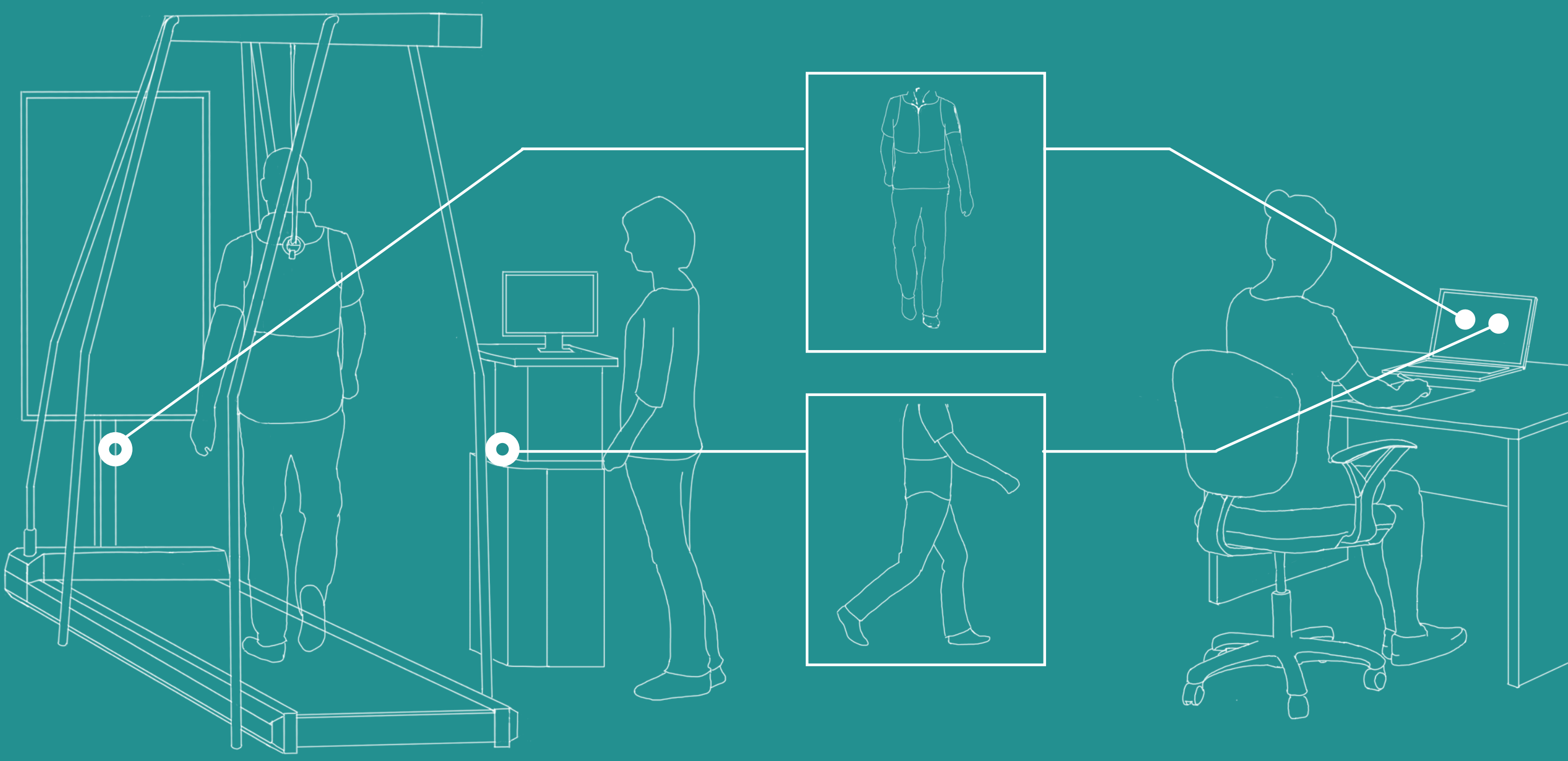
Perturbation training to reduce fall risk in elderly: validating the quantified recovery performance measure by means of the assessment by physiotherapists

Master's Thesis Marleen Meeuwsen



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by

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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 health care 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.

To make perturbation training accessible for elderly a system has been specified for a clinical setting in such way that is less expensive, less complex and requires less space than the systems currently used in research settings. In addition, this system should be capable of measuring the ability of clients to recover when encountering a perturbation. The quantification of the recovery performance is of importance to enable objective monitoring of progress over training sessions, which in turn can (1) help physiotherapists to consistently adjust perturbation difficulty to the ability of the client, (2) serve for motivational purposes for the client and (3) help to convince health care providers of the positive effect of perturbation training.

Previous studies have used several indicators to quantify elements of recovery performance, but these measures do not match with the requirements for the specified system. The measurement instrument is restricted to a one dimensional force plate, because of the constraints to the price, size and complexity of the system for the clinical application. Hence, measures which require a motion capture system or accelerometer like the margin of stability (Hof et al., 2005), the feasible stability region (Pai & Patton, 1997) and trunk kinematics (Owings et al., 2001; Sessoms et al., 2014) cannot be used. Furthermore, the measure should be calculated without manual post-processing of the physiotherapist or clinician for time efficiency and simplicity of use. When no manual post-processing can be used, the measure cannot rely on the detection of gait events, such as heel strike and toe-off, directly following a perturbation. Gait events are detected based on someone's gait pattern, consequently automatic gait event detection will not be possible when someone's gait pattern is perturbed (for more details, see Appendix D). Spatio-temporal gait parameters such as step length and step width rely on the detection of gait events, which means that no measures can be implemented which use the time to recover to the baseline value of spatio-temporal gait parameters (Krasovsky et al., 2012). In addition to this, multiple recovery strategies are observed for trips (Eng et al.,1994) and for slips (Yang et al., 2008) and some subjects perform cross-steps (Vlutters et al., 2016) and steps back (Yang et al., 2014). Hence, the measure should be able to quantify recovery performance for these different ways of recovering, with a force plate only and without gait event detection directly following a perturbation.

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 constructed QRP is based on the fact that humans have a relatively constant pattern during unperturbed gait, the required movements for each gait cycle are approximately the same. This gait pattern also results in a relatively constant pattern of the center of pressure (COP) trajectory, as the COP trajectory is determined by foot placement and the control of the center of mass (COM). The proposed measure for the QRP utilizes this property of gait, since a perturbation will result in a deviation from this pattern. The amount of deviation from the unperturbed walking pattern after a perturbation is used as a measure to quantify someone's recovery performance. In other words, if someone deviates a lot from their unperturbed walking pattern this will result in a low QRP. Whereas someone who is able to continue walking without large deviations from the unperturbed walking pattern will get a high QRP. This measure reflects the magnitude of a deviation in foot placement and the COM control, but it also incorporates the time to recover from a perturbation. The QRP can be calculated for the COP trajectory in the anteroposterior (AP) and mediolateral (ML) plane, resulting in a QRP_{AP} and QRP_{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 QRP_{AP} and QRP_{ML}. Second, by studying the effect of the specified difficulty (SpD) of a perturbation on the QRP_{AP} and QRP_{M}. When increasing the SpD of the perturbation, it is expected that the QRP_{AP} and QRP_{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 QRP_{AP} and the RRP and between the QRP_{AP} and SpD are expected when compared to the relations with the QRP_{ML}.

The SpD of the perturbations used throughout this study are based on previous work by the Clinical Applications department of Motekforce Link. The perturbation characteristics for each SpD are based on a test with eleven healthy young subjects who experienced perturbations with a variety of acceleration, deceleration and duration combinations for different walking speeds. The perceived difficulty (PD_{HY}) reported by these healthy young subjects for each perturbation, was used to perform a regression analysis. The outcome of this regression analysis was used to specify perturbations difficulties. To verify that the SpD also holds for the healthy elderly of this study, consistency between the SpD (based on the PD_{HY} which followed from the regression) with the perceived difficulty as reported by the healthy elderly subjects (PD_{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_{AP} and the relation between the SpD and the QRP_{ML}, since the ability to recover from perturbations will differ across subjects and the reduction in QRP_{AP} and QRP_{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_{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.

