Perturbation training to reduce fall risk in elderly: validating the quantified recovery performance measure by means of the assessment by physiotherapists

Master's Thesis Marleen Meeuwsen
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by

Marleen Meeuwsen

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Perturbation training to reduce fall risk in elderly: validating the quantified recovery performance measure by means of the assessment by physiotherapists

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ABSTRACT
Implementation of perturbation training for elderly requires a validated measure to quantify someone’s ability to recover when encountering a perturbation. A quantified recovery performance has been constructed for the anteroposterior (QRP_{AP}) and for mediolateral (QRP_{ML}) plane, the QRP_{AP} and QRP_{ML} reflect the amount of deviation of the center of pressure trajectory from the unperturbed walking pattern. The QRP_{AP} and QRP_{ML} were calculated for eleven elderly subjects (>65 years), who experienced 66 perturbations (accelerations and decelerations) during treadmill walking. The constructed QRP_{AP} and QRP_{ML} were validated in this study (1) by comparing them to the rated recovery performance (RRT) as provided by physiotherapists and (2) by studying how they were affected by an increased specified difficulty (SpD) of perturbations. The used perturbation characteristics for the SpD’s were validated with the perceived difficulty (PD) as reported by the subjects for each perturbation. A positive relation confirmed the increase of PD with an increase of SpD. Both for the QRP_{AP} and the QRP_{ML} a positive relation was found with the RRP and a negative relation was found with the SpD. The QRP_{AP} showed a stronger relation with the RRP and was found to be more sensitive when compared to the QRP_{ML}. The relation of the QRP_{AP} with the RRP was consistent across physiotherapists. Implementation of the QRP_{AP} during perturbation training will decrease the attention demanded of physiotherapists and will remove the offset observed across physiotherapists. Progress can be monitored objectively and training difficulty can be adjusted accordingly.

1. INTRODUCTION
Approximately one third of the elderly population (> 65 years) experiences a fall annually (World Health Organization, 2007), greatly affecting the mental and physical health of both healthy and frail elderly. Tinetti (2003) reported that 1 out of 10 of these falls among elderly result in serious injuries, such as (hip)fractures, soft tissue injury or head injury. The high prevalence and impact of falls among elderly combined with the growing size of the elderly population around the world (World Health Organization, 2015) poses a serious problem on healthcare demands globally.

Currently, the best available intervention for fall risk reduction is suggested to be multicomponent physical exercise, especially when including balance and strength components (Barnett et al., 2003; Gillespie et al., 2009; Karlsson et al., 2013; Luk et al., 2015). However, it is important to consider that Berg et al. (1997) indicated that most falls occur during gait. More specifically, of all falls 59%-75% occur due to gait perturbations such as trips or slips (Gabell et al., 1985). Although multicomponent physical exercise targets important elements of fall risk, research suggests that fall risk can be further reduced by adding gait perturbation training (Mansfield et al., 2015; Pai et al., 2014; Rosenblatt et al., 2013).

By directly targeting the cause of most falls during training, i.e. gait perturbations, transfer of learning is minimized. In other words, instead of improving balance in quite stance, as for many conventional balance exercises, perturbation training enhances balance for more relevant high risk dynamic conditions. Additionally, perturbation training can improve the recovery from large perturbations such as trips or slips, rather than only improving the attenuation of ever-present small perturbations (Bruijn et al., 2013). Pai et al. (2014) illustrated the potential of perturbation training, as they reported a 50% fall risk reduction for the perturbation training group when compared to the control group.
The QRP can be calculated for the COP trajectory in the anteroposterior (AP) and mediolateral (ML) plane, resulting in a $\text{QRP}_{\text{AP}}$ and $\text{QRP}_{\text{ML}}$, respectively.

