CHAPTER 2

Assessing gait adaptability in people with a unilateral amputation on an instrumented treadmill with a projected visual context

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Abstract

Background. Gait adaptability, including the ability to avoid obstacles and to take visually guided steps, is essential for safe movement through a cluttered world. This aspect of walking ability is important for regaining independent mobility but is difficult to assess in clinical practice.

Objective. The objective of this study was to investigate the validity of an instrumented treadmill with obstacles and stepping targets projected on the belt’s surface for assessing prosthetic gait adaptability.

Design. This was an observational study.

Methods. A control group of people who were able bodied (n=12) and groups of people with transtibial (n=12) and transfemoral (n=12) amputations participated. Participants walked at a self-selected speed on an instrumented treadmill with projected visual obstacles and stepping targets. Gait adaptability was evaluated in terms of anticipatory and reactive obstacle avoidance performance (for obstacles presented 4 steps and 1 step ahead, respectively) and accuracy of stepping on regular and irregular patterns of stepping targets. In addition, several clinical tests were administered; these included timed walking tests and reports of incidence of falls and fear of falling.

Results. Obstacle avoidance performance and stepping accuracy were significantly lower in the groups with amputations than in the control group. Anticipatory obstacle avoidance performance was moderately correlated with timed walking test scores. Reactive obstacle avoidance performance and stepping accuracy performance were not related to timed walking tests. Gait adaptability scores did not differ in groups stratified by incidence of falls or fear of falling.

Limitations. Because gait adaptability was affected by walking speed, differences in self-selected walking speed may have diminished differences in gait adaptability between groups.

Conclusions. Gait adaptability can be validly assessed by use of an instrumented treadmill with a projected visual context. When walking speed is taken into account, this assessment provides unique, quantitative information about walking ability in people with a lower-limb amputation.
Introduction

Walking is a context-specific activity that demands gait adjustments based on environmental circumstances. For example, gait adjustments are essential during walking on uneven or cluttered terrains to secure adequate foot placement in relation to local environmental features, such as obstacles and stepping targets [1, 2]. Gait adaptability\(^1\), defined as the ability to adjust gait to such environmental circumstances, is an important determinant of the risk of falls [3] because most falls result from a trip, a slip, or a misplaced step [4]. However, gait adaptability is difficult to assess in clinical practice.

This study was conducted to assess the gait adaptability performance of a heterogeneous group of people who have a unilateral lower-limb amputation and who walk with a prosthesis. People with a lower-limb amputation are known to have an elevated risk of falls and a high incidence of falls (i.e., 52% experienced a fall in the previous year) [5]. Significant proportions of such people also have an increased fear of falling and reduced balance confidence (49% and 65%, respectively) [5, 6], which limit their participation [6]. Therefore, regaining the ability to walk safely within the constraints of daily life is of great concern to people with a lower-limb amputation [7, 8]. To help guide targeted interventions, a comprehensive assessment of walking ability is required; this assessment should include an evaluation of the ability to adjust gait to environmental circumstances given the aforementioned relationship between gait adaptability and risk of falls.

So far, prosthetic gait adaptability in relation to environmental constraints has been assessed in only a few studies. In these studies, gait adaptability was examined in terms of obstacle negotiation during overground walking [9-11] or treadmill walking [12, 13]. Although people with a lower-limb amputation crossed overground obstacles in a different, more cautious manner than people in control groups of participants who were able bodied [9, 10], they were all able to successfully avoid the obstacles without tripping or falling [9-11]. In contrast, for obstacle avoidance on a treadmill, when obstacles suddenly fell in front of the prosthetic or non-prosthetic foot, people with a traumatic transtibial amputation showed lower obstacle avoidance success rates than people in a control group who were able bodied [12, 13]. This result was predominantly seen when obstacles were presented under high time pressure, because of delayed and smaller-amplitude

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\(^1\) The terms gait adaptability and walking adaptability were initially interchangeably used in this thesis, but following Balasubramanian et al. (Stroke Res Treat 2014, 2014:591013) the latter is deemed preferable for the studied construct (i.e., adjustments relative to environmental context).
Assessing gait adaptability in people with lower-limb amputation

muscular responses [13]. These findings signified that people with a lower-limb amputation had an impaired ability to make online gait adjustments (e.g., obstacle avoidance under time pressure), but less so when they adjusted gait in response to obstacles that were visible earlier, for which relevant visual information is typically gathered 2 steps ahead of the obstacle and implemented in the avoidance response in an anticipatory manner [14, 15]. In addition, these findings indicated that a treadmill-based protocol, in which multiple obstacles can be presented consecutively under controlled response times to modulate the time pressure demands of obstacle avoidance, may offer a valid and clinically applicable assessment of prosthetic gait adaptability.