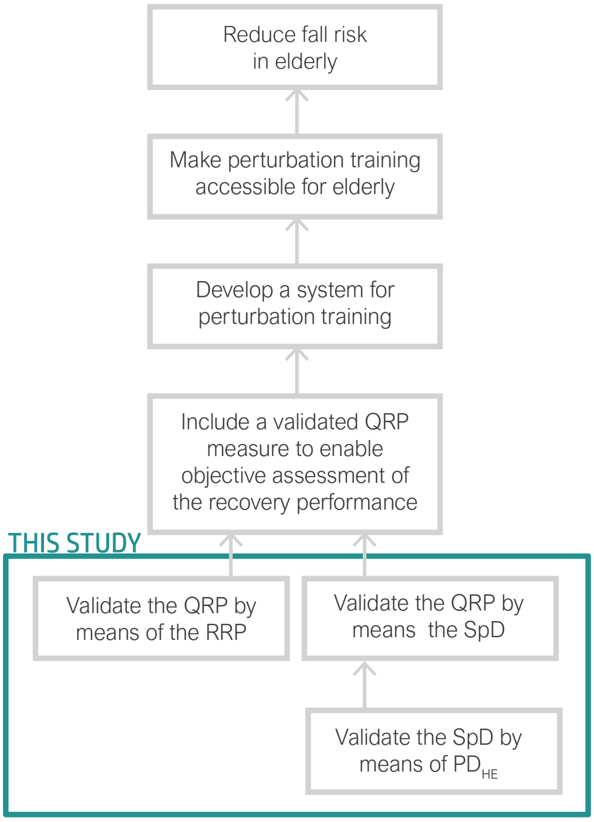

Figure 1: Overview of the scope of this study. For effective reduction of fall risk in elderly with perturbation training, a system is required which incorporates a validated measure to quantify the recovery performance of clients. During this study, the quantified recovery performance (QRP) will be validated by means of the rated recovery performance (RRP) provided by physiotherapists and by means of the specified difficulty (SpD). The used SpD will be validated by the perceived difficulty (PD_{HE}) of the subjects.

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_{AP} and the relation between the RRP and the QRP_{ML}. Additionally, an interaction effect is expected between the type of perturbation and the relationship between the SpD and the QRP_{AP} and the relation between the SpD and the QRP_{ML}, based on the expected difference in deviation from the unperturbed walking pattern. The SpD was defined with a regression for accelerations and decelerations separately, readily taking into account a part of the effect of type. However, as the SpD test is based on a relatively small sample (n = 11) of healthy young subjects, it is expected that some effect of type can still be observed for this study with healthy elderly. One type may be perceived more or less difficult than the other type and the effect of increased SpD may affect the PD_{HE} differently.

In summary, it was hypothesized that a positive relation exists between the RRP and the QRP_{AP} and between the RRP and the QRP_{ML} and a that negative relation exists between the SpD and the QRP_{AP} and between the SpD and the QRP_{ML}. These relations are expected to be stronger with the QRP_{AP} than with the QRP_{ML}. Furthermore, a positive relation between the SpD and the PD is expected. It is expected that the RRP and QRP_{AP} and the RRP and QRP_{ML} relation is influenced by the physiotherapist. The relation of the SpD with the QRP_{AP}, the SpD with the QRP_{ML} and the SpD with the PD_{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_{AP} and QRP_{ML} were measurement separately from the RRP, as depicted in Figure 2. Pilot studies were performed to verify that the required perturbation characteristics could be performed by the system and that gait event detection during unperturbed walking was acceptable (Appendix A and B).

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 PD_{HY} of the previous test indicated that walking speed influenced the PD_{HY} 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 PD_{HE} after each perturbation on a 15-points Borg scale (Chen et al., 2002). The PD_{HE} was written down by the researcher. Table 1 shows the specified perturbation characteristics

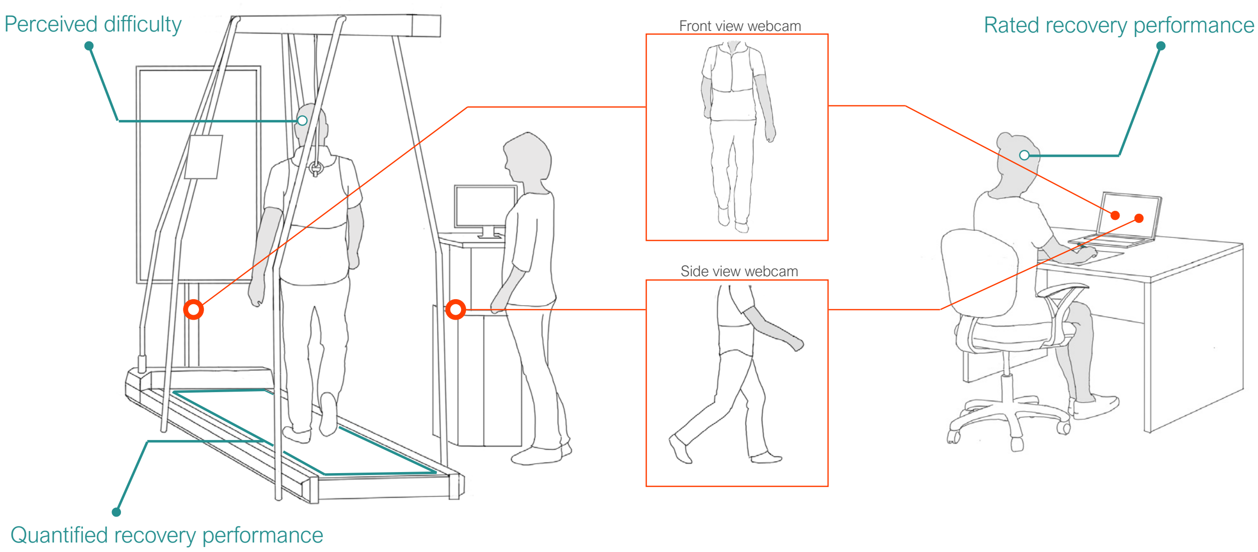

Figure 2: Overview of the two parts of this study. Left side: Elderly subjects experienced perturbations (accelerations and decelerations) while walking on a treadmill. The quantified recovery performance (QRP) was calculated for each perturbation. In addition to this, subjects were instructed to verbally communicate the perceived difficulty (PD_{HE}) 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_{HY} 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. The variability of the position of the subject on the treadmill is removed by means of a 0.5 Hz high-pass second order Butterworth filter.

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_{AP} and QRP_{ML} respectively.

Step 1: Selecting the pre- and post-perturbation window

A 5 second pre-perturbation and a 5 second post-perturbation window of the COP trajectory was selected.

Step 2: Constructing unperturbed walking template

CueFors (Software, Motekforce Link, Amsterdam) was used to detect gait events during the pre-perturbation window. Automatic gait event detection can be used for this pre-perturbation window, as the subject is not perturbed in this window and no large deviation from the gait pattern occurs. The gait cycles were determined by using toe-off right as the start and end of a gait cycle. The average gait cycle length was calculated and the gait cycles were time normalized to this average gait cycle length. The constructed 'average' gait cycle was repeated to construct the template of unperturbed walking.

Table 1: The accelerations and durations for specified difficulties (SpD) used during this study. The second column shows the percieved difficulty for healthy young subjects PD_{HY} based on the regression of the previous study. A 1 m/s² acceleration/deceleration is used for all SpD to return to the walking speed.

Type	SpD	PD_{HY}	Acceleration (m/s²)	Duration (s)
Acc	Low	3.1	1.5	0.27
	Medium	4.7	2	0.33
	High	7.1	2.5	0.46
Dec	Low	3.1	-1.5	0.26
	Medium	4.7	-2	0.31
	High	7.1	-2.5	0.42

Step 3: Aligning the post-perturbation signal to the template signal

To align the post-perturbation COP trajectory with the constructed unperturbed walking template, the cross-correlation coefficient between the two signals was calculated. The maximum value of the cross-correlation coefficient was used to determine the required time shift to align the two signals.

Step 4: Calculation of the amount deviation

The Pearson correlation coefficient of the unperturbed walking template and the post-perturbation signal can now be calculated to get the QRP_{AP} and QRP_{ML}.