The aim of this study is to validate the constructed QRP for healthy elderly (Figure 1). First, by comparing it to the rating of the recovery performance by physiotherapists. The ratings provided by physiotherapists are considered the best available method, since no other validated or widely accepted measure is available for the recovery performance after a perturbation. Furthermore, physiotherapists will be one of the important parties to work with and accept the measure. Therefore, it is of particular interest to examine whether the rated recovery performance (RRP), based on the assessment of physiotherapists, is consistent with the proposed $\text{QRP}_{\text{AP}}$ and $\text{QRP}_{\text{ML}}$. Second, by studying the effect of the specified difficulty (SpD) of a perturbation on the $\text{QRP}_{\text{AP}}$ and $\text{QRP}_{\text{ML}}$. When increasing the SpD of the perturbation, it is expected that the $\text{QRP}_{\text{AP}}$ and $\text{QRP}_{\text{ML}}$ will be lower. This study will focus on acceleration and deceleration belt perturbations, primarily affecting subjects in the AP plane. Since the AP plane will be affected more by the perturbations than the ML plane, a stronger relation between the $\text{QRP}_{\text{AP}}$ and the RRP and between the $\text{QRP}_{\text{AP}}$ and SpD are expected when compared to the relations with the $\text{QRP}_{\text{ML}}$.

Taking these constraints into account, a quantified recovery performance (QRP) measure was constructed (Castelblanco Cruz, Internal document Motekforce Link, 2017). The constructed measure has been further simplified by Gijsbers, currently working at the Clinical Applications department of Motekforce Link.

The SpD of the perturbations used throughout this study are based on previous work by the Clinical Applications department of Motekforce Link. To verify that the SpD also holds for the healthy elderly of this study, consistency between the SpD (based on the $\text{PD}_{\text{HY}}$, which followed from the regression) with the perceived difficulty as reported by the healthy elderly subjects ($\text{PD}_{\text{HE}}$) will be studied. As a result of the age differences, a small
positive offset and increased coefficient is expected for the healthy elderly of this study; i.e. elderly are expected to perceive the perturbations as slightly more difficult and are expected to be affected more by an increase of the SpD.

Variability across physiotherapists is expected to result in an offset and difference in extremeness of the RRP rating across physiotherapists, i.e. some physiotherapists may score higher or lower than others and the range of scores used to rate the recovery performance may differ across physiotherapists. Across subject variability is expected to influence the relation between the SpD and the QRP\textsubscript{AP} and the relation between the SpD and the QRP\textsubscript{ML}, since the ability to recover from perturbations will differ across subjects and the reduction in QRP\textsubscript{AP} and QRP\textsubscript{ML} due to increased SpD will also differ across subjects. In line with this, across subject variability is also expected to influence the relation between the SpD and the PD\textsubscript{HE}, as some subjects are expected to perceive the perturbations as more or less difficult than others and an increase of the SpD is also expected to affect subjects differently.

In line with the different strategies observed for trips and slips (Eng et al., 1994; Yang et al., 2008), accelerations and decelerations are expected to result in different recovery strategies. Although no general consensus exists about ‘good’ or ‘bad’ recovery strategies, different movements are observed for different strategies which may affect the assessment of the physiotherapist. Similarly, these different strategies for accelerations and decelerations are expected to result in a different amount of deviation from the unperturbed walking pattern. Hence, an interaction effect is expected between the type of perturbation and the relation between the RRP and the QRP\textsubscript{AP} and the relation between the RRP and the QRP\textsubscript{ML}.

In summary, it was hypothesized that a positive relation exists between the RRP and the QRP\textsubscript{AP} and between the RRP and the QRP\textsubscript{ML} and a that negative relation exists between the SpD and the QRP\textsubscript{AP} and between the SpD and the QRP\textsubscript{ML}. These relations are expected to be stronger with the QRP\textsubscript{AP} than with the QRP\textsubscript{ML}. Furthermore, a positive relation between the SpD and the PD is expected. It is expected that the RRP and QRP\textsubscript{AP} and the RRP and QRP\textsubscript{ML} relation is influenced by the physiotherapist. The relation of the SpD with the QRP\textsubscript{AP}, the SpD with the QRP\textsubscript{ML} and the SpD with the PD\textsubscript{HE} are expected to be influenced by the subject. All relations are expected to be affected by the type of perturbation.

2. Methods
For practical reasons, the QRP\textsubscript{AP} and QRP\textsubscript{ML} were measurement separately from the RRP, as depicted in Figure 2.
2.1 PART I: QRP & PD

2.1.1 Subjects
Twelve elderly subjects (7 female, 4 male; age 73.8 (±4.99) yrs; height 168 (±7.18) cm; mass 72.3 (±12.0) kg) participated in this study after screening them for being capable of walking without assistive device and with no known neurological pathology or cognitive impairment (for more details see Appendix C). One subject was excluded from the study, since the subject did not complete all trials. Resulting in eleven subjects completing the study. All subjects volunteered to take part in this research and provided written informed consent. The study was approved by the TU Delft ethics committee.