The aim of this study was to test the face validity and construct validity of a treadmill-based protocol for objectively assessing the ability of people with a lower-limb amputation to adjust their gait in an online and anticipatory manner to various environmental circumstances. We used an instrumented treadmill with a visual context (i.e., visual obstacles and stepping targets) projected on the treadmill surface by means of a projector [16-18]. The visual context was used in 2 conditions. In condition 1, visual obstacles were presented either 1 or 4 steps ahead, and gait adaptability was evaluated in terms of success rates for either reactive or anticipatory obstacle avoidance, respectively. In condition 2, regular and irregular patterns of visual stepping targets were presented on the treadmill, and gait adaptability was evaluated in terms of the accuracy of visually guided stepping. Face validity was determined by examining whether gait adaptability scores (i.e., success rates and stepping accuracy) could discriminate among 3 groups of participants: participants with a transfemoral amputation (TF group), participants with a transtibial amputation (TT group), and participants who were able bodied and served as controls (CO group). Because walking ability has been shown to depend on the level of amputation [6, 8], we expected inferior gait adaptability scores for the TF group, intermediate scores for the TT group, and superior scores for the CO group. Construct validity was determined by examining the relationships between gait adaptability scores and various clinical test scores, including timed walking tests and self-reported incidence of falls and fear of falling. Here, we expected only moderate associations, because gait adaptability scores were deemed to reflect a unique, complementary aspect of walking ability that is related, but not equal, to the walking ability constructs of the aforementioned clinical tests.
Method

Participants
A convenience sample of people with a unilateral prosthesis after transfemoral amputation \( (n=12) \) or transtibial amputation \( (n=12) \) and people who were able bodied and served as controls \( (n=12) \) participated in this study. Only people who were 18 to 70 years of age and who were able to walk without walking aids for at least 4 minutes were included. People with a lower-limb prosthesis additionally had to meet the following criteria: be equipped with a well-fitted prosthesis, be free of stump problems, and have Special Interest Group in Amputee Medicine (SIGAM) mobility scale grades of C to F (i.e., being able to walk independently with or without an assistive device) [19]. All participants were free of any cardiorespiratory, neurological, and orthopedic pathologies (i.e., other than related to the amputation) that could affect walking ability. All participants gave informed consent to participate in this study.

Instrumentation
An instrumented treadmill with a large embedded force platform (ForceLink BV, Culemborg, the Netherlands), which allowed for the online detection of gait events (e.g., heel-strike and toe-off) and gait characteristics (e.g., cadence and step length), was used to assess gait adaptability. The procedure used to derive gait events from center-of-pressure (COP) profiles on a single force platform embedded in a treadmill was previously outlined and validated by Roerdink et al. [20]. The treadmill was connected to a projector to project visual objects (moving toward the participant at belt speed) on the treadmill belt in response to detected gait events [16]. Specifically, visual obstacles could be presented so that a person would step on them if he or she did not adjust gait (Figure 2.1A and 2.1B). Likewise, a sequence of stepping targets could be presented (Figure 2.1C) to correspond to a person’s step length and cadence determined online (see video, available at ptjournal.apta.org and https://youtu.be/sHnlDICC8L8) [17, 18].

Protocol and data collection
Before the treadmill-based gait adaptability tests, the following standard timed walking tests were administered to people in the TT and TF groups: the 10-m walk test at comfortable \( (10\text{MWT}_{\text{comf}}) \) and maximal \( (10\text{MWT}_{\text{max}}) \) walking speeds [21] the Timed “Up & Go” Test (TUG) [22], and the sub-item obstacle avoidance of the Emory Functional Ambulation Profile (Emory-FAP) [23]. In addition, the
Assessing gait adaptability in people with lower-limb amputation

Activities-specific Balance Confidence Scale (ABC) was administered [24], and the self-reported incidence of falls during the past 12 months [5] and fear of falling [6] were scored.

Subsequently, all participants practiced treadmill walking for a minimum of 5 minutes at various belt speeds. Participants were encouraged to walk unsupported, but handrail support was allowed if necessary. All participants walked with their own prosthesis and comfortable walking shoes. They wore a safety harness that was suspended over the treadmill (no weight bearing). The self-selected comfortable treadmill walking speed was determined by gradually increasing the belt speed until a comfortable walking speed was reported. Belt speed was then increased beyond the just-reported comfortable walking speed and subsequently gradually decreased until a comfortable walking speed was reported. Belt speed was set to the average of the 2 reported comfortable treadmill walking speeds (hereafter referred to as “self-selected walking speed”) for the execution of the following 2 conditions (offered in sequential order).