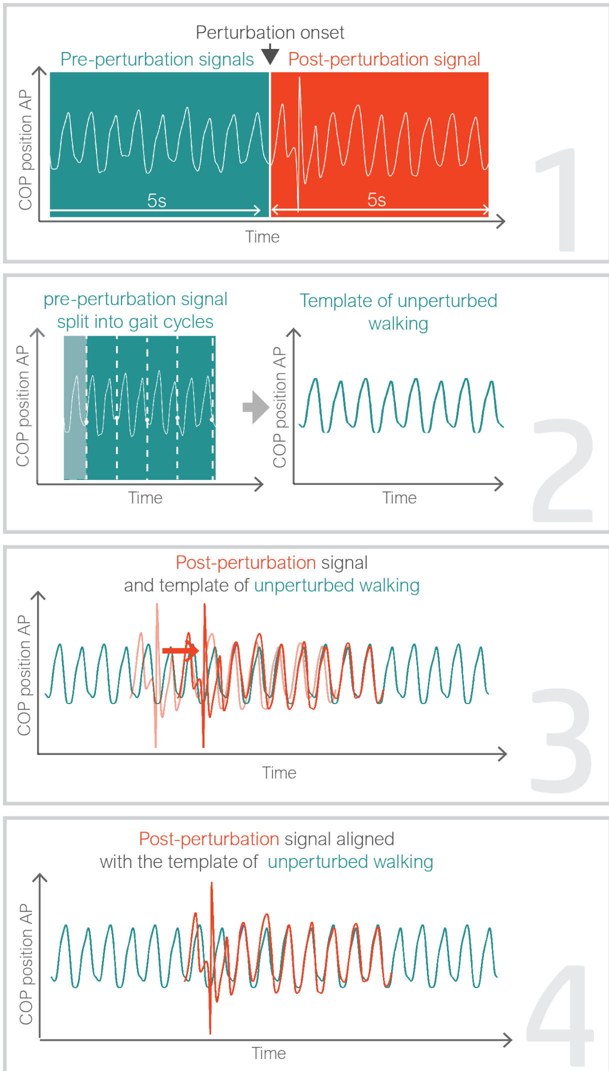

Figure 3: The fours steps to calculate the quantified recovery performance (QRP) illustrated for the AP plane. (1) A 5 second pre- and post-perturbation window are selected. (2) Gait cycles are detected and used to create a template of unperturbed walking. (3) The post-perturbation signal is aligned with the unperturbed walking pattern by means of a cross-correlation. (4) The Pearson correlation is calculated for the aligned signals.

C. *Correcting for errors*
Before performing the statistical analysis, a visual inspection of the data was performed. Boxplots of the QRP_{AP} and the QRP_{ML} for the SpD for all elderly subjects were inspected for the acceleration and deceleration perturbations. Perturbations for which the QRP_{AP} or QRP_{ML} deviated considerable from the other perturbations of the subject were listed and the signals were analysed in more detail. By inspecting the signals of these perturbations, it was discovered that some of the pre-perturbation windows coincided with the post-perturbation window of the previous perturbation. Hence, a recovery response was observed in the pre-perturbation window, which resulted in an incorrect unperturbed walking template. This occurred for 76 out of the total 660 perturbations, for these perturbations the pre-perturbation window was reduced to 3 seconds. Furthermore, problems occurred due to inaccurate or no gait event detection or an irregular gait pattern in the pre-perturbation window. Additionally, a measurement error was found and one perturbation was not executed by the system. This resulted in the removal of a total of 12 perturbations from the data. Appendix D shows examples of the observed problems for QPR_{AP} and QRP_{ML} calculation.

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_{AP} and of the relation of the RRP and the QRP_{ML}. In the same way, a linear mixed analysis was performed for the relation of the SpD with the QRP_{AP} and the relation of the SpD with the QRP_{ML} and for the relation of the SpD with the PD_{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_{AP} and for the relation of the RRP with the QRP_{ML}. Similarly, the subjects were included as a random intercept and slope for the relation of the SpD with the QRP_{AP}, for the relation of the SpD with the QRP_{ML} and the for the relation of the SpD with the PD_{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_{HE}, the first trial (12 perturbations) was excluded from this analysis for all subjects, as not all subjects were able to report their PD_{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_{AP} and QRP_{ML} validation

Positive relations were found between the RRP and the QRP_{AP} and between the RRP and the QRP_{ML} ($p < 0.01$). Negative relations were found between the SpD and the QRP_{AP} and between the SpD and the QRP_{ML} ($p < 0.01$). The coefficient of the relation between the RRP and the QRP_{AP} is twice as high when compared with the relation between the RRP and the QRP_{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_{AP} and the QRP_{ML} can be observed. The QRP_{ML} is mainly positioned in the upper half of the graph (Figure 5), while the QRP_{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_{AP} and between the SpD and the $QRP_{ML,}$ with similar standard errors. Figures 6 and 7 show that there is an offset between the QRP_{ML} and QRP_{AP} values. Again, the scores of the QRP_{ML} are more densely positioned in the upper part of the graph, while the QRP_{AP} values are lower and have a higher variation.

SpD validation

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

Physiotherapist effect

For the QRP_{AP} a significant variance of intercept across physiotherapists was found ($var(u_{oj})$ = 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_{AP}. No significant variance of intercept across physiotherapists was found for the relation between the RRP and the QRP_{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 variates significantly for the relation between the SpD and the QRP_{AP}, $var(u_{oj})$ = 0.01, indicating an offset for this relation across subjects (Figure 8). Both the intercepts and the slope across subjects vary significantly for the relation between the SpD and the QRP_{ML}, $var(u_{oj})$ = 2.54e-3 and

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

Relation between RRP and QRP_{AP}				
Fixed effects	Coef	SE	χ^2 (1)	p
RRP	*0.08*	*0.01*	*28.21*	*< 0.01*
Type	*-0.12*	*0.07*	*0.06*	*0.80*
*RRP * Type*	*0.02*	*0.01*	*3.08*	*0.08*
Random effects	Var		χ^2 (1)	p
PT intercept	*1.89e-3*		*13.20*	*< 0.01*
PT slope	*0.00*		*0.00*	*1*
Relation between RRP and QRP_{ML}				
Fixed effects	Coef	SE	χ^2 (1)	p
RRP	*0.04*	*0.01*	*25.78*	*< 0.01*
Type	*-0.18*	*0.09*	*4.32*	*< 0.05*
*RRP * Type*	*0.02*	*0.01*	*2.60*	*0.12*
Random effects	Var		χ^2 (1)	p
PT intercept	*3.84e-4*		*0.79*	*0.37*
PT slope	*0.00*		*0.00*	*1*
Relation between SpD(PD_{HY}) and QRP_{AP}				
Fixed effects	Coef	SE	χ^2 (1)	p
SpD	*-0.08*	*5.15e-3*	*38.94*	*< 0.01*
Type	*-0.24*	*0.04*	*5.31*	*< 0.01*
*SpD * Type*	*0.04*	*0.01*	*32.74*	*< 0.01*
Random effects	Var		χ^2 (1)	p
Subject intercept	*0.01*		*149.47*	*< 0.01*
Subject slope	*0.00*		*0.00*	*1*
Relation between SpD(PD_{HY}) and QRP_{ML}				
Fixed effects	Coef	SE	χ^2 (1)	p
SpD	*-0.079*	*5.91e-3*	*29.52*	*< 0.01*
Type	*-0.21*	*0.03*	*7.59*	*< 0.01*
SpD Type*	*0.04*	*0.01*	*29.35*	*< 0.01*
Random effects	Var		χ^2 (1)	p
Subject intercept	*2.54e-3*		*48.74*	*< 0.01*
Subject slope	*1.51e-4*		*13.92*	*< 0.01*
Relation between SpD(PD_{HY}) and PD_{HE}				
Fixed effects	Coef	SE	χ^2 (1)	p
SpD	*0.79*	*0.11*	*18.06*	*< 0.01*
Type	*1.13*	*0.59*	*0.04*	*0.84*
*SpD * Type*	*-0.24*	*0.11*	*4.39*	*< 0.05*
Random effects	Var		χ^2 (1)	p
Subject intercept	*2.76*		*371.81*	*< 0.01*
Subject slope	*0.08*		*12.94*	*< 0.01*

$var(u_{1j})$=1.51e-4, indicating an offset and a different coefficient for this relation across subjects. For the relation of the SpD with the PD_{HE}, the intercept between subjects varies significantly ($var(u_{oj})$ = 2.76) as well as the slope between subjects ($var(u_{1j})$=0.08), this can be observed in Figure 10. An offset of the PD_{HE} exists between subjects as well as a different coefficient for the SpD and the PD_{HE} relation.

Type effect

For the relation of the RRP and the QRP_{ML}, a 0.18 lower QRP_{ML} was found for decelerations when compared with accelerations. No such significant type effect was observed for the QRP_{AP}. No significant influence of type was found for the relation between the RRP and the QRP_{AP} or between the RRP and the QRP_{ML}. For the relation of the SpD and the QRP_{AP} and for the relation of the SpD and the QRP_{ML}, the QRP_{AP} and the QRP_{ML} were found to be 0.24 and 0.21 lower for decelerations respectively. The relation between the SpD and the QRP_{AP} and the relation between SpD and QRP_{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_{AP} and QRP_{ML} for decelerations are less affected by an increased SpD. Type does not significantly predict the PD_{HE}. Type significantly influenced the relation between the SpD and the PD_{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_{HE} for accelerations more than for decelerations.

4. Discussion

QRP_{AP} and QRP_{ML} validation

A stronger positive relation was found between the RRP and the QRP_{AP} than for the relation between RRP and the QRP_{ML}, observed by a coefficient twice as high for the relation with the QRP_{AP} when compared with the relation with the QRP_{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_{AP} and the relation of the SpD with the QRP_{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_{AP} is a more sensitive measure than the QRP_{ML}.