2.1.2 Research set up
Subjects were instructed to walk on a treadmill with a one dimensional force plate (C-mill, Motekforce Link, Amsterdam, The Netherlands) wearing a safety harness to prevent injury in case of an accidental fall. The handrails were removed from the system. A front and side webcam (1MP and 30fps, Logitec, Newark, California) were used to video record the subjects’ recovery response after a perturbation. An overview of the PD scale was presented on a paper in front of them approximately at eye level. A VR landscape was provided on the front display in an attempt to take attention away from walking and enforce walking as the subjects normally would.

2.1.3 Protocol & Data collection
All subjects started with a familiarization trial to get used to treadmill walking and to establish their self-selected walking speed. All included subjects were able to walk 5 trials of approximately 2 to 4 minutes. Subjects walked at their self-selected walking speed up to a maximum of 1 m/s. This maximum walking speed was used to limit the difference in walking speeds across subjects, since the previously mentioned regression based on PDHY of the previous test indicated that walking speed influenced the PDHY for decelerations. Subjects were offered the possibility of a break after each trial, these breaks did not last longer than five minutes. During each trial subjects experienced 12 perturbations in pseudorandom order, with a pseudorandom number of 10 – 20 detected steps between perturbations. Three specified difficulties (low, medium, high) were used for the acceleration and deceleration perturbations, pseudorandomly applied to the left and the right leg. Consequently, all subjects experienced each perturbation type and difficulty combination 10 times, resulting in a total of 60 perturbations. Subjects were instructed that perturbations would occur, but were not told when. Additionally, they were instructed to try to continue walking and verbally communicate the PDHE after each perturbation on a 15-points Borg scale (Chen et al., 2002). The PDHE was written down by the researcher. Table 1 shows the specified perturbation characteristics.

Figure 2: Overview of the two parts of this study. Left side: Elderly subjects experienced perturbations (accelerations and decelerations) while walking on a treadmill. The quantified recovery performance (QRP) was calculated for each perturbation. In addition to this, subjects were instructed to verbally communicate the perceived difficulty (PDHE) for each perturbation and their recovery was recorded by two webcams. Middle: The two webcams recorded the front and side view of the subjects. Right side: Video clips of the recovery of the elderly subjects were shown to physiotherapists, who provided their rated recovery performance (RRP) for each video clip.
for the three acceleration and deceleration difficulties and the PD, as determined with the regression of the previous study, which was also reported on a 15-point Borg scale.

2.1.5 Data processing
A. Signal filtering
To reduce the measurement noise of the moment and force signals, the signals were low-pass filtered at 6Hz using a second-order Butterworth filter. These low-pass filtered signals were used to calculate the COP trajectory, by dividing the moment signal by the force signal.

B. The recovery performance measure
The following steps (Figure 4) were performed for the COP trajectory in the ML and AP plane, resulting in a QRP<sub>AP</sub> and QRP<sub>ML</sub> respectively.
C. Correcting for errors
Before performing the statistical analysis, a visual inspection of the data was performed. Boxplots of the QRP\textsubscript{AP} and the QRP\textsubscript{ML} for the SpD for all elderly subjects were inspected for the acceleration and deceleration perturbations. Perturbations for which the QRP\textsubscript{AP} or QRP\textsubscript{ML} deviated considerably from the other perturbations of the subject were listed and the signals were analysed in more detail.

2.2 PART II: RRP

2.2.1 Subjects
Five physiotherapists (4 female, 1 male; age: 49.4 (± 11.1) yrs) with an average of 25.8 (± 11.5) years of experience as a physiotherapist participated in this study (for more details see Appendix C). All subjects volunteered to take part in this research and have provided written informed consent. The study was approved by the TU Delft ethics committee.

2.2.2 Research set up
The research was conducted at a place selected by the subject, using a laptop provided by the researcher.

2.2.3 Protocol & Data collection
A short introduction was provided to introduce the topic of falls among elderly and the use of perturbation training to reduce fall risk. The need for to quantify someone’s recovery performance was explained. Followed by a short questionnaire to gain knowledge about the fall prevention, gait analysis and perturbation training experience of the physiotherapist.

Prior to asking the physiotherapists to rate the video clips of the elderly subject being perturbed, they were shown a compilation of 12 example videos. Each perturbation type and difficulty combination was shown two times in a random order and all elderly subjects were included at least once. This video was the same for all physiotherapist and familiarized them with the videos before the start of the actual rating of the videos.