**Condition 1: anticipatory and reactive obstacle avoidance**

This condition comprised two 4-minute trials during which participants were confronted with a series of 12 visual obstacles each. Obstacles were projected onto the treadmill belt as a white patch of light moving toward the participant at a speed corresponding to the belt speed. The obstacle dimensions were set according to the width of the belt and the size of the participant’s shoe. The starting position of the obstacle was such that it would arrive exactly beneath either the left foot or the right

![Figure 2.1](image-url) Instrumented treadmill with a projected visual context (i.e., visual obstacles and stepping targets) for assessing gait adaptability. (A) Anticipatory obstacle avoidance. (B) Reactive obstacle avoidance. (C) Visually guided stepping on patterns of stepping targets.
foot (6 each, in random order) if the participant continued walking in the way he or she had been walking, as indicated by the foot position determined online [20] and with the average length of the 8 preceding steps.

In the anticipatory obstacle avoidance trial, the 12 obstacles were presented at the moment of foot contact, 4 steps in advance of the anticipated contact (Figure 2.1A), allowing for an anticipatory gait adjustment to avoid the obstacle. In the reactive obstacle avoidance trial, the 12 obstacles were presented under time pressure, at the moment of foot-off, 1 step in advance of the anticipated contact (Figure 2.1B), requiring a reactive gait adjustment during the swing phase of the ongoing step to avoid the obstacle. Sufficient time was available between obstacles for participants to reach a steady-state walking pattern again. Anticipatory and reactive obstacle avoidance trials were presented in counterbalanced order, each followed by a 5-minute seated rest period.

Success rates (as percentages) in both obstacle avoidance trials were scored manually by one of the experimenters through visual inspection. To be classified as successful avoidance, both feet had to be positioned outside the area of the obstacle (i.e., no overlap of shoe and obstacle). This visual inspection was deemed superior to using available COP data because COP data do not reveal the real margins of the foot and hence cannot reveal whether part of the foot area was within the area of the obstacle. Sagittal video recordings were made for verification of uncertain obstacle crossings.

**Condition 2: walking on regular or irregular patterns of stepping targets**

In this condition, rectangular stepping targets (length: the participant’s shoe length; width: half the belt width) were projected onto the treadmill belt for both the left foot and the right foot. Participants were instructed to walk on the presented step pattern, aligning their feet as much as possible in the anterior and posterior directions on the stepping targets. Approximately 4 or 5 stepping targets were visible at each moment in time (Figure 2.1C). This condition consisted of 3 trials with different levels of regularity in the patterns of stepping targets (i.e., 0%, 20%, and 30% variations). The 0% trial consisted of a regular pattern of stepping targets corresponding to a participant’s mean gait pattern, as registered in the preceding 20 seconds of unconstrained treadmill walking [17, 18]. In the irregular trials, a random variation of 20% or 30% of a participant’s mean stride length was added to the aforementioned regular pattern of stepping targets. Each trial consisted of a sequence of 80 stepping targets. The 3 trials were offered in a counterbalanced order and were followed by a period of seated rest.
Stepping accuracy (in millimeters) was quantified in terms of the variation in foot placement relative to the stepping targets. The anterior-posterior COP position at mid-stance (i.e., the COP position halfway between the subsequent instants of foot-off and initial contact of the contralateral foot) was compared with the anterior-posterior position of the center of the stepping targets; the former position was used as a reference for the foot placement location on the treadmill. Note that although the COP position at mid-stance is close to the center of the foot, it is not necessarily perfectly so; in the pilot study on people who were able bodied ($n=12$; mean age=28.6 years, $SD=4.4$), we found a systematic error between the true center of the foot and the COP position at mid-stance of ±1 cm (95% confidence interval), depending on the manner in which people walked. As a consequence, a systematic offset between the center of the stepping target and the COP position at mid-stance may be observed, even when the foot is perfectly aligned on the stepping target. To circumvent such bias, we used the standard deviations of the distances between the COP position at mid-stance and the center of the stepping target (instead of the mean) as a measure of the accuracy of foot placement. The smaller this standard deviation, the more accurate the foot placement positions are relative to the stepping targets.

**Supplementary experiment: effect of walking speed on gait adaptability scores**

Walking speed may affect gait adaptability performance. In a supplementary experiment, we therefore assessed the effect of walking speed per se on the gait adaptability scores of participants in the CO group. These participants performed both conditions at their self-selected walking speed and at a slower speed (expected to represent the lower range of walking speeds observed in participants with an amputation), in randomized order, as further described in the Appendix (at page 40-42).