SpD validation

For a complete agreement between the SpD and the PD_{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_{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_{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_{HE} was less affected by an increase of the SpD

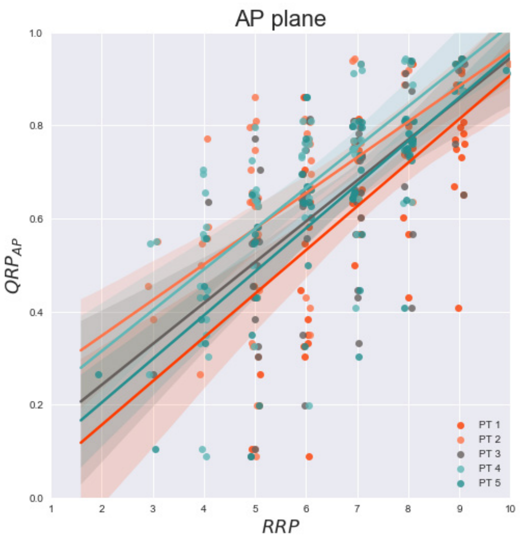

Figure 4: Scatter plot of the quantified recovery performance for the AP plane (QRP_{AP}) with respect to the rated recovery performance (RRP.) Regression lines are shown for physiotherapists separately.

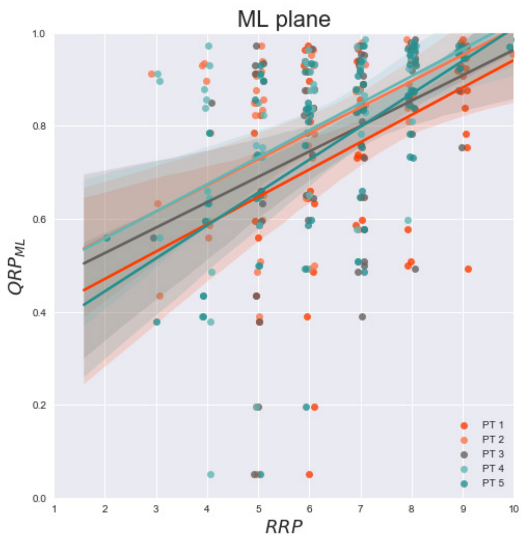

Figure 5: Scatter plot of the quantified recovery performance for the ML plane (QRP_{ML}) with respect to the rated recovery performance (RRP.) Regression lines are shown for physiotherapists separately.

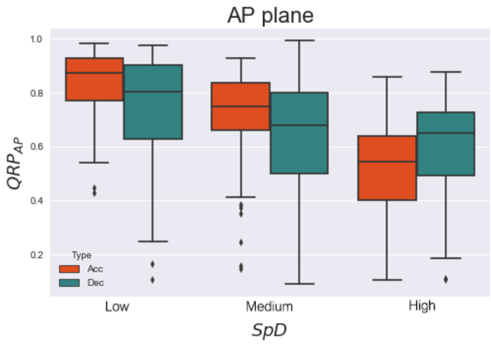

Figure 6: Box plot of the quantified recovery performance for the AP plane (QRP_{AP}) for the three specified difficulties (SpD). Separately shown by type; acceleration (red) and deceleration (green)

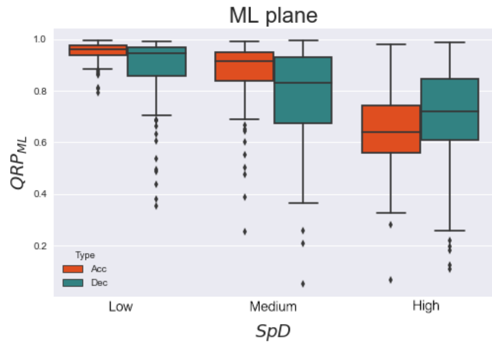

Figure 7: Box plot of the quantified recovery performance for the ML plane (QRP_{ML}) for the three specified difficulties (SpD). Separately shown by type; acceleration (red) and deceleration (green)

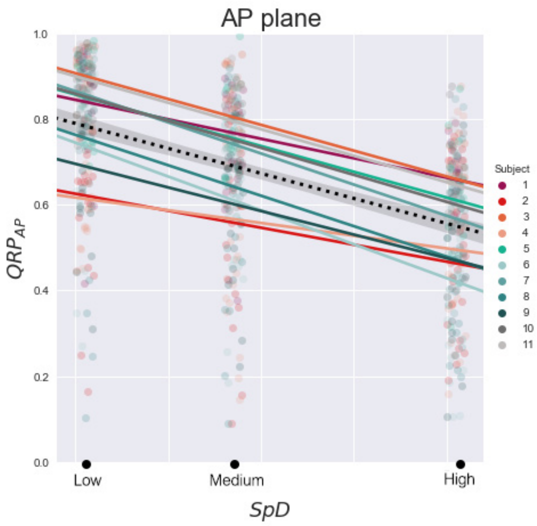

Figure 8: Scatter plot of the quantified recovery performance for the AP plane (QRP_{AP}) for the three specified difficulties (SpD). The black dotted line shows the relation on group level, the colored lines show the regression line for each subject. The three SpD's correspond to the regression values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

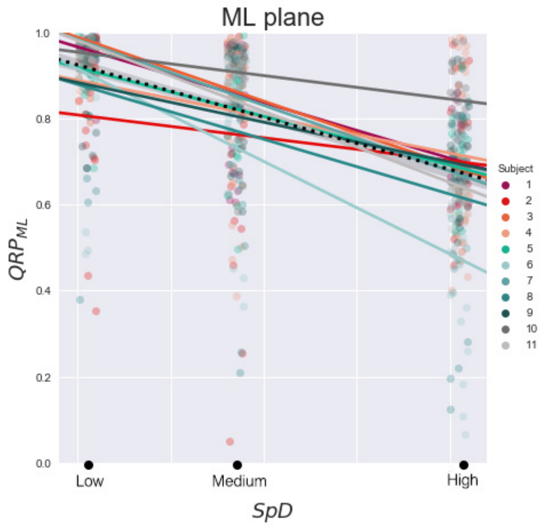

Figure 9: Scatter plot of the quantified recovery performance for the ML plane (QRP_{ML}) for the three specified difficulties (SpD). The black dotted line shows the relation on group level, the colored lines show the regression line for each subject. The three SpD's correspond to the regression values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

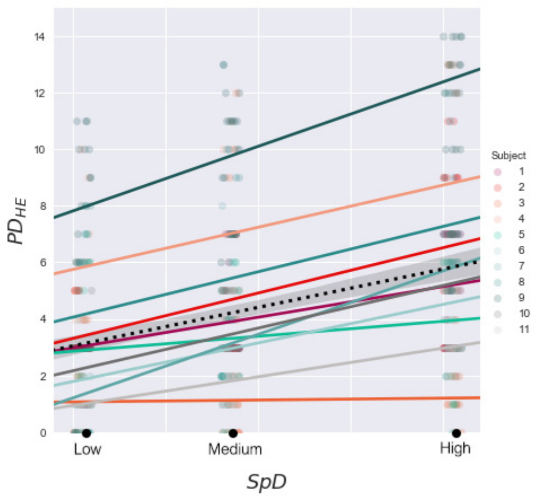

Figure 10: Scatter plot of the perceived difficulty (PD_{HE}) for the three specified difficulties (SpD). The black dotted line shows the relation on group level, the colored lines show the regression line for each subject. The three SpD's correspond to the regression values of PD_{HY} equal to 3.1 (low), 4.7 (medium) and 7.1 (high).

when compared to the previous PD_{HY} 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_{AP} and QRP_{ML}.

Physiotherapist effect

The physiotherapists have consistently provided the RRP in relation to the QRP_{AP} and QRP_{ML}, since no effect of slope was observed across physiotherapists. No offset of the RRP across physiotherapists was found for the relation with the QRP_{ML}, which may partially be due to the dense distribution of the QRP_{ML} for this relation. In line with the expectations, an offset was observed across physiotherapists for the RRP and QRP_{AP} 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_{ML}, while no slope variability across subjects was found for the relation between the SpD and the QRP_{AP}. One explanation may be that for some recovery strategies the QRP_{ML} 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_{ML}. A part of the decline in the QRP_{AP} and QRP_{ML}, 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_{AP} and QRP_{ML} 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_{HE}, 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_{HE} 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_{ML} 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_{AP} and QRP_{ML} 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_{AP} and between the SpD and the QRP_{ML} 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_{AP} and the QRP_{ML}. A lower QRP_{AP} and QRP_{ML} for decelerations show that subjects deviated more from their unperturbed walking template for decelerations than for accelerations. The QRP_{AP} and the QRP_{ML} of accelerations is more affected by an increase of the SpD when compared to the QRP_{AP} and the QRP_{ML} of decelerations. Figures 6 and 7 show that the low and medium SpD result in a lower QRP_{AP} and QRP_{ML} for decelerations, while a higher QRP_{AP} and QRP_{ML} 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_{AP} and QRP_{ML} 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). A high variability in the pre-perturbation window may reduce the sensitivity of the QRP_{AP} and QRP_{ML} to measure deviations. 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 increases 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. The QRP_{AP}, based on force plate data only, can remove the offset observed across physiotherapists and allows the physiotherapist to focus on the interaction with clients, as no manual-post processing or rating of the recovery performance is required. This can contribute to the effectiveness and efficiency of perturbation training, which can reduce fall risk in elderly.