Physiotherapists were asked to rate the recovery performance of the elderly in the video clips on a scale of 10 points. A random video clip of the six combinations of perturbation type and difficulty were selected of all elderly subjects. The same video clips were shown to all physiotherapists in a random order. The physiotherapists were asked to rate a total of 66 video clips, with a short break of approximately 5 minutes halfway. The video clips consisted of a pre- and post-perturbation time of approximately 5 seconds, resulting in 10 seconds video clips. A video clip was shown only once at normal speed. The frontal and sagittal video were shown side by side simultaneously. The next video clip was started after the subject had written down the score at the provided score form. The 10 points scale was provided on the score form and available throughout the experiment.

The acceptance of the QRP and perturbation training in general is also of importance for successful implementation, therefore both the elderly and the physiotherapists were asked some qualitative questions about these topics after completion of the experiment. These results are not discussed in this paper, but a summary of this qualitative part can be found in Appendix E and F respectively.

2.3 Statistical analysis
The statistical program R (R Core Team, 2017) and the package lme4 (Bates et al., 2015) were used to perform a linear mixed effects analysis of the relation of the RRP with the QRP\textsubscript{AP} and of the relation of the RRP with the QRP\textsubscript{ML}. In the same way, a linear mixed analysis was performed for the relation of the SpD with the QRP\textsubscript{AP} and the relation of the SpD with the QRP\textsubscript{ML} and for the relation of the SpD with the PD\textsubscript{HE}. To account for the expected influences of an offset and difference in extremeness of ratings across physiotherapists, a random intercept and slope for the physiotherapist was modeled for the relation of the RRP with the QRP\textsubscript{AP} and for the relation of the RRP with the QRP\textsubscript{ML}. Similarly, the subjects were included as a random intercept and slope for the relation of the SpD with the QRP\textsubscript{AP} and the relation of the SpD with the QRP\textsubscript{ML} and the for the relation of the SpD with the PD\textsubscript{HE}. The type of perturbation was included in the all three relations as a fixed effect with an interaction term, to account for the expected influence of type on the relations. For the relation of the SpD with the PD\textsubscript{HE}, the first trial (12 perturbations) was excluded from this analysis for all subjects, as not all subjects were able to report their PD\textsubscript{HE} during the first trial.
For the described linear mixed effects models, residual plots were visually inspected to reveal deviations from homoscedasticity or normality. P-values were obtained by likelihood ratio tests of the full model with the effect in question against a model without the effect in question (Bates et al., 2015). The significance level was set to 0.05. The assumed covariance matrix was diagonal for all models.

3. Results
The results of the linear mixed models analysis are summarized in Table 2.

**QRP\textsubscript{AP}, and QRP\textsubscript{ML} validation**
Positive relations were found between the RRP and the QRP\textsubscript{AP} and between the RRP and the QRP\textsubscript{ML} (p < 0.01). Negative relations were found between the SpD and the QRP\textsubscript{AP} and between the SpD and the QRP\textsubscript{ML} (p < 0.01). The coefficient of the relation between the RRP and the QRP\textsubscript{AP} is twice as high when compared with the relation between the RRP and the QRP\textsubscript{ML}, with similar standard errors. The data points in Figures 4 and 5 represent the same perturbations and thus RRP values, but a difference in the distribution of the QRP\textsubscript{AP} and the QRP\textsubscript{ML} can be observed. The QRP\textsubscript{ML} is mainly positioned in the upper half of the graph (Figure 5), while the QRP\textsubscript{AP} values are more widely spread over the graph area (Figure 4). Equal coefficients were found for the relation between the SpD and the QRP\textsubscript{AP} and between the SpD and the QRP\textsubscript{ML} with similar standard errors. Figures 6 and 7 show that there is an offset between the QRP\textsubscript{ML} and QRP\textsubscript{AP} values. Again, the scores of the QRP\textsubscript{ML} are more densely positioned in the upper part of the graph, while the QRP\textsubscript{AP} values are lower and have a higher variation.

**SpD validation**
A positive relation was observed between the SpD and the PD\textsubscript{HE} (p < 0.01) with a coefficient of 0.79 ± 0.11 (SE). This relationship intercepts with the PD\textsubscript{HE} of zero at the SpD of 0.51.

