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The influence of age, muscle strength and speed of information processing on recovery responses to external perturbations in gait

R. Senden^{a,b,*}, H.H.C.M. Savelberg^b, J. Adam^b, B. Grimm^a, I.C. Heyligers^{a,b}, K. Meijer^b

^a Atrium Medical Centre, Department of Orthopaedics & Traumatology, Henri Dunantstraat 5, P.O. Box 4446, 6401 CX Heerlen, The Netherlands

^b Maastricht University, Department of Human Movement Science, Faculty of Health, Medicine and Life Sciences, Universiteitssingel 50, 6229 ER Maastricht, The Netherlands

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ABSTRACT

Dynamic imbalance caused by external perturbations to gait can successfully be counteracted by adequate recovery responses. The current study investigated how the recovery response is moderated by age, walking speed, muscle strength and speed of information processing. The gait pattern of 50 young and 45 elderly subjects was repeatedly perturbed at 20% and 80% of the first half of the swing phase using the Timed Rapid Impact Perturbation (TRiP) set-up. Recovery responses were identified using 2D cameras. Muscular factors (dynamometer) and speed of information processing parameters (computer-based reaction time task) were determined. The stronger, faster reacting and faster walking young subjects recovered more often by an elevating strategy than elderly subjects. Twenty three per cent of the differences in recovery responses were explained by a combination of walking speed ($B = -13.85$), reaction time ($B = -0.82$), maximum extension strength ($B = 0.01$) and rate of extension moment development ($B = 0.19$). The recovery response that subjects employed when gait was perturbed by the TRiP set-up was modified by several factors; the individual contribution of walking speed, muscle strength and speed of information processing was small. Insight into remaining modifying factors is needed to assist and optimise fall prevention programmes.

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1. Introduction

The rapidly increasing elderly population is associated with an increasing incidence of falls, which has serious consequences for both the individual and the health care system [1]. Near falls, such as trips, are relevant markers of fall risk [2]. They account for approximately 59% of the falls in elderly subjects [3]. A near fall is defined as a temporary disturbance in dynamic balance which is caused by external perturbations. Healthy individuals have remarkable capacity to counter the forward momentum of the centre of mass which results from an external perturbation, by a concerted action of the perturbed leg and supporting leg [4,5]. In general two recovery strategies have been identified, either the obstructed leg is placed on the ground immediately after being perturbed while a

recovery step is taken with the contra-lateral leg (lowering strategy, LS), or the obstructed leg can be elevated after being perturbed in order to continue walking (elevating strategy, ES).

Previous studies have shown that the choice for the recovery response depends on perturbation characteristics, e.g. perturbation duration [6] and obstruction timing in the gait cycle [4–9]. For instance early swing perturbations mainly evoke ES, while late swing perturbations mainly evoke LS. Interestingly, similar perturbation conditions yield different recovery responses in young and elderly subjects [8,9]. Studies have shown that elderly subjects recover more often by LS [8,9], which has been attributed to (for example) an impaired limb positioning and reduced lower limb strength [9]. Moreover studies have found that elderly subjects are less successful in their recovery, as indicated by higher failure rates, defined as taking additional steps, having secondary contact with the obstacle and even fall events. For instance the study of Pijnappels et al. showed that young subjects recovered successfully from mid swing perturbations by ES, while elderly subjects used ES and LS to recover from identical perturbations, but failed more often in their recovery [8]. The less adequate recovery responses in elderly subjects have been associated with age related physiological changes such as lower peak moments, poorer placement of the recovery limb, and reduced response time

* Corresponding author at: Atrium Medical Centre, Department of Orthopaedics & Traumatology, Henri Dunantstraat 5, P.O. Box 4446, 6401 CX Heerlen, The Netherlands. Tel.: +31 455766416.

E-mail addresses: rachel.senden@atriummc.nl (R. Senden), hans.savelberg@maastrichtuniversity.nl (H.H.C.M. Savelberg), jos.adam@maastrichtuniversity.nl (J. Adam), b.grimm@atriummc.nl (B. Grimm), i.heyligers@atriummc.nl (I.C. Heyligers), kenneth.meijer@maastrichtuniversity.nl (K. Meijer).