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Appendix

APPENDIX A

Subject characteristics - Elderly and physiotherapists

Table A.1 Subject characteristics of the elderly subjects.

Subject	Age (years)	Male (0) / female (1)	Length (m)	Weight (kg)	Walking speed (m/s)	12-months fall history	Excluded from study
1	65	0	1.78	85,8	0,9	0	0
2	76	1	1.56	64,4	0,4	1	0
3	73	1	1.70	75,3	0,7	1	1
4	70	0	1.70	74,6	1	0	0
5	77	1	1.65	49,9	0,3	0	0
6	69	1	1.62	61,5	1	0	0
7	71	1	1.72	78,5	1	0	0
8	77	0	1,76	74,1	1	0	0
9	80	1	1.64	82,3	1	0	0
10	82	0	1.78	87,9	0,7	0	0
11	77	1	1.60	52,8	0,7	0	0
12	68	1	1.60	80,9	1	0	0

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.

			Experience			
Subject	Age	Male (0)/ Female (1)	As physiotherapist (# years)	With fall prevention (# years)	Gait analysis (# years)	Perturbation training (# year)
1	57	1	30	14	0	0
2	48	1	26	0	2	3
3	61	1	40	10	0	0
4	29	0	5	0	**	**
5	52	1	28	*	**	***

* Sometimes
** Just started
*** Could not express in years

APPENDIX B

Summary and examples of QRP calculations problems

Table A.3 Summary of problems observed for calculation the QRP_{AP} and the QRP_{ML}, the actions that were performed to deal with these problems and the frequency of the occurrence.

Problem	Action	Frequency
1. Time between perturbations too short	Shorten pre-perturbation window	76
2. Inaccurate/no gait event detection	Remove perturbation from analysis	7
3. Irregularity in pre-perturbation window	Remove perturbation from analysis	2
4. Measurement/filter error	Remove perturbation from analysis	1
5. Perturbation not executed by treadmill	Remove perturbation from analysis	2

Table A.3 shows a summary of the problems encountered for the QRP_{AP} and QRP_{ML} calculations for this study. This appendix will shortly address each problem and provide figures to illustrate the problems.

1. Time between perturbations too short

The recovery from a previous perturbation was in some cases visible in the pre-perturbation window of the next perturbation (Figure A.1). This deviation from the baseline walking pattern results in an incorrect template to which the post-perturbation signal will be compared (Figure A.2). This has been adjusted by using a 3 sec pre-perturbation window instead of 5 seconds for these trials.

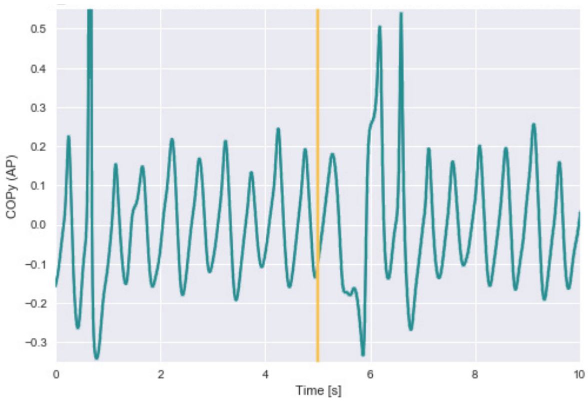

Figure A.1: Example of the recovery response from the previous perturbation in the pre-perturbation window of the current analyzed perturbation.

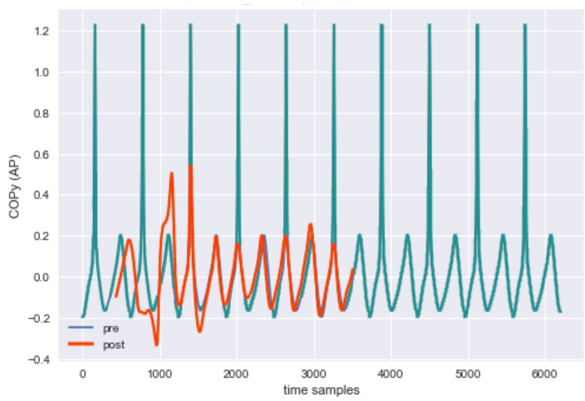

Figure A.2: Example of an incorrect unperturbed walking template as a result of the recovery response in the pre-perturbation window.

2. Inaccurate/no gait event detection
For some of the pre-perturbation windows gait events were not detected properly (Figure A.3). When one or multiple gait events are not detected, the estimation of the gait cycle fails and the constructed template will be incorrect (Figure A.4). This was observed for 7 perturbations, which were excluded from the data analysis.

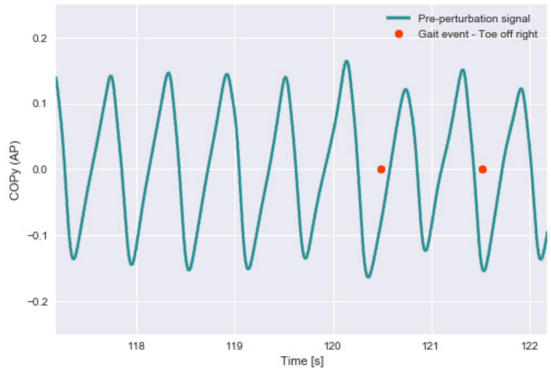

Figure A.3: Example of gait events not detected properly.

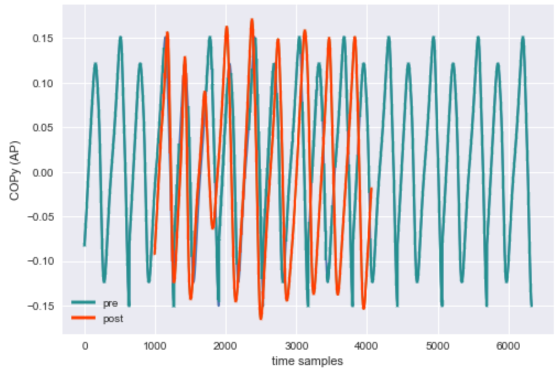

Figure A.4: Example of an incorrect unperturbed walking template as a result of missing gait events.

3. Irregularity in pre-perturbation window
In some cases, the pre-perturbation window contained some deviation of the regular pattern without any known reason (Figure A.5). This will be reflected in the template by which the post-perturbation signal is compared (Figure A.6). This occurred two times and these two perturbations were excluded from the analysis.

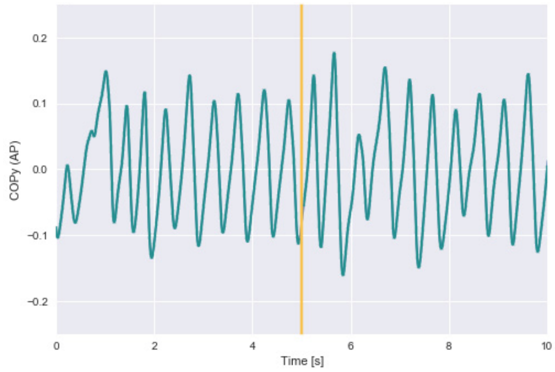

Figure A.5: Example of deviation from regular pattern in pre-perturbation window.

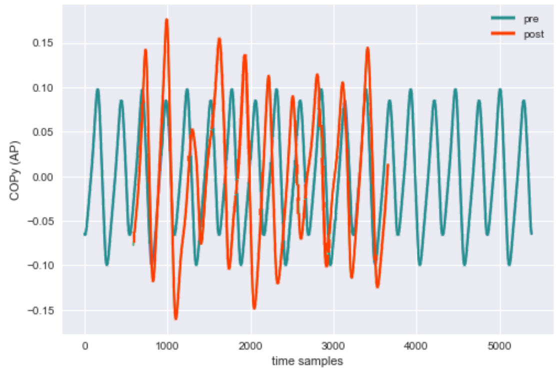

Figure A.6: Example of an incorrect unperturbed walking template as a result a deviation in the pre-perturbation window.