**Physiotherapist effect**
For the QRP\textsubscript{AP}, a significant variance of intercept across physiotherapists was found (var(u\textsubscript{p}) = 1.89e-3), this can be observed in Figure 4 by looking at the offset between the lines of the physiotherapists. The line associated with physiotherapist 1 is positioned more to the right when compared to the other physiotherapists, indicating that this physiotherapists reported a higher RRP for the same QRP\textsubscript{AP}. No significant variance of intercept across physiotherapists was found for the relation between the RRP and the QRP\textsubscript{ML}. No significant effect of random slopes was found across physiotherapists, which is reflected by the similar slopes of the physiotherapists in Figures 4 and 5. The extremeness of the ratings does not vary significantly across physiotherapists.

**Subject effect**
The intercept across subjects varies significantly for the relation between the SpD and the QRP\textsubscript{AP}, var(u\textsubscript{s}) = 2.54e-3 and

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**Table 2**: The results of the linear mixed effects analysis. Including the coefficient (coef), standard error (SE), Chi-square (χ²), p-value (p) and variance (var) for all fixed and random effects.

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<th>Relation between RRP and QRP\textsubscript{AP}</th>
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<th>SE</th>
<th>χ² (1)</th>
<th>p</th>
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A stronger positive relation was found between the RRP and the QRP\textsubscript{AP} than for the relation between RRP and the QRP\textsubscript{ML}, observed by a coefficient twice as high for the relation with the QRP\textsubscript{AP} when compared with the relation with the QRP\textsubscript{ML} (Figures 4 and 5). The coefficient difference confirms that the amount of deviation from the walking pattern is higher in the AP plane than in the ML plane, most probably as a result of applying the perturbations in the AP plane. In contrast, equal coefficients were found for the relation of the SpD with the QRP\textsubscript{AP} and the relation of the SpD with the QRP\textsubscript{ML}. However, the offset indicates that a higher amount of deviation is measured in the AP plane when compared with the ML plane, suggesting that the QRP\textsubscript{AP} is a more sensitive measure than the QRP\textsubscript{ML}.

**Type effect**

For the relation of the RRP and the QRP\textsubscript{ML}, a 0.18 lower QRP\textsubscript{ML} was found for decelerations when compared with accelerations. No such significant type effect was observed for the QRP\textsubscript{AP}. No significant influence of type was found for the relation between the RRP and the QRP\textsubscript{AP} or between the RRP and the QRP\textsubscript{ML}. For the relation of the SpD and the QRP\textsubscript{AP} and for the relation of the SpD and the QRP\textsubscript{ML}, the QRP\textsubscript{AP} and the QRP\textsubscript{ML} were found to be 0.24 and 0.21 lower for decelerations respectively. The relation between the SpD and the QRP\textsubscript{AP} and the relation between SpD and QRP\textsubscript{ML} were both significantly influenced by the type of perturbation. The coefficient for these relations are 0.04 higher for decelerations than for accelerations, indicating that the QRP\textsubscript{AP} and QRP\textsubscript{ML} for decelerations are less affected by an increased SpD. Type does not significantly predict the PD\textsubscript{HE}. Type significantly influenced the relation between the SpD and the PD\textsubscript{HE}, with a 0.24 lower coefficient for decelerations when compared to accelerations. Hence, increasing the SpD results in a higher increase of the PD\textsubscript{HE} for accelerations more than for decelerations.

**SpD validation**

For a complete agreement between the SpD and the PD\textsubscript{HE}, a coefficient of 1 would be observed (as indicated by the dotted line in Figure 10). Based on the age differences between the two experiment groups, it was expected that elderly would have a small positive offset and/or a coefficient slightly higher than 1. Especially for the decelerations of subjects with a low walking speed. Based on the results of the previous study of PD\textsubscript{HY}, they would experience the perturbations about 1.8 point higher as a result of the walking speed dependency found by the regression. In contrast, the relation between the SpD and PD\textsubscript{HE} has a small negative offset and coefficient of 0.79. These results suggest that the elderly subjects of this study perceived the perturbations as less difficult and their PD\textsubscript{HE} was less affected by an increase of the SpD.

