Gait control after stroke
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Chapter 6

Step characteristics during obstacle avoidance in hemiplegic stroke

Abstract
Whereas several animal studies have pointed at the important role of the motor cortex in the control of voluntary gait modifications, little is known about the effects of cortical lesions on gait adaptability in humans. Obstacle avoidance tasks provide an adequate paradigm to study the adaptability of the stepping pattern under controlled, experimental conditions. In the present study, an exploratory assessment was made of the failure rate, the preferred stepping strategies (step lengthening vs. step shortening), and the spatiotemporal stride characteristics (percentage increase in stride length, duration, and velocity of the crossing and the post crossing stride) during obstacle avoidance, in 11 hemiplegic stroke patients and 7 healthy controls. Patients were less successful in avoiding obstacles than controls (14 % failure rate vs. 0.5 % in controls), independent of whether the affected or the unaffected leg led the obstacle avoidance. The number of failed trials increased systematically when the available response time became shorter. During successful trials, lengthening of the step was generally preferred over shortening. This bias towards step lengthening was more pronounced in stroke patients (step lengthening in 91 % of the trials vs. 75 % in controls), irrespective of the side of obstacle presentation. For both groups, overall strategy preference did not adhere to a principle of minimal foot displacement, since step lengthening was used even if it would be more spatially efficient to shorten the step. No statistically significant group differences were found for the increase in length, duration and velocity of the crossing and the post crossing stride. However, for a subgroup of more slowly walking patients, large percentual increases were found in crossing stride length, duration, and velocity. Similar results were obtained for the post crossing stride indicating that, for this subgroup of patients, restoration of the normal walking cadence was more difficult. Overall, no systematic differences were found between the affected and the unaffected leg in stroke patients, in either failure rates, stepping strategies or spatiotemporal measures of obstacle avoidance. The present findings suggest that the ability to adequately modify the stepping pattern in response to imposed spatiotemporal constraints, is impaired in persons with stroke, especially when modifications have to be performed under time pressure. In addition, the stepping strategies employed by subjects with stroke are different from those found in controls, possibly to reduce the complexity of the avoidance manoeuvre and to enhance safety. Finally, unilateral cortical damage results in an impaired ability to avoid obstacles on both sides of the body, suggesting that the reduced ability of stroke patients to negotiate obstacles may be related to problems of a more general coordinative nature.
Introduction

During unperturbed human walking, the spatial and temporal characteristics of the steps are relatively fixed and typically show low step-to-step variability. The ability to impose intentional, ‘on–line’ modifications upon these tight spatiotemporal relationships, represents a fundamental aspect of human locomotor skill that allows persons to maneuver safely over varied terrain. Such modifications often involve a rigorous re-parameterization of forces within a short time window, and require a high level of neuromuscular control (Bonnard and Pailhous, 1993). Consequently, people with impaired neuromuscular functioning (e.g. due to age or neurological disorders) may be more vulnerable to perturbations of the ongoing stepping pattern, which could explain the high incidence of falls that has been reported for these groups (Blake et al. 1988; Tutuarima et al. 1997; Forster and Young 1995). Arguably, experimental studies on the spatiotemporal flexibility of walking in these groups may aid our understanding of what causes these people to fall, and may help to develop better preventive training programs.

One way to study the ‘on-line’ adaptability of human gait is to have people avoid obstacles that are placed on the walking surface. The avoidance of obstacles requires the selection of an alternative landing area for the foot, the planning of a new step, as well as a reorganisation of the ongoing movement sequence to execute the newly planned step. Whereas evidence from cat studies has shown the importance of corticospinal pathways for successful negotiation of obstacles (Drew, 1988,1996), information on obstacle avoidance in humans with central lesions is still scarce. In two studies by Said and coworkers (1999, 2001) it was shown that the performance of stroke patients in an obstacle avoidance task was impaired, and that patients used different modifications of the lead limb trajectory during successful crossing steps. The present study further explores obstacle avoidance in stroke patients with special emphasis on the role of time pressure in these tasks. As has been evidenced by studies in healthy young and elderly subjects, the time that is available to modify the walking pattern following obstacle presentation is an important determinant of the failure rate in this type of task (cf. Patla et al. 1991; Chen et al., 1994, 1996; Weerdesteijn et al. 2001). Hence, this parameter can be used in experimental settings to systematically vary task complexity, and to test flexibility of the stepping pattern under varying degrees of time constraint. From work done by Chen and coworkers (1994, 1996) we know that failure rates on avoidance tasks increase when the time available to respond becomes shorter. The effects of time constraints on the adaptability of gait may be
even more outspoken for individuals with hemiplegic stroke. The motor impairments associated with damage to sensorimotor areas may lead to an inability to initiate fast adaptive movements during gait. In addition, the general slowness of information processing that is often present in these patients (Gerritsen et. al, 2003), could make quick re-planning of ongoing gait movements difficult. These impairments will make patients vulnerable in situations that require on-line modifications of the stepping pattern, which may lead to increased failure rates on avoidance tasks when the available response time becomes short.