4. Measurement/filter error
For one perturbation, the post-perturbation window showed an asymptotic positive and negative peak which had values outside of the limits of the treadmill (Figure A.7). The origin of this error is unknown, but it is evident that this signal is not realistic. Therefore this perturbation was excluded from the analysis.

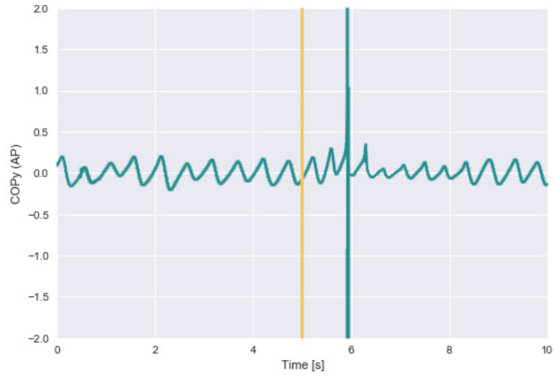

Figure A.7: Example of a post-perturbation signal with a positive and negative asymptotic peak.

APPENDIX C

Pilot test: verify whether the specified perturbations can be accurately executed by the system

The system used for this study has been used for perturbations before, but no specific validation has been performed for the perturbation characteristics of the specified difficulties (SpD's). The SpD is based on a previous study by the Clinical Application department. Based on the reported perceived difficulty of eleven healty young subjects for a variaty of accelerations, durations an at different walking speeds, a regression analysis was done estimate the PD_{HY}. The regression showed a dependency of the PD_{HY} on the duration, acceleration and the walking speed. This regression based PD_{HY} was used throughout this study to determine the SpD:

For accelerations: PD_{HY}= -2,65 + 14.07*(duration – 0.05 * walking speed – 1.3*acceleration)
For decelerations: PD_{HY} = -0.8 + 14.64*(duration - 2.46 *walking speed – 1.78* acceleration)

To determine whether the perturbations characteristics of the SpD are correctly executed by the system, some pilot tests were done. For the first pilot accelerations and decelerations of three specified difficulties (SpD's) were tested for three walking trials at different walking speeds, performed by a healthy young subject of approximately 63 kg(Table A.4).

Table A.4: The perturbation characteristics used for the first pilot test. The three specified difficulties (SpD's) and three different walking speeds.

			Walking speed 0.6 m/s		Walking speed 1 m/s		Walking speed 1.2 m/s	
	SpD	PD_{HY}	Acceleration (m/s²)	Duration (s)	Acceleration (m/s²)	Duration (s)	Acceleration (m/s²)	Duration (s)
Acc	Low	1.5	-2	0.11	-2	0.11	-2	0.11
	Medium	4.7	-3	0.24	-3	0.24	-3	0.24
	High	8.7	-4	0.43	-4	0.43	-4	0.43
Dec	Low	1.5	2	0.02	2	0.09	2	0.13
	Medium	4.7	3	0.12	3	0.19	3	0.23
	High	8.7	4	0.27	4	0.34	4	0.38

The results indicated that the low SpD and the high SpD accelerations were not executed as specified, especially for the walking speed of 1 m/s and 1.2 m/s. For the low SpD's the system was not able to apply perturbations which such short durations, as this requires a very high precision. From the plots of the high SpD accelerations it was observed that the velocity profile was correctly executed up to approximately 2.2 m/s seconds, above this point the acceleration started do decrease slightly. The observed velocity profiles were not acceptable for the use during this experiment, especially when considering that higher deviations may be observed for a subject with a higher weight. However, these perturbation characteristics are not the only way to apply these SpD, as the PD_{HY} regression is a linear relation of the acceleration and duration for certain walking speeds.

Table A.5: The perturbation characteristics used for the first pilot test. The three specified difficulties (SpD's) and three different walking speeds.

			Walking speed 0.6 m/s		Walking speed 1 m/s		Walking speed 1.2 m/s	
	SpD	PD_{HY}	Acceleration (m/s²)	Duration (s)	Acceleration (m/s²)	Duration (s)	Acceleration (m/s²)	Duration (s)
Acc	Low	1.5	1	0,20	1	0,20	1	0,20
	Medium	4.7	2	0,33	2	0,33	2	0,33
	High	8.7	3	0,53	3	0,53	3	0,53
Dec	Low	1.5	-1	0,14	-1	0,22	-1	0,25
	Medium	4.7	-2	0,24	-2	0,31	-2	0,35
	High	8.7	-3	0,39	-3	0,46	-3	0,50

Therefore, a second pilot test was performed, with the same procedure but with lower accelerations and decelerations for a longer duration (Table A.5), and including trials with a subject with a higher weight of about 100kg. For these perturbation characteristics, resulting in the same SpD (or PDHY), the velocity profile was observed to be correct for most perturbations. The velocity profile of the high SpD acceleration for the subject of 100kg at 1 m/s walking speed showed a small, deviation from the intended perturbation characteristics. A slightly larger deviation from the specified perturbation characteristics was observed for the high SpD acceleration for the subject of 100kg at a 1.2m/s walking speed. All low SpD were correctly executed by the system.

The walking speed for this study was limited for to 1 m/s, for this walking speed acceptable velocity profiles of the perturbations were observed during this pilot study. Especially when considering the slightly lower high SpD used in this study (Table 1), assuming that subjects will not exceed the weight of 100kg.

Conclusion

The specified perturbation characteristics as stated in Table 1 can be accurately executed by the system.

APPENDIX D

Pilot test: determine time to restore gait event detection after a perturbation

Spatio-temporal gait parameters are commonly used to analyze human gait, to determine these parameters gait event detection is required. The detection of gait events on a force plate instrumented treadmill are based on the ‘butterfly’ pattern (Roerdink et al. 2008), which is observed by plotting the center of pressure (COP) trajectory of the anteroposterior (AP) plane versus the mediolateral (ML) plane. As the gait event detection thus depends on a regular gait pattern, gait events cannot be detected directly following a perturbation. Figures A.8 and A.9 illustrate this; for the plot of perturbed gait the ‘butterfly’ pattern cannot be observed, which means that gait event detection is not possible. Therefore, the quantified recovery performance (QRP) could not rely on any measures that need gait event detection directly following a perturbation. However, the question remained how long it takes before the system can detect gait events again. This should be determined as the proposed QRP uses gait event detection in the pre-perturbation window, perturbation timing also requires gait event detection. To validate whether gait event detection restores within an acceptable amount of time for this study with perturbations, a pilot study was done to determine the amount of time required for gait event detection to be restored.

Accelerations and decelerations of three specified difficulties (SpD’s) were tested for three walking trials at different walking speeds, performed by a healthy young subject (Table A.4). The COP trajectory and the gait events detected by Cuefors (Software, Motekforce Link, Amsterdam) were visually inspected for these walking trials. By means of visual inspection, the time required to restore gait event detection could be estimated.

The high SpD was the only difficulty for which the gait event detection did not work for a couple of steps after the acceleration or deceleration perturbations. It could be observed for both high and low speed that the gap for which no gait events were detected was at most 5 steps, which was approximately 3.5 seconds.

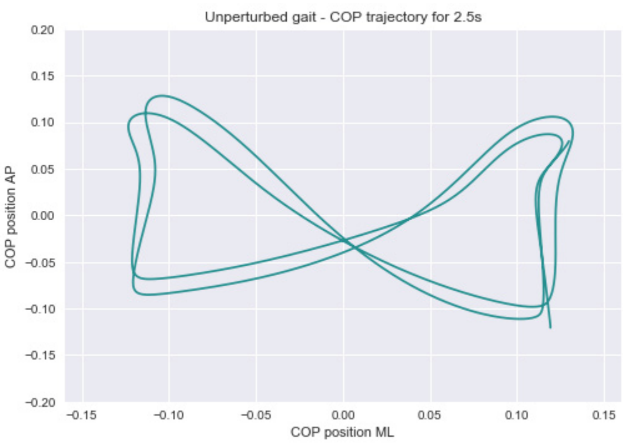

Figure A.8: Example of the center of pressure (COP) trajectory for unperturbed gait. A ‘butterfly’ pattern can be observed. This pattern is used to detect gait events.

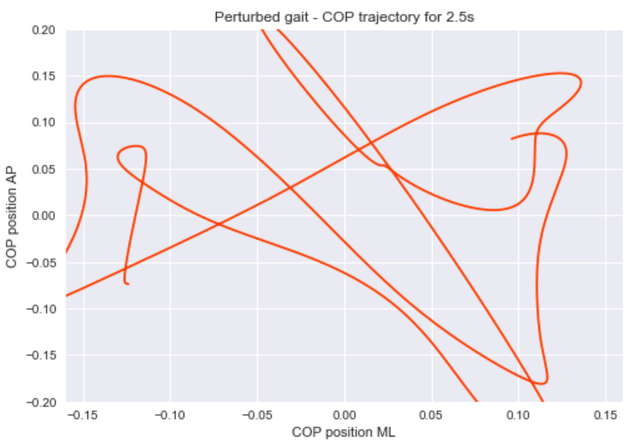

Figure A.9: Example of the center of pressure (COP) trajectory for perturbed gait. The ‘butterfly’ pattern cannot be observed, which means that it cannot be used to detect gait events.