### 4. Discussion

![Figure 4: Scatter plot of the quantified recovery performance for the AP plane (QRP\textsubscript{AP}) with respect to the rated recovery performance (RRP). Regression lines are shown for physiotherapists separately.](image)

![Figure 5: Scatter plot of the quantified recovery performance for the ML plane (QRP\textsubscript{ML}) with respect to the rated recovery performance (RRP). Regression lines are shown for physiotherapists separately.](image)
Figure 6: Box plot of the quantified recovery performance for the AP plane (QRP_{AP}) for the three specified difficulties (SpD). Separately shown by type: acceleration (red) and deceleration (green).

Figure 7: Box plot of the quantified recovery performance for the ML plane (QRP_{ML}) for the three specified difficulties (SpD). Separately shown by type: acceleration (red) and deceleration (green).

Figure 8: Scatter plot of the quantified recovery performance for the AP plane (QRP_{AP}) for the three specified difficulties (SpD). The black dotted line shows the relation on group level, the colored lines show the regression line for each subject. The three SpD’s correspond to the regression values of PD_{HE} equal to 3.1 (low), 4.7 (medium) and 7.1 (high).

Figure 9: Scatter plot of the quantified recovery performance for the ML plane (QRP_{ML}) for the three specified difficulties (SpD). The black dotted line shows the relation on group level, the colored lines show the regression line for each subject. The three SpD’s correspond to the regression values of PD_{HE} equal to 3.1 (low), 4.7 (medium) and 7.1 (high).

Figure 10: Scatter plot of the perceived difficulty (PD_{HE}) for the three specified difficulties (SpD). The black dotted line shows the relation on group level, the colored lines show the regression line for each subject. The three SpD’s correspond to the regression values of PD_{HE} equal to 3.1 (low), 4.7 (medium) and 7.1 (high).
when compared to the previous PD<sub>p</sub> study. The reason for this difference is unclear and might partially originate from experiment differences, such as the system used, the prior expectations of the subjects and the provided safety instructions. Nonetheless, the positive relation does support the validity of the medium, high and low SpD used to validate the QRP<sub>AP</sub> and QRP<sub>ML</sub>.

**Physiotherapist effect**
The physiotherapists have consistently provided the RRP in relation to the QRP<sub>AP</sub> and QRP<sub>ML</sub> since no effect of slope was observed across physiotherapists. No offset of the RRP across physiotherapists was found for the relation with the QRP<sub>ML</sub>, which may partially be due to the dense distribution of the QRP<sub>ML</sub> for this relation. In line with the expectations, an offset was observed across physiotherapists for the RRP and QRP<sub>AP</sub> relation, reflecting the tendency of some physiotherapists to rate higher or lower than others. Although no studies were found with a similar comparison of the assessment of physiotherapists or other clinicians with a quantified performance measure, a few studies have examined the inter-rater variability across physiotherapists or other clinicians. The study by Smidt et al. (2002) compared the assessment of two physiotherapists for four outcome measures (severity of complaints, grip strength, and pressure pain threshold). A good inter-rater agreement was found for all outcome measures, but systematic differences were found for two of the outcome measures. Similarly, Antonaci et al. (1998) found a good inter-rater reliability when assessment of pain perception threshold was compared between two trained observers, while again a systematic difference between observers was found. These results are in line with the present study, which shows an consistency across physiotherapists with an offset. Hence, the QRP can serve as a measure which is consistent with the assessment of the physiotherapists, but without the offset observed across physiotherapists. The automatic calculation when compared to the observation by physiotherapists will reduce the attention demands of the physiotherapists, and will allow for more interaction with the client.

**Subject effect**
Slope variability was found across subjects for the relation of the SpD with the QRP<sub>ML</sub>, while no slope variability across subjects was found for the relation between the SpD and the QRP<sub>AP</sub>. One explanation may be that for some recovery strategies the QRP<sub>ML</sub> is affected more by an increased SpD than for other recovery strategies. As recovery strategies may differ across subjects, this would explain the differences in slopes observed for the relation between the SpD and the QRP<sub>ML</sub>. A part of the decline in the QRP<sub>AP</sub> and QRP<sub>ML</sub> as a result of an increased SpD, is inherent to the increase in the mechanically applied perturbation. To maintain a safe position on the treadmill for a higher SpD perturbation, it is required to make larger adjustments and thus deviate more from the unperturbed walking pattern. However, the offset across subjects indicates that a difference in QRP<sub>AP</sub> and QRP<sub>ML</sub> for all used SpD's can be measured for the relatively healthy elderly of this study (Figures 8 and 9). The offset suggests that a difference in performance can be measured across subjects.