[4,6,8–12]. Most studies on balance recovery focus on success/failure rates. They are conducted on small groups and tend to rely on limited amounts of perturbation and therefore investigate mainly a single physiological aspect at a time. For instance, Schillings et al. investigated muscular responses during stumbling over obstacles [4] and Lamoureaux et al. examined the effect of muscle strength on obstacle negotiation [10]. In daily life, elderly subjects have to deal simultaneously with several age related physiological changes such as an impaired speed of information processing and reduced muscle strength. Currently it is unclear how these changes and the combined effect of these changes are associated with recovery responses. It is hypothesised that there is a graded response to external perturbations, where physiological deterioration is initially coped with by relying on the LS and changes in gait. In later stages, failure to recover is expected to become more prominent. The current study aims to investigate how the recovery response to external perturbations in gait is moderated by age, walking speed, muscle strength and speed of information processing, relying on a sizable population of young and elderly subjects and a large number of controlled perturbations.

2. Materials and methods

2.1. Subjects

Fifty healthy young (23 M/27 F, 24 ± 4 years) and 45 healthy elderly (20 M/25 F, 67 ± 6 years, Table 1) subjects were included. Exclusion criteria were cardiac problems, breathing problems, diabetes, neurological diseases, hearing or sight impairments, use of psychoactive or sedative medication, use of a walking aid, unable to walk, or Tinetti score <24 indicating risk for falling. The study was approved by the local ethical committee; all participants were informed and signed informed consent was obtained before participating.

2.2. Measurements and outcomes

2.2.1. TRiP experiment

The ‘Timed Rapid Impact Perturbation’ (TRiP) set-up, a specially designed trip set-up consisting of a treadmill (Medifit) equipped with a safety harness and two pneumatic braking devices, was used to induce perturbations in a standardised way (Fig. 1) [13]. The TRiP can perturb the swinging leg at specific instants during the first half of the swing phase, with specific blocking durations and perturbation forces, thereby triggering LS and ES (online supplement [13]). A fixed protocol was used to induce 10 perturbations at 20% (early swing perturbations) and 10 perturbations at 80% (mid swing perturbations) of the first half of the swing phase (Fig. 2). Perturbations were equally distributed over both

legs, had a fixed duration of 150 ms and were induced with a fixed braking pressure of 3 bar. The time between successive perturbations was sufficient to enable subjects to regain their normal walking pattern. Video recordings were used to assess the recovery strategy. A pilot study on 300 perturbations showed that this assessment method had an overall agreement of 93% between instructed observers. The proportion of perturbations recovered by an ES (%) assessed over the complete experiment was used as a measure for the recovery response.

Prior to the TRiP experiment, subjects walked a 20 m straight distance to determine their comfortable walking speed. This speed was used during the TRiP experiment as a faster or slower speed may have an effect on the recovery response [13]. Moreover before the experiment, subjects walked 2 min on the treadmill, first without and subsequently with the TRiP to become accustomed to the set-up. Comparing the gait of five young and five elderly subjects using acceleration-based gait analysis showed no significant differences in gait between overground walking and treadmill walking, neither between treadmill walking with and without the TRiP (results not shown).

2.2.2. Muscular factors

Isometric knee extension and flexion strength was measured using a dynamometer (Biodex III) [14,15]. Subjects were seated with their hip and knee in 90° of flexion and were asked to successively produce maximal isometric knee extension and flexion contractions as fast as possible, while maintaining maximal force for 5 s. Only the right leg was tested [16]. Maximum knee flexion and extension moments and the rate of moment development (RMD), defined as the percentage of the maximum moment attained 200 ms after the start of the contraction was determined [14,15]. All participants were consistently verbally encouraged.