Figure A.10 and A.11 show a low speed (0.6 m/s) walking trial with decelerations and accelerations respectively. CueFors (Software, Motekforce Link, Amsterdam) indicated some gait events to be invalid, shown by a red dot, and in some cases did not specify a gait event at all. The plots show that the low and medium SpD accelerations and decelerations did not cause any problems for gait event detection, while the high SpD accelerations and decelerations caused a short loss of gait event detection.

It should be considered that gait events detection depends on the variability of someone's gait pattern. In general, elderly tend to have a more variable gait pattern than young adults (Mirelman et al., 2015), which means that these result might not be generalizable to the elderly population. However, the time required to restore gait event detection was found to be about 3.5 seconds, which means that the amount of time would be acceptable for this study even if it takes twice as much time for elderly subjects.

Conclusion
It can be concluded that the performance of the gait event detection by the system is sufficient for trials with acceleration and deceleration perturbations when used with a healthy young subject. A maximum of 3.5 seconds was required before the gait event detection was recovered, no problems of gait event detection are expected for this study.

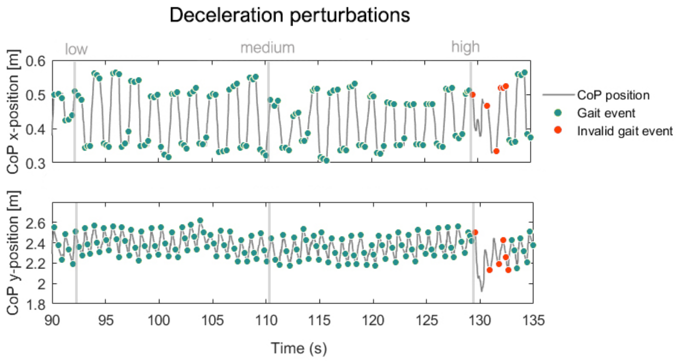

Figure A.10: Center of pressure trajectory in the x- and the y-direction, corresponding to the mediolateral (ML) and anteroposterior (AP) plane, for the low speed walking trial with deceleration perturbations with low, medium and high specified difficulty.

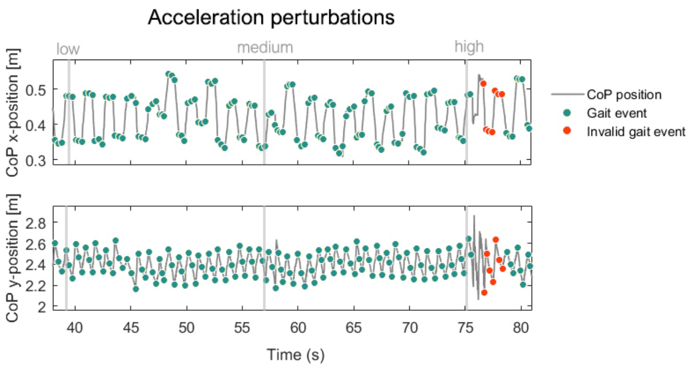

Figure A.11: Center of pressure trajectory in the x- and the y-direction, corresponding to the mediolateral (ML) and anteroposterior (AP) plane, for the low speed walking trial with deceleration perturbations with low, medium and high specified difficulty.

References

Mirelman, A., Bernad-Elazari, H., Nobel, T., Thaler, A., Peruzzi, A., Plotnik, M., … Hausdorff, J. M. (2015). Effects of aging on arm swing during gait: The role of gait speed and dual tasking. *PLoS ONE*, 10(8), 1–11. https://doi.org/10.1371/journal.pone.0136043

Roerdink, M. et al. 2008. "Online Gait Event Detection Using a Large Force Platform Embedded in a Treadmill." *Journal of Biomechanics* 41(12): 2628–32.

APPENDIX E

Elderly subjects: the attitude of elderly towards perturbation training and a quantified recovery performance.

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 en 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.

	Subject										
	1	2	3	4	5	6	7	8	9	10	11
1. "Hoe klinkt het idee om op deze manier valrisico te verlagen?"	+	+	?	+	+	+	+	+	+	+	+
2.a "Zou u deel nemen aan een dergelijke training om valrisico te verminderen?"	+	-	-	-						-	
2.b "Zou u deelnemen aan een dergelijke training als dit u helpt om fit oud te worden?"					+	+	-	+	+	-	+
3. "Focus fit oud worden: zou u betalen voor een dergelijke training?"	+	-	-	-	+	+	-		+		+
4. "Zouden andere mensen hier baat bij kunnen hebben?"		+	+	+			+			+	
5. "Zou u het fijn vinden om een score te krijgen aan het einde van een training?"					+	+	+				
6. "Zou u per verstoring een score willen zien?"					-	-					

From the first line of Table A.6 it can be seen that, except for one subject, all subject 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 where 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.

APPENDIX F

Physiotherapists: their attitude towards and understanding of perturbation training & the quantified recovery performance

Physiotherapists will be the primary user of the system, their understanding of and attitude towards both the training principle and the quantified recovery performance (QRP) are of interest. The physiotherapists of this study were also asked a few qualitative questions regarding their opinion about the use of perturbation training and the QRP. Although not completely within the scope of the paper and the relatively unscientific methods used, the information gained during this part is valuable for further development of perturbation training and the QRP. Therefore, this qualitative part of the study will be discussed in this appendix.

This qualitative part took place after the quantitative part of this study, during which the physiotherapists were asked to rate the recovery performance of the video clips showing perturbed elderly.

A. Outline

The following elements were discussed during the qualitative part, described in chronological order corresponding to order they were asked during the interview.

1. Attitude toward perturbation training

To gain insights about the attitude of the physiotherapists towards perturbation training, the following questions were asked:

- What do you think of the idea of perturbation training?
- Do you think it can attribute to fall risk reduction among elderly?
- Would you recommend perturbation training to elderly?
- Do you think elderly would be willing to pay for perturbation training?

2. Understanding of the quantified recovery performance measure.

To determine the amount of explanatory material required for physiotherapists to understand the QRP, information was deliberately provided piece by piece. First, the physiotherapists received an explanation in words only:

“De herstelmaat is gebasseerd op het feit dat lopen een vast patroon volgt: het looppatroon. Dit patroon verschilt een klein beetje per persoon, maar is relatief constant binnen een persoon. De manier waarop je je ene voet voor de ander zet en daarbij je gewicht verplaatst, is vrij constant voor elke stap. Dit kunnen we zien door de herhalende bewegingen, maar het is ook te meten door de krachten die een patiënt op de grond uitoefend tijdens het lopen. Deze krachten kunnen we meten met een krachtplaat. Om te bepalen hoe goed iemand herstelt na een verstoring berekenen we hoeveel het looppatroon na de verstoring verschilt van het looppatroon voor de verstroring. Wanneer een patiënt zich goed en snel herstelt, zal het patroon na de verstoring weinig afwijken van het ‘normale’ patroon van voor de verstoring. Terwijl een slechter herstel na een verstoring zal zorgen voor een grote afwijking van het ‘normale’ looppatroon van voor de verstoring. De hoeveelheid afwijking van het ‘normale’ looppatroon bepaald de score . ”

After this explanation, physiotherapists were asked whether the measure was clear to them and whether they could work with this measure. When it seemed like the measure was not completely clear to them, another piece of information was provided in the form of graphs. The graphs are depicted in Figure A.12 and showed an example of what a high and what a low score center of pressure (COP) trajectory in the ML plane would look like. Followed by a graph which showed the aligned pre- and post-perturbation signal.

Again the physiotherapists were asked about their understanding of the measure. If needed, a final piece of information would be provided by means of two animations. During these animation a video of the frontal view of subject was shown synchronized with a graph showing the COP signal in the ML plane (Figure A.13), One animation showing a high score and one animation showing a low score.

3. Acceptance of the QRP
Next, the physiotherapists were asked to provide their opinion of the QRP. This was done by asking them:
- Would you be able to work with this QRP?
- Do you believe that this measure reflects someone's recovery performance?

4. Implementation of the QRP
Finally, a few questions were asked regarding a proper implementation of the QRP for perturbation training:
- Would you like to know the score for each perturbation during a training or would you rather see one mean score at the end of the training?
- How do you currently manage the required time to go through client information and interpret test results?
- What kind of information, apart from the QRP, would you like to see at the end of a perturbation training?
- Would you also like to be able to record and view videos of the perturbation training?