As expected, a high variance can be observed between the intercepts of subjects for the relation between the SpD and the PD<sub>HE</sub>, since some subjects will perceive the perturbations as more or less difficult than other subjects (Figure 10). In addition to this, the slopes also vary significantly across subjects, which confirms that the PD<sub>HE</sub> of subjects is affected differently by a change of SpD. Multiple subjects mentioned that the scale was difficult to use, which may also explain some of the variability across subjects.

**Type effect**
The lower QRP<sub>ML</sub> for decelerations observed for the relation with the RRP, suggests that the deviation in the ML plane from the unperturbed walking template was higher for decelerations than for accelerations. Possibly, this is a result of different strategies for the decelerations and accelerations (Eng et al., 1994; Yang et al., 2008), different movements may result in higher or lower deviations. The absence of an interaction effect between the type and the relation of RRP with QRP<sub>AP</sub> and QRP<sub>ML</sub> indicates that the extremeness of the scores provided by physiotherapists is not different for accelerations and decelerations.

The influence of type on the relation between the SpD and the QRP<sub>AP</sub> and between the SpD and the QRP<sub>ML</sub> suggests that the different strategies used for accelerations and decelerations (Eng et al., 1994; Yang et al., 2008) are reflected by differences in the QRP<sub>AP</sub> and the QRP<sub>ML</sub>. A lower QRP<sub>AP</sub> and QRP<sub>ML</sub> for decelerations show that subjects deviated more from their unperturbed walking template for decelerations than for accelerations. The QRP<sub>AP</sub> and the QRP<sub>ML</sub> of accelerations is more affected by an increase of the SpD when compared to the QRP<sub>AP</sub> and the QRP<sub>ML</sub> of decelerations. Figures 6 and 7 show that the low and medium SpD result in a lower QRP<sub>AP</sub> and QRP<sub>ML</sub> for decelerations, while a higher QRP<sub>AP</sub> and QRP<sub>ML</sub> for decelerations is shown for the high SpD. This may be a direct result of the mechanical characteristics of the perturbations. The acceleration and deceleration differ most in duration for the high SpD (Table 1), for which the duration of the acceleration perturbation is higher. The lower QRP<sub>AP</sub> and QRP<sub>ML</sub> for accelerations...
with the high SpD may partially be explained by this difference, although this relatively small difference of about 10% unlikely explains the lower QRP_{AP} and QRP_{ML} for accelerations completely.

The interaction of type with the relation between the SpD and the PD_{HE} is significant, with a higher coefficient for the accelerations than for the deceleration perturbations. In other words, increasing the SpD affected the PD_{HE} more for acceleration than for decelerations. This is in line with the higher impact of the SpD on the QRP_{AP} and QRP_{ML} for accelerations. Apparently, the QRP_{AP} and QRP_{ML} and the PD_{HE} are similarly affected by the increase in SpD.

**Study limitations**

This study has several limitations. First, the subjects of this study were relatively healthy, community-dwelling elderly without any known (age-related) neurological pathologies or cognitive impairment. Hence, it remains unclear whether the results of this study generalize to the elderly population. Elderly have a higher gait variability (Mirelman et al., 2015), with an even higher variability observed among elderly fallers when compared to non-fallers (Barak et al., 2006).

Further research including frail elderly, with a more variable walking pattern, would be desired to validate whether the measure is still consistent with the RRP and the SpD. Second, the results of this study only apply for acceleration and deceleration perturbations, as the relations with the QRP_{AP} and the QRP_{ML} may be different for perturbations applied in the ML plane.

**Recommendations**

Providing normative data will help both physiotherapists and clients to better interpret the obtained QRP.

5. **Conclusions**

Although both for the QRP_{AP} and the QRP_{ML}, a positive relation was found with the RRP and a negative relation was found for the SpD, the results suggest that especially the QRP_{AP} is a promising measure. For the types of perturbations addressed in this study, accelerations and decelerations, the QRP_{AP} was found to have a stronger relation with the RRP and was observed to be a more sensitive measure when compared to the QRP_{ML}. The positive relation between the SpD and the PD_{HE} supports the assumed increase in difficulty with the specified perturbation characteristics for the SpD. Consistency across physiotherapists and the sensitivity to measure differences across subjects for the three SpD’s shows that the QRP_{AP} can be used to objectively measure the recovery performance of healthy elderly subjects.