2.2.3. Speed of information processing factors

Speed of information processing was determined using a computer-based four-choice finger-cuing reaction time task [17]. Subjects were seated behind a computer with the index and middle finger of both hands on specific keys on the bottom row of the keyboard. A row of four squares was continuously visible in red outlines on the computer monitor, while two conditions were presented. Within the un-cued condition, all the four squares were coloured red, and after an interval of 100, 250, 500, 750 or 1000 ms, one of these four squares was coloured green. In the cued condition, only two out of the four squares (either the two left most or the two right most) were coloured red, and after one of the above mentioned intervals, one of the non-red squares was coloured green. The cue indicated the preparation of the response hand opposite to the location of the cue. Subjects had to respond as quickly and accurately as possible by pressing the key that corresponded to the green coloured square on the screen. At the

Table 1

Averages $\pm$ standard deviation [ranges] for subject characteristics, tinetti scores, speed of information processing and strength measures for young and older subjects.

	Young ($n = 48$)	Elderly ($n = 43$)	p -Value
Age (years)	24.4 ± 4.0 [18–36]	67.4 ± 6.2 [60–82]	0.00*
Height (m)	1.76 ± 0.09 [1.60–1.94]	1.70 ± 0.10 [1.48–1.92]	0.00*
Body mass (kg)	69.7 ± 10.3 [50.0–92.0]	74.1 ± 12.2 [43.0–100.0]	0.64
Tinetti score	28.0 ± 0.0 [28–28]	26.9 ± 1.4 [24–28]	<0.01*
Max. flexion (Nm)	90.0 ± 30.1 [36.6–162.6]	60.6 ± 22.8 [24.5–148.2]	<0.01*
RMD flexion (%)	62.8 ± 19.3 [25.4–97.7]	39.1 ± 17.6 [8.6–81.3]	<0.01*
Max. extension (Nm)	232.8 ± 73.7 [114.0–392.2]	166.0 ± 51.6 [84.8–270.4]	<0.01*
RMD extension (%)	44.7 ± 20.3 [4.5–86.0]	26.8 ± 21.2 [4.3–85.4]	<0.01*
Avg. reaction time (ms)	360.0 ± 32.7 [297.5–437.5]	534.8 ± 82.1 [377.9–820.7]	<0.01*
Cognitive flexibility (ms)	136.3 ± 56.9 [15.0–269.0]	51.9 ± 136.6 [–280–370]	<0.01*
Walking speed (km/h)	4.9 ± 0.6 [3.7–6.0]	3.8 ± 0.6 [2.7–5.5]	<0.01*
Quality of recovery response (% perturbations recovered by ES)	31	21	<0.01*

* Significant difference ($p < 0.05$).

Fig. 1. The Timed Rapid Impact Perturbation (TRiP) set-up, used to evoke controlled perturbations in a standardised way, consists of a treadmill and two trip devices (online supplement). The triaxial accelerometer shown in this figure is not part of the TRiP set-up. The accelerometer, as presented here, was used to investigate the effect of the trip on gait, which showed to have no effect.

start of each trial, a warning signal was presented as a small red square midway between the two inner boxes [17]. Subjects performed 100 trials in the un-cued condition and 100 trials in the cued condition, making a total of 200 trials, randomly mixed. For each subject, the average reaction time over both cue conditions and five time intervals was calculated. An additional parameter was calculated, cognitive flexibility, defined as the ability to prepare responses indicated by the cue. This was calculated as the difference in reaction time between the un-cued (4-choice; no preparation) and cued (2-choice; advance preparation) condition. A positive value indicated a reaction benefit; a negative value indicated a reaction time cost [17].

2.3. Statistical analysis

Age differences were investigated using independent *t*-test or Mann Whitney *U*-test and the Chi-square test. Pearson's *r* correlation was performed to investigate correlations between the parameters; recovery response, age, walking speed, speed of information processing parameters, muscle strength parameters. Linear regression analysis (backward method) using recovery response as the outcome measure and muscle strength parameters, speed of information processing parameters, age and walking speed as independent variables, was performed to investigate the combined effect of these parameters on the recovery response. All statistics were calculated in SPSS 15.0, using a significance level of 0.05.

3. Results

In total, 1900 trips were recorded, of which 34 were missed due to minor technical issues. One reaction time test was missed due to computer problems and four muscle strength measurements were excluded because of measurements errors, as indicated as extreme outliers in a box plot. Further analyses were based on 48 young and 43 elderly subjects.