**Data analysis**

*General group characteristics and self-selected treadmill walking speed*

The 3 groups were compared in terms of age, body weight, height, and self-selected treadmill walking speed by use of separate 1-way analyses of variance (ANOVAs) (factor: group; levels: CO, TT, and TF) followed by post hoc independent $t$ tests for significant group effects. The TT group and the TF group were compared in terms of the side and the cause of amputation by use of chi-square tests and in terms of the time since amputation and the time using the current prosthesis by use of independent $t$ tests.
Condition 1
Nonparametric statistics were used to examine group effects on obstacle avoidance success rates. First, Wilcoxon signed rank tests were performed to compare anticipatory and reactive obstacle avoidance success rates separately for the 3 groups. Differences in success rates between groups were evaluated with Kruskal-Wallis tests; Mann-Whitney $U$ tests were used for post hoc follow-up in case of significant group effects.

Condition 2
Differences in stepping accuracy between groups were tested by use of a repeated-measures ANOVA with the between-subject factor group (3 levels: TF, TT, and CO) and the within-subject factor pattern regularity (3 levels: 0%, 20%, and 30%). Post hoc comparisons were performed with independent $t$ tests (group effects) or paired-sample $t$ tests (pattern regularity effects).

Gait adaptability performance in relation to clinical test scores
Gait adaptability scores were related to 10MWT$_{com}$, 10MWT$_{max}$, TUG, Emory-FAP, and ABC scores by use of Spearman (success rates) or Pearson (stepping accuracy) correlation coefficients. To examine the relationships between gait adaptability scores and self-reported incidence of falls and fear of falling, we stratified the groups into subgroups (fallers/non-fallers and fearful/non-fearful) and then used Mann-Whitney $U$ tests to compare obstacle avoidance success rates for these subgroups. Likewise, to compare stepping accuracies for the stratified subgroups, we used repeated-measures ANOVAs for subgroup (2 levels: fallers versus non-fallers and fearful versus non-fearful) × pattern regularity (3 levels: 0%, 20%, and 30%).

All statistical tests were performed with SPSS version 17.0 (SPSS Inc, Chicago, Illinois). Level of significance ($\alpha$) was set at 0.05 for testing main and interaction effects. For post hoc tests, $\alpha$ was corrected for multiple comparisons by dividing 0.05 ($\alpha$) by the number of post hoc comparisons performed. In general, for post hoc tests among the 3 subgroups, $\alpha$ was 0.017.

Role of the Funding Source
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Results

All participants were able to complete conditions 1 and 2 successfully and were highly motivated to complete the tasks. Seven of 12 participants in the TF group required handrail support for confidence.

Table 2.1 General group characteristics and clinical test scores

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>TF Group</th>
<th>TT Group</th>
<th>CO Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, years</td>
<td>51 (10)</td>
<td>43 (14)</td>
<td>44 (12)</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>74 (13)</td>
<td>79 (13)</td>
<td>76 (13)</td>
</tr>
<tr>
<td>Height, m</td>
<td>1.75 (0.13)</td>
<td>1.80 (0.07)</td>
<td>1.78 (0.09)</td>
</tr>
<tr>
<td>Sex, n men/women</td>
<td>7/5</td>
<td>10/2</td>
<td>6/6</td>
</tr>
<tr>
<td>SIGAM, n grades D/E/F</td>
<td>6/2/4</td>
<td>0/1/11</td>
<td></td>
</tr>
<tr>
<td>Time since amputation, months</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean (SD)</td>
<td>213 (214)</td>
<td>208 (218)</td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>6-648</td>
<td>14-540</td>
<td></td>
</tr>
<tr>
<td>Time using current prosthesis, months</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean (SD)</td>
<td>15 (15)</td>
<td>22 (17)</td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>2-48</td>
<td>2-60</td>
<td></td>
</tr>
<tr>
<td>Cause of amputation, n trauma/vascular condition</td>
<td>8/4</td>
<td>11/1</td>
<td></td>
</tr>
<tr>
<td>Side of amputation, n right/left</td>
<td>5/7</td>
<td>6/6</td>
<td></td>
</tr>
<tr>
<td>Clinical test scores</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10MWT_comf, s</td>
<td>9.2 (1.2)</td>
<td>7.5 (0.8)</td>
<td></td>
</tr>
<tr>
<td>10MWT_max, s</td>
<td>7.7 (1.2)</td>
<td>5.9 (0.8)</td>
<td></td>
</tr>
<tr>
<td>TUG, s</td>
<td>10.8 (2.5)</td>
<td>8.4 (1.8)</td>
<td></td>
</tr>
<tr>
<td>Emory-FAP, s</td>
<td>13.1 (2.3)</td>
<td>9.5 (0.8)</td>
<td></td>
</tr>
<tr>
<td>ABC-score, %</td>
<td>88.1 (8.1)</td>
<td>95.2 (4.5)</td>
<td></td>
</tr>
<tr>
<td>Incidence of falls, n faller/non-faller</td>
<td>7/5</td>
<td>2/10</td>
<td></td>
</tr>
<tr>
<td>Fear of falling, n yes/no</td>
<td>4/8</td>
<td>2/10</td>
<td></td>
</tr>
</tbody>
</table>