During successful obstacle avoidance, an alternative foot landing location is chosen in order to avoid undesirable contact with the obstacle. When the landing area has to be chosen in the plane of progression, two types of stepping strategies are available, i.e. the perturbed step can either be lengthened or shortened. It has been suggested that, for young adults, the stepping strategy that is preferred serves to minimize the amount of foot displacement relative to the normal landing area (Patla et al, 1999). However, this rule may not apply to other categories of subjects. A recent study on obstacle avoidance in elderly subjects has shown that a simple criterion of spatial efficiency alone may not be sufficient to account for the stepping strategies employed by these subjects (Weerdesteijn et al. 2001). More specifically, subjects showed a strong bias towards lengthening of the step, even under conditions where a shortening of the step would have been more appropriate in terms of spatial efficiency. These results warrant further research on obstacle related stepping strategies, especially in groups with reduced locomotor skills (i.e. hemiplegic stroke), because inadequate or inefficient selection of alternative foot landing areas endangers ambulatory safety and may lead to falls.

Another interesting aspect of obstacle avoidance in persons with locomotor impairments regards the implementation of the avoidance steps. With respect to hemiplegic gait, aberrations in the spatiotemporal properties of the stepping pattern (e.g. lower step length and cadence, asymmetries in stance / swing time distribution) have been reported on several occasions in the literature (Lehman, Condon, Price, & deLateur, 1987; Nakamura, Handa, Watanabe, & Morohahsi, 1988; Olney, Griffin, Monga & McBride, 1991). Within the context of the present study it would be interesting to know how hemiplegic patients manage to adjust both the timing and amplitude of the stepping movement, when solutions are spatially and temporally constrained by an obstacle avoidance task. A recent study showed that hemiplegic stroke patients generally use larger toe clearances and step durations than controls during obstacle crossing, possibly to reduce the risk of
contact with the obstacle (Said et al., 2001). Such information is important for a better understanding of how these patients accomplish step pattern modifications, and how such modifications contribute to either enhancement or reduction of ambulatory safety. It is important to note that adaptation of spatiotemporal stride characteristics may involve the post-crossing stride as well.

Another interesting aspect of hemiplegic walking is the presence of sensorimotor asymmetry. Despite the primarily unilateral nature of the motor impairment, studies by Said et al. (1999, 2001) have shown that patients showed no preference to lead with the affected or the unaffected leg although they performed worse when the affected leg led the obstacle-crossing maneuver. Apparently, the complex coordinative adaptations involved in obstacle avoidance pose a considerable challenge to stroke patients, regardless of whether the avoidance manoeuvre is led by the affected or the unaffected leg. Whereas modification of the trajectory of the affected leg may cause problems because of the reduced ability to generate and sustain fast corrective movements, the reduced weight bearing ability and diminished propulsive power on the affected side may affect obstacle avoidance performance on the unaffected side. More information is needed to better evaluate the role of sensorimotor asymmetry in obstacle avoidance tasks, with regard to the failure rate, the employed stepping strategies, and the spatiotemporal stride characteristics.

In this study, obstacle avoidance in hemiplegic stroke patients is studied under conditions of time pressure. The following hypotheses are put forward. First, with regard to task performance, it is expected that stroke patients will make more failures than healthy subjects on the avoidance task. In addition, we predict that the relative number of failed trials will increase when the time that is available to respond becomes short, and that these time pressure effects will be more pronounced in stroke patients. Second, in line with previous work on healthy elderly (Weerdesteijn et al., 2001), we expect that the relative number of shortening trials will increase when this will be spatially more efficient, but that subjects will not necessarily adhere to a principle of minimal foot displacement.

Methods
Subjects
11 hemiplegic stroke patients (mean age 62.73 yrs (range 29-83 yrs)) and 7 healthy controls (mean age 69.1 yrs (range 54 – 73 yrs)), participated in this study. Mean
time post-stroke for the patient group was 14.1 months (range 4-21 months). Six patients suffered from right-sided hemiparesis and five patients suffered from left sided hemiparesis.