B. Results
1. Attitude towards perturbation training.
All five physiotherapists were convinced that perturbation training could reduce fall risk among elderly. Most of them noted that it should be implemented in addition to other elements. Strength and balance training should still be part of the fall prevention intervention, as should be other factors such as assessing the shoes, vision, medication use and diagnosis of (cognitive) impairments. One of the physiotherapists who primarily works with elderly,

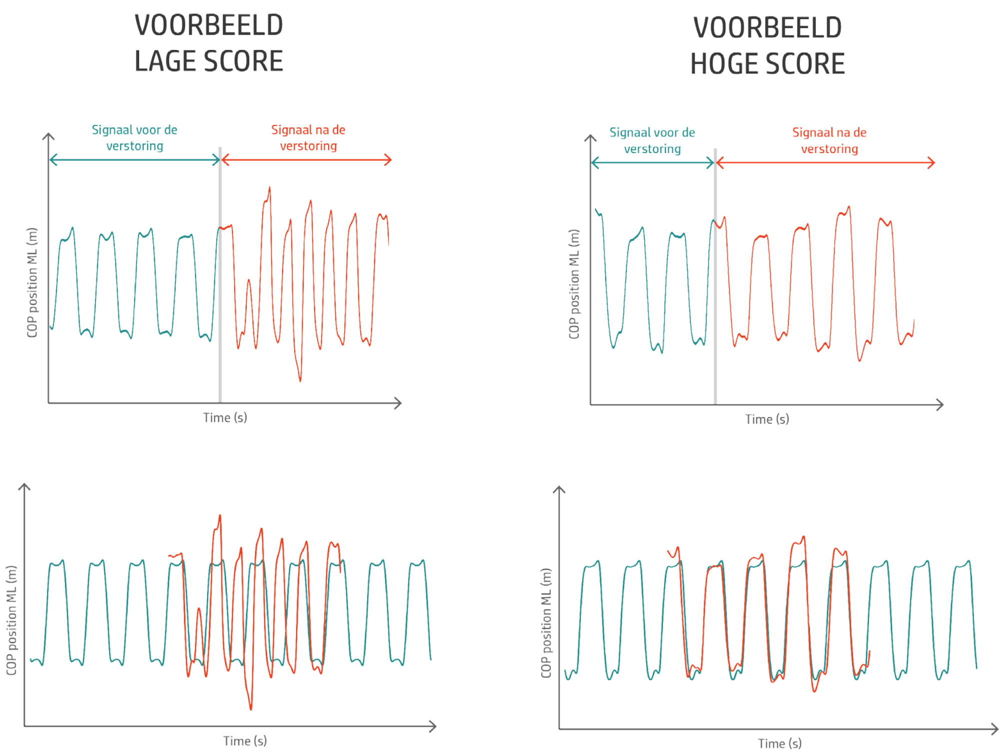

Figure A.12: Examples of a low and high QRP score in the ML plane, as provided to the physiotherapists to further explain the QRP.

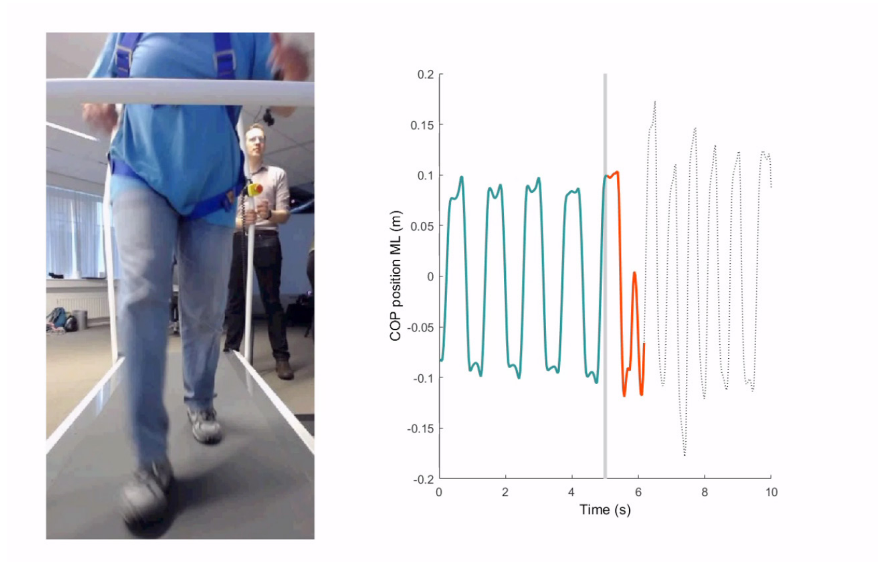

Figure A.13: Screenshot of the animation for a low QRP score in the ML plane, as shown to the physiotherapist.

mentions that she questions whether elderly with cognitive impairments such as dementia will be able to improve their recovery performance. Another physiotherapist mentions that she is a bit reserved when it comes to treadmill training, as she primarily focuses on functional training. She can imagine that, despite the use of a treadmill, perturbation training itself can be considered functional training. Two of the physiotherapists mention how gaining more self-confidence with this type of training will probably also affect elderly positively.

Three out of five physiotherapists thought that elderly would be willing to pay for such training, although the amount of money would not be high. The other two physiotherapists thought it would be difficult to get elderly to pay for this training. One of the main factors, also recognized by the other physiotherapists, is that elderly do not (want to) recognize their need for fall prevention training. One of these physiotherapists mentions that the functional characteristic of perturbation training could be an advantage, as this will be appealing to people. Two physiotherapists suggest that it might help to provide some sort of try-out training or screening, to make the training more accessible to elderly.

This brings us to the next point, also identified during the qualitative analysis of part I; elderly seem to have a negative attitude towards fall prevention training. Multiple physiotherapists confirm that perturbation training will probably be accepted more easily when its purpose is to stay fit and healthy, rather than to reduce fall risk. Elderly seem to find it difficult to admit that they might need fall prevention training, instead most of them need to experience serious falls before they are willing to actively do something about it. One physiotherapist states that the general practitioner could play an important role in getting elderly to participate in such training. Another physiotherapists tells that experiencing a certain type of training earlier in life, for example because of rehabilitation of some sort, also increases the likeliness that someone will participate in a perturbation training. Also, implementation of perturbation training as part of coping with certain pathologies experienced by elderly might increase the acceptance of the training by elderly.

2. Understanding of the quantified recovery performance

One physiotherapists needs all three pieces of information before understanding the measure. Three physiotherapists seem to fully understand the concept of the QRP after explanation with the graphs. One of the physiotherapists understands the measure immediately with the explanation with words only. Three physiotherapists start to wonder about the influence of strategies on this measure. They mention that different strategies will influence their COP trajectory differently and wonder how this will affect this measure and whether one strategy would be better than another strategy. Furthermore, three physiotherapists mention that the difficulty of the perturbation will also influence their performance. One physiotherapists mentions that the QRP thus incorporates both the magnitude of the deviation, but also the time to recover.

3. Acceptance of the quantified recovery performance

One of the physiotherapists state that this measure will probably be more reliable than the estimates which are provided by the physiotherapists. All physiotherapists agree that the measure will reflect someone's recovery performance, at least to some extent. One of them doubts whether arm movements should be taken into account. Another physiotherapist indicates that other tests are still required, such as physical examinations and clinimetrics.

4. Implementation of the quantified recovery performance
All physiotherapists indicate that a score for each perturbation would be too extensive, just a score per type and difficulty of perturbation at the end of a session would be sufficient. All but one physiotherapist would really like to be able to view videos at the end of the training. This enables them to both show what people are doing correct or incorrect, and to motivate them and show improvement over sessions. Multiple physiotherapists indicate that a part of the processing of test results is done by directly discussing it with the client, as a means of providing feedback to them. One of the physiotherapists suggest the use of dual-tasks for those with a relatively high performance.

A physiotherapist currently using the GRAIL (Motekforce Link, Amsterdam, The Netherlands) is very positive about this type of measure, as it includes some of the unique features of this type of devices; the COP measurements. Currently, they only provide measures such as walking speed or duration to clinicians who want to know progress made on the GRAIL. These type of measures can also be observed in a regular room without the GRAIL. These types of measures could further exploit the possibility of the technology available in this kind of systems.

C. Conclusions

- The physiotherapists were positive about perturbation training and its fall risk reducing effect.
- Most physiotherapists were able to grasp the concept of the QRP by a short explanation and an example graph.
- Although some physiotherapist would like to have more information than just the QRP, all physiotherapists though that the QRP expressed the recovery performance to some extent.
- A QRP value for each perturbation type and difficulty at the end of the training is suggested to be sufficient.