aData are presented as mean (standard deviation [SD]) unless stated otherwise. TF=participants with a transfemoral amputation, TT=participants with a transtibial amputation, CO=participants who were able bodied (controls), SIGAM=Special Interest Group in Amputee Medicine, 10MWT\_comf=10-m walk test at a comfortable walking speed, 10MWT\_max=10-m walk test at the maximal walking speed, TUG=Timed “Up & Go” test, Emory-FAP=Emory Functional Ambulation Profile, ABC=Activities-specific Balance Confidence scale.
General group characteristics
The 3 groups did not differ in terms of age, body weight, and height (all $F(2,35)<1.50$, $p>0.239$). The TT group and the TF group did not differ in terms of the side and the cause of amputation (all $\chi^2(1)<2.27$, $p>0.131$) or in the time since amputation and the time using the current prosthesis (all $t(22)<1.02$, $p>0.320$). Table 2.1 shows the group characteristics. All participants in the TT and TF groups wore their own custom-designed prosthesis. The types of prosthetic components used varied among the participants, but all participants in the TT group used a type of dynamic foot. Within the TF group, 6 of twelve participants used a processor-controlled knee (C-leg; Otto Bock, Duderstadt, Germany), 5 participants used a mechanically controlled knee, and 1 participant used a rigid knee.

Self-selected Treadmill Walking Speed
Self-selected comfortable treadmill walking speeds differed significantly among the groups ($F(2,35)=6.35$, $p<0.001$), with participants in the TF group walking significantly more slowly (2.3 km/h) than participants in both the TT group (3.3 km/h; $t(22)=2.90$, $p=0.008$) and the CO group (3.8 km/h; $t(22)=6.12$, $p=0.001$). The speed difference between the TT group and the CO group did not reach significance ($t(22)=1.98$, $p=0.060$).

Condition 1: Anticipatory and Reactive Obstacle Avoidance Performance
Success rates for anticipatory obstacle avoidance were significantly higher than those for reactive obstacle avoidance for all 3 groups (Figure 2.2) (TF group: $z=2.786$, $p=0.005$; TT group: $z=2.764$, $p=0.006$; CO group: $z=2.375$, $p=0.018$). Furthermore, significant group effects were observed for both anticipatory obstacle avoidance ($H(2)=13.40$, $p=0.001$) and reactive obstacle avoidance ($H(2)=8.45$, $p=0.015$) (Figure 2.2). Post hoc comparisons revealed that success rates were significantly lower for the TF group than for the CO group for both anticipatory obstacle avoidance ($U=12.0$, $p<0.001$) and reactive obstacle avoidance ($U=23.5$, $p=0.005$). The TT group showed intermediate success rates for both anticipatory obstacle avoidance and reactive obstacle avoidance. However, post hoc comparisons revealed that differences in success rates between the TT group and the CO group (anticipatory: $U=45.0$, $p=0.062$; reactive: $U=35.0$, $p=0.030$) as well as between the TT group and the TF group (anticipatory: $U=42.5$, $p=0.078$; reactive: $U=69.0$, $p=0.862$) did not reach significance (bearing in mind the corrected $\alpha$ of 0.017).
Assessing gait adaptability in people with lower-limb amputation

**Figure 2.2** Success rates for anticipatory and reactive obstacle avoidance assessments for participants who were able bodied (controls) (CO), participants with a transtibial amputation (TT), and participants with a transfemoral amputation (TF).

**Figure 2.3** Stepping accuracy for participants who were able bodied (controls) (CO), participants with a transtibial amputation (TT), and participants with a transfemoral amputation (TF). Accuracy was determined from visually guided stepping on regular and irregular (20% and 30%) patterns of stepping targets.
Condition 2: Walking on Regular or Irregular Patterns of Stepping Targets
Data from 1 person in the TF group were lost because of measurement error. The effect of group tended toward significance ($F(2,32)=2.55, p=0.094$), with seemingly inferior stepping accuracy for the TF group (43 mm), intermediate stepping accuracy for the TT group (36 mm), and superior stepping accuracy for the CO group (31 mm). Furthermore, a significant effect of pattern regularity ($F(2,64)=23.19, p<0.001$) was observed, with higher stepping accuracy for the regular sequence of stepping targets (31 mm) than for both irregular stepping target sequences (20%: 38 mm, $p<0.001$; 30%: 41 mm, $p<0.001$). As indicated in Figure 2.3, all groups showed lower stepping accuracy for more irregular patterns of stepping targets; the interaction of group and pattern regularity was not significant ($F(4,64)=0.32, p=0.862$).