Elderly subjects were significantly weaker, produced lower RMD, and had a higher reaction time and a lower cognitive flexibility than young subjects. Elderly subjects also had a slower comfortable walking speed than young subjects (Table 1). Both elderly and young subjects employed mainly LS (73% of all perturbations) to recover from perturbations in gait. Elderly subjects recovered less by ES than young subjects (21% vs. 31% of the perturbations, $p < 0.01$). Of the mid swing perturbations 96% were recovered by LS (young: 94%, elderly: 99%, $p < 0.001$) and 50% of the early swing perturbations were recovered by ES (young: 57%, elderly: 42%, $p < 0.001$). Eight elderly and four young subjects used the handrails of the treadmill at least once during recovery (30/1900 perturbations). This occurred at the beginning of the experiment. These trials were included in the analysis because the recovery had already started before the hands were used.

The recovery response correlated weakly with age ($r = -0.23$, $p < 0.05$), reaction time ($r = -0.24$, $p < 0.05$), RMD-extension ($r = 0.23$, $p < 0.05$) and maximum flexion strength ($r = 0.28$, $p < 0.05$) individually, but not with walking speed ($r = -0.04$, $p > 0.05$), cognitive flexibility ($r = 0.05$, $p > 0.05$), maximum extension strength ($r = 0.19$, $p > 0.05$) and RMD-flexion (r -range: 0.15, $p > 0.05$). In combination however, these parameters had an effect on the recovery response: 23% of the variability in recovery response was explained by a combination of slow walking speed ($B = -13.85$), fast reaction time ($B = -0.08$), high maximum extension strength ($B = 0.05$) and high RMD-extension ($B = 0.19$). Age and cognitive flexibility were removed from the model.

Strong correlations were found between knee extension and flexion strength parameters (r -range: 0.6–0.8). Therefore, only the extension strength parameters were included in the model. The strength in extensor muscles was preferred because the extensors play an important role during recovery, especially to provide adequate push-off forces in the support limb [8,18]. Age correlated positively with reaction time ($r = 0.82$) and negatively with maximum extension strength ($r = -0.45$), RMD-extension ($r = -0.38$), maximum flexion strength ($r = -0.48$), RMD flexion ($r = -0.55$), cognitive flexibility ($r = -0.41$) and walking speed

Fig. 2. Perturbations applied during the first half of the swing phase. The dotted blue lines represent the swing phase of the gait cycle which starts with toe off (0%), followed by mid swing (100%) and ending with heel strike (0%). Perturbations were induced during the first half of the swing phase (toe off – mid swing); at 20% (early swing perturbations) and 80% (mid swing perturbations), as is shown by the red dotted lines. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

($r = -0.67$). Walking speed showed a weak to moderate correlation with strength parameters (r -range: 0.45–0.55), speed of information processing parameters (r -range: 0.30–0.71) and age ($r = 0.68$).

4. Discussion

This is the first study where a sizable population ($n = 95$) of young and elderly subjects have been exposed to controlled perturbations during walking. The objective was to investigate associations between age, walking speed, speed of information processing, muscle strength and the recovery response to perturbations in gait. The recovery response was expressed as the proportion of perturbations recovered by ES (%). Contrary to expectation, the recovery response was only weakly associated with walking speed, knee extension strength, rate of extension moment development and reaction time. In addition, it showed no relationship with age or cognitive flexibility.

