YC. Generalization of gait adaptation for fall prevention: from moveable
421 platform to slippery floor. *J Neurophysiol*. 2009;101(2):948-57. doi: 10.1152/jn.91004.2008.
422 PubMed PMID: 19073804; PubMed Central PMCID: PMC2657073.
- 423 12. Yang F, Wang TY, Pai YC. Reduced intensity in gait-slip training can still improve
424 stability. *J Biomech*. 2014;47(10):2330-8. doi: 10.1016/j.jbiomech.2014.04.021. PubMed
425 PMID: 24835473; PubMed Central PMCID: PMC4098761.

- 426 13. Bhatt T, Pai YC. Immediate and latent interlimb transfer of gait stability adaptation
427 following repeated exposure to slips. *J Mot Behav.* 2008;40(5):380-90. doi:
428 10.3200/JMBR.40.5.380-390. PubMed PMID: 18782713; PubMed Central PMCID:
429 PMCPMC2614623.
- 430 14. Wang TY, Bhatt T, Yang F, Pai YC. Generalization of motor adaptation to repeated-slip
431 perturbation across tasks. *Neuroscience.* 2011;180:85-95. doi:
432 10.1016/j.neuroscience.2011.02.039. PubMed PMID: 21352898; PubMed Central PMCID:
433 PMCPMC3390205.
- 434 15. Pavol MJ, Runtz EF, Pai YC. Young and older adults exhibit proactive and reactive
435 adaptations to repeated slip exposure. *J Gerontol A Biol Sci Med Sci.* 2004;59(5):494-502.
436 PubMed PMID: 15123760.
- 437 16. Wang TY, Bhatt T, Yang F, Pai YC. Adaptive control reduces trip-induced forward gait
438 instability among young adults. *J Biomech.* 2012;45(7):1169-75. doi:
439 10.1016/j.jbiomech.2012.02.001. PubMed PMID: 22377431; PubMed Central PMCID:
440 PMCPMC3378399.
- 441 17. Pijnappels M, Bobbert MF, van Dieen JH. Contribution of the support limb in control of
442 angular momentum after tripping. *J Biomech.* 2004;37(12):1811-8. doi:
443 10.1016/j.jbiomech.2004.02.038. PubMed PMID: 15519588.
- 444 18. Pijnappels M, Bobbert MF, van Dieen JH. How early reactions in the support limb
445 contribute to balance recovery after tripping. *J Biomech.* 2005;38(3):627-34. doi:
446 10.1016/j.jbiomech.2004.03.029. PubMed PMID: 15652564.
- 447 19. Pijnappels M, Reeves ND, Maganaris CN, van Dieen JH. Tripping without falling;
448 lower limb strength, a limitation for balance recovery and a target for training in the elderly. *J*
449 *Electromyogr Kinesiol.* 2008;18(2):188-96. doi: 10.1016/j.jelekin.2007.06.004. PubMed PMID:
450 17761436.

- 451 20. Systems VM. Plug-in Gait: Product Guide - Foundation Notes 2010 [cited 2018 1
452 February]. Available from: [https://www.vicon.com/downloads/documentation/plugin-gait-](https://www.vicon.com/downloads/documentation/plugin-gait-product-guide)
453 [product-guide](https://www.vicon.com/downloads/documentation/plugin-gait-product-guide).
- 454 21. Yang F, Pai YC. Automatic recognition of falls in gait-slip training: Harness load cell
455 based criteria. J Biomech. 2011;44(12):2243-9. doi: 10.1016/j.jbiomech.2011.05.039. PubMed
456 PMID: 21696744; PubMed Central PMCID: PMC3390207.
- 457 22. Hof AL, Gazendam MG, Sinke WE. The condition for dynamic stability. J Biomech.
458 2005;38(1):1-8. doi: 10.1016/j.jbiomech.2004.03.025. PubMed PMID: 15519333.
- 459 23. Eng JJ, Winter DA, Patla AE. Strategies for recovery from a trip in early and late swing
460 during human walking. Exp Brain Res. 1994;102(2):339-49. PubMed PMID: 7705511.
- 461 24. Bhatt T, Wang TY, Yang F, Pai YC. Adaptation and generalization to opposing
462 perturbations in walking. Neuroscience. 2013;246:435-50. doi:
463 10.1016/j.neuroscience.2013.04.013. PubMed PMID: 23603517; PubMed Central PMCID:
464 PMC3809766.
- 465 25. Moyer BE, Chambers AJ, Redfern MS, Cham R. Gait parameters as predictors of slip
466 severity in younger and older adults. Ergonomics. 2006;49(4):329-43. doi:
467 10.1080/00140130500478553. PubMed PMID: 16690563.
- 468 26. Parijat P, Lockhart TE. Effects of moveable platform training in preventing slip-induced
469 falls in older adults. Ann Biomed Eng. 2012;40(5):1111-21. Epub 2011/12/03. doi:
470 10.1007/s10439-011-0477-0. PubMed PMID: 22134467; PubMed Central PMCID:
471 PMC3319506.
- 472 27. Mansfield A, Peters AL, Liu BA, Maki BE. Effect of a perturbation-based balance
473 training program on compensatory stepping and grasping reactions in older adults: a
474 randomized controlled trial. Phys Ther. 2010;90(4):476-91. Epub 2010/02/20. doi:
475 10.2522/ptj.20090070. PubMed PMID: 20167644.

476

477 **Supporting information**

478 **S1 Dataset. Dataset used in this study.**

479 **S2 Appendix. An analysis on free gait without gait regulation.**

480

Previous step (Pre-Slip)

Recovery step (Post-Slip)

1. Right leg
Fix location

2. Left leg
Fix location

3. Random leg
and location

1. Right leg
Fix location

2. Left leg
Fix location

3. Random leg
and location

Previous step (Pre-Trip)

Recovery step (Post-Trip)

1. Right leg
Fix location

2. Left leg
Fix location

3. Random leg
and location

1. Right leg
Fix location

2. Left leg
Fix location

3. Random leg
and location

A ■ Backward step □ Forward step

B ■ Lowering □ Elevating-contact □ Elevating-cross

1. Right leg Fix location	2. Left leg Fix location	3. Random leg Random location
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1. Right leg Fix location	2. Left leg Fix location	3. Random leg Random location
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