Gait Adaptability Performance in Relation to Clinical Test Scores
Anticipatory obstacle avoidance success rates were negatively correlated with $10MWT_{\text{comf}}, 10MWT_{\text{max}}, \text{TUG}$, and Emory-FAP scores (Table 2.2); higher success rates were associated with faster test completion. All significant correlations were of intermediate strength. No significant correlations were found for reactive obstacle avoidance. No difference in anticipatory and reactive obstacle avoidance success rates was found for subgroups stratified into non-fallers and fallers ($U=61.5, p=0.712$ and $U=50.0, p=0.294$, respectively) or for subgroups stratified by fear of falling ($U=33.0, p=0.148$ and $U=35.5, p=0.215$, respectively).

Stepping accuracy was not significantly correlated with the outcomes of the clinical tests (Table 2.2), nor did stepping accuracy differ for subgroups stratified into fallers ($F(1,21)=0.11, p=0.742$) or fear of falling ($F(1,21)=0.17, p=0.682$).

Discussion
In the present study, an instrumented treadmill with projected visual obstacles and stepping targets was successfully used to assess gait adaptability in 3 groups of participants: 2 groups with amputation (TF group and TT group) and a control group (CO group). We expected and found significant differences in gait adaptability performance among the groups, with inferior gait adaptability scores for the TF group, intermediate scores for the TT group, and superior scores for the CO group. Besides these between-group differences, large intragroup variations in
Table 2.2 Correlations between clinical test scores and gait adaptability performance

<table>
<thead>
<tr>
<th>Condition</th>
<th>10MWT&lt;sub&gt;conf&lt;/sub&gt;</th>
<th>10MWT&lt;sub&gt;max&lt;/sub&gt;</th>
<th>TUG</th>
<th>Emory-FAP</th>
<th>ABC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obstacle avoidance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anticipatory</td>
<td>-0.608</td>
<td>-0.557</td>
<td>-0.425</td>
<td>-0.589</td>
<td>0.257</td>
</tr>
<tr>
<td>Reactive</td>
<td>-0.376</td>
<td>-0.288</td>
<td>-0.207</td>
<td>-0.249</td>
<td>0.345</td>
</tr>
<tr>
<td>Pattern walking</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0% variation</td>
<td>0.105</td>
<td>0.067</td>
<td>0.221</td>
<td>0.344</td>
<td>-0.221</td>
</tr>
<tr>
<td>20% variation</td>
<td>0.052</td>
<td>0.070</td>
<td>0.127</td>
<td>0.265</td>
<td>-0.147</td>
</tr>
<tr>
<td>30% variation</td>
<td>-0.180</td>
<td>-0.093</td>
<td>-0.079</td>
<td>0.076</td>
<td>-0.056</td>
</tr>
</tbody>
</table>

* In terms of success rates for anticipatory and reactive obstacle avoidance and accuracy of stepping on regular and irregular patterns of stepping targets. Bold type indicates significant correlations. 10MWT<sub>conf</sub>=10-m walk test at a comfortable walking speed, 10MWT<sub>max</sub>=10-m walk test at the maximal walking speed, TUG=Timed “Up & Go” test, Emory-FAP=Emory Functional Ambulation Profile, ABC=Activities-specific Balance Confidence scale.

Gait adaptability scores were observed. Although these variations reduced the likelihood of finding significant differences among the groups, they reflected the variations in walking ability that can be expected in a convenience sample of people with a lower-limb amputation; such variations can be due to the cause of amputation, type of prosthesis, prosthetic fit, comorbidities, and age [8, 25-27]. Consequently, the large intragroup variations testify to the sensitivity of the selected gait adaptability assessments for identifying individual within-group differences, thereby promoting their face validity. The sensitivity of the gait adaptability assessments was further underscored by 2 strong within-subject effects that held for all groups; obstacle avoidance success rates decreased when fewer steps were available for obstacle avoidance (Figure 2.2), and stepping accuracy decreased with increased pattern irregularity (Figure 2.3).