Elderly subjects who were weaker and who reacted more slowly recovered less frequently by ES compared to the stronger

and faster reacting young subjects. This is similar to previous studies showing that elderly subjects less often adopt an ES compared to young subjects [8,9,11] and confirms the hypothesis suggesting that there is a shift from ES to LS with physiological changes. Age, walking speed, strength parameters, reaction time and cognitive flexibility have individually no or only a small influence on the recovery response (R^2 range = 0.002–0.06). In combination however, their contribution increases although the association with the recovery response remains weak: only 23% of the variability in recovery response can be explained by fast reaction time, high muscle strength and slow walking speed. The fact that these factors are involved in balance recovery corresponds to previous studies showing clear effects of muscular responses, muscle strength, lower limb positioning, coordination parameters, and reaction times on walking stability and the obstacle avoidance [4,8–11,19]. The weak associations imply that other factors have a bigger impact, or that a combination of multiple factors including walking speed, speed of information processing, muscle strength related factors and other internal (coordination [19]) and external (environment) factors modify the recovery response. The influence of external factors has been investigated in the study of Schillings et al. showing that the final recovery response is adjusted to the demands of the task, moderated by afferent information during the perturbation (e.g. mechanoreceptor feedback) [4].

Age was excluded from the model, suggesting that the recovery response is indirectly affected by age via its deteriorating effects on physiological factors (e.g. via adjusted muscle strength) [20,21]. This is also indicated by the moderate to strong correlations found between age and physiological factors and is supported by the weak correlation observed between the recovery response and age individually.

No effect of comfortable walking speed was found on the recovery response for individuals, and only a small effect was found in the combined regression analysis. However walking speed may have an effect. Pavol et al. showed that a faster walking speed is associated with falls following a trip in healthy elderly subjects [11]. Moreover, a pilot study showed that similar perturbations were less frequently recovered by ES when walking at 6 km/h (20%) compared to walking at 3 km/h (77% [13]). This suggests that not walking speed per se, but deviations from the comfortable walking speed (faster or slower than preferred) may influence the recovery response. This requires further examination.

The strength of the associations may have been mitigated by the fact that the elderly subjects were all healthy subjects, not at risk of falling (Tinetti score > 24) [22]. The inclusion of elderly subjects at risk for falling may result in more pronounced effects. This is assumed based on previous studies indicating that elderly subjects with a fall history have a slower reaction time than elderly subjects without a fall history [23] and that elderly fallers are weaker, producing lower joint moments than elderly non-fallers [24,25]. Moreover the current study focused only on perturbations induced during the first half of the swing phase. Further insight into the associations between the recovery response to external perturbations in gait and physiological factors can be achieved by including perturbations induced during the second half of the swing phase. In addition it can be argued that a more in-depth evaluation of the underlying biomechanics of recovery strategies (for example, hip moments) could attenuate the results, which currently rely on quantitative measures (%ES). Finally, recovery responses induced by the TRiP set-up may not be representative of the type of perturbation typically experienced by subjects in daily life. The TRiP creates an ankle blockage, while tripping over an obstacle may create an impact at the foot, which may affect the recovery response employed. For instance, to cross an obstacle in daily life, the use of an LS may be impeded as subjects avoid the obstacle.

Furthermore, the treadmill may create differences in recovery response compared to over ground walking as subjects are forced to keep up with the speed of the treadmill [6]. These are general problems of standardised laboratory-based trip set-ups and experiments. Many factors may play a role in tripping during daily life (for example, the environment) which can only be captured by monitoring tripping reactions in daily life. The TRiP set-up however is a good approach to investigate recovery responses for a specific kind of perturbation, as it allows simulating perturbations of different compliance by controlling the duration of the perturbation, the perturbation force and the timing of the obstruction in the swing phase. Moreover qualitative agreement (seen in comparable recovery responses) was found with studies using different approaches to induce perturbations in gait [4–6,8,9,11].

Previous studies have shown that trip recovery responses may be improved by training [26,27]. Therefore it is important to further investigate factors that modify the recovery response, which may include balance, coordination and reflex reactions. This insight may help guide fall prevention programmes aiming to improve recovery responses after gait is perturbed.

5. Conclusion

The recovery responses that subjects employ when gait is perturbed using the TRiP set-up are moderated by several mediating factors in which the contribution of comfortable walking speed, muscle strength, and speed of information processing related factors is small. Insight into remaining factors modifying the recovery response is needed to assist and optimise fall prevention programmes.

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Conflict of interest statement

None of the authors had financial and personal relationships with other people or organisations that could inappropriately influence their work.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.gaitpost.2013.08.033>.

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