This can contribute to the effectiveness and efficiency of perturbation training, which can reduce fall risk in elderly.

**Acknowledgments**

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**References**


Appendix
APPENDIX

Subject characteristics - Elderly and physiotherapists

Table A.1 Subject characteristics of the elderly subjects.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age (years)</th>
<th>Male (0) / Female (1)</th>
<th>Length (m)</th>
<th>Weight (kg)</th>
<th>Walking speed (m/s)</th>
<th>12-months fall history</th>
<th>Excluded from study</th>
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<tr>
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<td>64.4</td>
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<td>0</td>
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<td>1</td>
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<td>74.6</td>
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<tr>
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<td>49.9</td>
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<td>0</td>
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<td>1.60</td>
<td>80.9</td>
<td>1</td>
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Table A.2 Subject characteristics of the physiotherapists. The physiotherapists were asked to report their years of experience as a physiotherapists, with fall prevention training, performing gait analysis and with perturbation training.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age</th>
<th>Male (0) / Female (1)</th>
<th>As physiotherapist (# years)</th>
<th>With fall prevention (# years)</th>
<th>Gait analysis (# years)</th>
<th>Perturbation training (# year)</th>
</tr>
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<tr>
<td>3</td>
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<td>1</td>
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<td>10</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
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<td>0</td>
<td>5</td>
<td>0</td>
<td>**</td>
<td>**</td>
</tr>
<tr>
<td>5</td>
<td>52</td>
<td>1</td>
<td>28</td>
<td>*</td>
<td>**</td>
<td>***</td>
</tr>
</tbody>
</table>

* Sometimes
** Just started
*** Could not express in years
The elderly subjects of part I of this study were asked a view questions before and after experiencing the perturbations on the treadmill with regard to their attitude towards perturbation training. This was performed in a setting of a conversation with open questions to gain input, rather than an interview following a strict protocol. Therefore, questions differed a bit from subject to subject. The answers to these questions are summarized in Table 6. Question 1 and 2 were asked prior to the walking trials, whereas the other questions were asked after the experiencing the perturbations. This qualitative part of the study described in this appendix as some important conclusions could be drawn based on these conversations, regarding the implementation of perturbation training and the use of a quantified recovery performance (QRP) to motivate elderly.

Table A.6: A summary of the attitudes observed in elderly when asked some of the six questions listed. Green (+) indicates a positive attitude, red(-) indicates a negative attitude and gray (?) indicates that no clear response was provided. The empty cells indicate that the question was not asked for this subject, as a result of the conversation rather than interview structure.
From the first line of Table A.6 it can be seen that, except for one subject, all subjects had a positive attitude towards perturbation training to reduce fall risk. One subject stated to not have an opinion before experiencing it. Especially noteworthy was the effect of the terminology when subjects were asked whether they would participate in this type of training (question 2.a or 2.b). It became evident that elderly were less likely to answer positively when it was defined as fall prevention, as opposed to defining it as exercise to stay fit while getting older. This could in part be due to the relatively healthy group of elderly, but is likely to be generalizable to the elderly population to some extent. The three subjects who were asked whether they would like a score at the end of a training session all replied positively towards this idea. A score for each perturbation would be too excessive.

Furthermore, four subjects mentioned that they felt safe walking on the treadmill, especially due to the assurance brought by wearing the harness. Multiple subjects noted that the handrails were missing and one subject noted that the system is quite large. Two subjects reached to a pole in front of them during the highest difficulty acceleration perturbation, this pole is part of the safety portal to which the harness is connected. One of these subjects kept holding onto this pole due to a panic reaction, which lead to an unsafe situation and finally resulted in an emergency stop caused by the connection of the harness to the safety portal. This subject did not finish the trials as she felt uncomfortable to continue.

One subject felt like the perturbations were unrealistic, while multiple subjects stated that the deceleration perturbations were more closely resembling real life perturbations. In addition to this, three subjects suggested that sideways perturbations could be included to resemble real life perturbations and increase the difficulty of the perturbations.

**Conclusions**

- The elderly subjects had a positive attitude towards the use of perturbations to reduce fall risk.
- The training should be phrased to elderly as a way to keep fit, rather than a fall prevention training.
- There should either be a handrail or nothing to grab at all.
- A performance score at the end of a training will motivate elderly.