Significant correlations between gait adaptability scores and timed walking test outcomes were found only for anticipatory obstacle avoidance success rates (Table 2.2). In particular, a significant correlation was expected and found between anticipatory obstacle avoidance success rates and the sub-item obstacle avoidance of the Emory-FAP [23]. This test best resembled the construct of anticipatory obstacle avoidance because it assesses obstacle negotiation performance on an overground obstacle course, and visual information about the obstacle is available several steps in advance. In contrast, the correlation with the Emory-FAP was not significant for reactive obstacle avoidance success rates (Table 2.2). Because reactive obstacle avoidance requires gait adjustments under time pressure [13], this condition apparently represents a different construct. Similarly, we can draw a more
general conclusion that the observed moderate correlations (e.g., for anticipatory obstacle avoidance success rates) in combination with several non-significant correlations (for reactive obstacle avoidance success rates and stepping accuracy) indicated that our gait adaptability scores quantified a unique, complementary aspect of walking ability. This unique aspect, putatively related to the ability to make online gait adjustments under time pressure, was not captured by any of the timed walking tests in isolation.

In addition to timed walking tests, we related gait adaptability scores to markers related to the risk of falls, including self-reported incidence of falls, fear of falling, and ABC scores. Gait adaptability and risk of falls, fear of falling, and balance confidence are related but different constructs [24, 28], as evidenced by the absence of significant correlations between gait adaptability scores and ABC scores as well as the absence of systematic differences in gait adaptability scores for subgroups stratified by fear of falling and incidence of falls. Gait adaptability scores objectively reflect a person’s ability to adjust gait during obstacle negotiation and visually guided stepping, whereas ABC scores report about fear of falling and represent a person’s confidence with regard to those activities and potentially the willingness to engage in such events [24]. Obviously, the incidence of falls is determined by the combination of (1) gait adaptability and (2) balance confidence and fear of falling. For example, the incidence of falls can differ between people with equally low gait adaptability scores because of different activity intensities or differences in risk-taking propensities in relation to personal variations in fear of falling or balance confidence. Notwithstanding the mediating effect of fear of falling on the incidence of falls, reduced gait adaptability performance itself seems to be an important, independent determinant of the risk of falls [3, 12]. The present study paves the way for a meaningful assessment of a person’s capacity to adjust gait to the environmental context (such as stepping targets and obstacles) with established face validity and construct validity.

Limitations
Before our conclusions can be accepted, the effect of walking speed as a potential confounding factor for gait adaptability performance must be considered for 2 reasons. First, the group showing inferior gait adaptability scores (TF group) also performed the tests at the slowest self-selected treadmill speed. Second, the supplementary experiment revealed that walking speed directly affected gait adaptability scores for stepping accuracy and reactive obstacle avoidance performance. Both scores improved with walking at a speed that was slower than
the self-selected speed (Appendix, page 40-42). On the basis of these results, it could be hypothesized that people with a reduced capacity to adjust gait adopt a slower walking speed to be better able to cope with environmental circumstances that demand gait adjustments. As a consequence, reactive obstacle avoidance and guided stepping performance of groups or individuals walking at a slower self-selected walking speed may have been overestimated in the present study relative to the performance of groups or individuals walking at a faster self-selected speed. Therefore, a comprehensive analysis of gait adaptability should not only examine gait adaptability performance but also evaluate this performance with respect to possible changes in self-selected walking speed.

In addition to having a slower walking speed, 7 of 12 participants in the TF group used handrail support for confidence during the treadmill tests. This handrail support probably facilitated their performance on obstacle avoidance and stepping tasks, thereby diminishing group differences due to an overestimation of gait adaptability scores in the TF group. Like the effect of walking speed on gait adaptability performance (as discussed above), this factor must be considered in the interpretation of between-group effects (or the absence thereof).

The present study was a first attempt to explore the use of an instrumented treadmill with projected visual obstacles and stepping targets for assessing prosthetic gait adaptability. We observed that all participants, representing a heterogeneous sample of people with diverse characteristics (e.g., level and cause of amputation, age, and time since amputation) (Table 2.1), were well able to complete and enjoy obstacle avoidance and guided stepping tasks. In addition, we established the face validity and construct validity of such assessments. However, to fully determine the usefulness of an instrumented treadmill with a projected visual context (i.e., visual obstacles and stepping targets) for routine clinical evaluation, future research must next establish the reproducibility of the selected gait adaptability tests and sensitivity to change after clinical interventions.

Conclusion

We successfully assessed and compared gait adaptability in 3 groups of participants using obstacle avoidance and visually guided stepping tasks on an instrumented treadmill with a projected visual context (i.e., visual obstacles and stepping targets). The gait adaptability performance scores so obtained indicated adequate face validity, as evidenced by significant between-group differences in gait adaptability. The assessment of construct validity revealed that gait adaptability performance
adds unique information to commonly used timed walking tests and self-reported incidence of falls and fear of falling. This added information reflects a person’s ability to make step adjustments under time pressure. We, therefore, propose that a gait adaptability assessment should be considered an integral part of a walking ability evaluation, especially when this construct is the main goal of intervention, such as with novel microprocessor-controlled prosthetic components or functional gait training. Because walking speed can affect gait adaptability performance, it should be taken into account in the interpretation of gait adaptability scores for different individuals or over time.
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References

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Appendix: Walking speed affects gait adaptability performance

The effect of walking speed on gait adaptability performance is currently unknown but is important because of the frequent differences in self-selected walking speeds between people without and people with a lower-limb amputation [1-3]. Moreover, walking speed generally scales with the proximal-distal level of the amputation, with slower self-selected walking speeds in people with a transfemoral amputation than in those with a transtibial amputation [3, 4].

In a supplementary experiment, we examined the effect of walking speed on the gait adaptability performance of a control group of people who were able bodied. They were invited to perform conditions 1 and 2 from the main study twice: once at their self-selected comfortable treadmill walking speed and once at a speed that was slower than the comfortable speed. When people walk more slowly, step times typically increase. Consequently, more time will be available to adjust gait to the visual context projected on the treadmill. We, therefore, expected improved gait adaptability performance when participants walked at a speed that was slower than their self-selected comfortable speed.

Method
The order of the 2 speed conditions was counterbalanced over participants, such that 6 participants first performed conditions 1 and 2 at their self-selected speed and subsequently performed conditions 1 and 2 at a fixed speed of 2.1 km/h (and vice versa for the other 6 participants). The latter speed was estimated to correspond to the self-selected speed of a representative group of people with a lower-limb amputation (based on the studies of Hofstad et al. [1], Houdijk et al. [2] and Waters et al. [3]). Outcome measures for condition 1 (obstacle avoidance success rates) and condition 2 (stepping accuracy) were determined as described for the main study.

The effect of walking speed on obstacle avoidance success rates was statistically tested using separate Wilcoxon signed rank tests separately for anticipatory obstacle avoidance and reactive obstacle avoidance. The effect of walking speed on stepping accuracy was evaluated with a repeated-measures analysis of variance for speed (2 levels: self-selected and fixed) × pattern regularity (3 levels: 0%, 20%, and 30%) followed by post hoc paired-sample t tests in case of significant pattern regularity effects.
Results
The average self-selected comfortable treadmill walking speed was 3.8 km/h (range=3.3-4.2 km/h) and, therefore, was always considerably faster than the fixed speed of 2.1 km/h.

Effect of Treadmill Speed on Obstacle Avoidance Success Rates
Anticipatory obstacle avoidance was not affected by walking speed ($z=0.74$, $p=0.458$), evidently because of a ceiling effect, with nearly perfect success rates (99%) at both speeds. In contrast, reactive obstacle avoidance was significantly affected by walking speed ($z=2.21$, $p=0.027$), with higher success rates at the slower, fixed speed (95%) than at the faster, self-selected speed (81%).

Effect of Treadmill Speed on Stepping Accuracy
Significant main effects were observed for speed ($F(1,11)=19.01$, $p=0.001$) and pattern regularity ($F(2,22)=18.85$, $p<0.001$). Stepping was more accurate at the slower, fixed speed than at the faster, self-selected speed (25 mm and 31 mm, respectively). Paired-sample $t$ tests showed that stepping accuracy differed significantly at all 3 levels of pattern regularity (all $p<0.009$), with superior performance for the 0% variation condition (23 mm), intermediate performance for the 20% variation condition (28 mm), and inferior performance for the 30% variation condition (32 mm).

Discussion
The supplementary experiment clearly showed that walking speed affected gait adaptability performance, with the expected superior performance at the slower, fixed walking speed. Specifically, reactive obstacle avoidance success rates improved by 15% and stepping accuracy improved by 6 mm. Anticipatory obstacle avoidance success rates were not significantly affected by walking speed; however, this finding was simply due to a ceiling effect, with most participants reaching 100% success rates at both the self-selected speed and the slower, fixed speed.

The implication of this finding is that walking speed effects may play a confounding role in evaluations of gait adaptability in various groups of people, who may walk at different self-selected speeds; this situation will favor the gait adaptability scores of the group with the slowest self-selected walking speed. Because slower self-selected walking speeds were expected for participants with a transfemoral amputation than for those with a transtibial amputation or those who were able bodied [3, 4], group effects (or the absence thereof) on gait adaptability
performance scores in the main study should be interpreted with reference to the relationship between gait adaptability performance and walking speed observed in the supplementary experiment.

**References**