To be included in this study, patients had to satisfy the following criteria: a cortical stroke due to infarction or haemorrhage, (past or continuing) rehabilitation training for balance and gait problems, and the ability to ambulate independently without the use of walking aids or orthoses. The time post onset for patients had to be at least 4 months. Exclusion criteria were: a Mini- Mental State score less than 25 (Folstein et. al, 1975); medical conditions unrelated to the cerebrovascular accident that are known to affect walking performance; severe cognitive, emotional or behavioural impairments, resulting in insufficient comprehension, understanding, or collaboration. Also, the presence or absence of visuospatial neglect was judged after administration of the line bisection task (Schenkenberg, Bradford, & Ajax, 1980), the letter cancellation task (Diller et al., 1974), the Bells test (Gauthier et al., 1989) and clock drawing (Wilson et al, 1987). None of the tested patients scored abnormally on more than one of these tests, so that all tested patients could eventually participate in the study. For all patients, the degree of lower extremity motor selectivity (i.e. the Brünnstrom stage of recovery) the presence or absence of contractures, clonus, sensory problems, higher order perceptual disorders, and the quality of trunk control were assessed by an experienced physician using standard clinical procedures (see Table 1 for patient characteristics). Subjects in the group of healthy controls reported not to suffer from any neurological or orthopaedic disorder that is known to affect walking performance. All patients gave their written informed consent prior to experimentation. The study was approved by the Medical Ethic Committee of the Sint Maartensclinic in Nijmegen.

**Experimental setup**

During the experiment, subjects walked on a motor driven treadmill (dimensions of the walking surface: 2000 mm (l) * 700 mm (w)). At the front end of the treadmill a chipboard obstacle (dimensions: 400 mm (l) * 300 mm (w) * 15 mm (h)) was attached to an electromagnet (similar to the method described by Schillings et al., 1996). The length of the obstacle corresponds to approximately 25-30% of the step length that has been reported for healthy adults at normal walking speed (Perry, 1992). Based on these data, we assumed that the required step length modifications would be feasible for our subjects, but that they would still be sufficiently
challenging to bring about a serious disruption of the ongoing walking pattern. On the other hand, the height of the obstacle is relatively small, hence the required modifications are related primarily to the length of the step, and to a lesser extend to the amount of vertical clearance.

In order to record movement of the foot relative to the obstacle, lightweight reflective markers were attached to the most posterior end of the shoe (heel marker), the most anterior end of the shoe (toe marker) and the front end of the obstacle. Movements of the markers were recorded in 3D using a Primas™ infrared camera system. Movement data were sampled at 100Hz and stored on hard disk using Winread™ data acquisition software. All trials were also recorded on video.

For the objectives of the present study, it was essential that both obstacle presentation and the initial avoidance response would take place within one step cycle, thus achieving obstacle avoidance under time critical conditions. Furthermore, it was our intention to present the obstacle during different phases of the step cycle, thereby varying the Available Response Time (ART). In order to experimentally control the available response time it was necessary to predict the unaltered landing position of the foot relative to the obstacle, as well as the normal, unperturbed stride duration. For this purpose, information of the heel marker signal was fed to a computer, during a series of unperturbed steps. By recording the foot landing position and the stride duration for a number of successive steps, an online estimate could be made of the normal landing location and stride duration. Based on this information, the landing location and landing time of the following

Table 1. Patient characteristics

<table>
<thead>
<tr>
<th>Subject</th>
<th>Speed (m/s)</th>
<th>Age</th>
<th>Time post stroke (months)</th>
<th>Type of lesion</th>
<th>Side of lesion</th>
<th>Sensibility</th>
<th>Brunstrom stage</th>
<th>Trunk control</th>
<th>Higher order perceptual disorders</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1 A</td>
<td>0.56</td>
<td>49</td>
<td>4</td>
<td>infarction</td>
<td>left</td>
<td>normal</td>
<td>6</td>
<td>normal</td>
<td>not present</td>
</tr>
<tr>
<td>S1 B</td>
<td>0.56</td>
<td>71</td>
<td>18</td>
<td>hemorrhage</td>
<td>right</td>
<td>normal</td>
<td>6</td>
<td>normal</td>
<td>not present</td>
</tr>
<tr>
<td>S1 C</td>
<td>0.56</td>
<td>65</td>
<td>13</td>
<td>infarction</td>
<td>right</td>
<td>severely impaired</td>
<td>5</td>
<td>mildly impaired</td>
<td>occasionally present</td>
</tr>
<tr>
<td>S1 D</td>
<td>0.56</td>
<td>57</td>
<td>8</td>
<td>infarction</td>
<td>right</td>
<td>normal</td>
<td>6</td>
<td>normal</td>
<td>not present</td>
</tr>
<tr>
<td>S1 E</td>
<td>0.56</td>
<td>78</td>
<td>19</td>
<td>infarction</td>
<td>left</td>
<td>normal</td>
<td>6</td>
<td>mildly impaired</td>
<td>not present</td>
</tr>
<tr>
<td>S1 F</td>
<td>0.56</td>
<td>63</td>
<td>14</td>
<td>infarction</td>
<td>left</td>
<td>normal</td>
<td>6</td>
<td>mildly impaired</td>
<td>not present</td>
</tr>
<tr>
<td>S2 A</td>
<td>0.17</td>
<td>79</td>
<td>16</td>
<td>infarction</td>
<td>left</td>
<td>normal</td>
<td>5</td>
<td>mildly impaired</td>
<td>not present</td>
</tr>
<tr>
<td>S2 B</td>
<td>0.25</td>
<td>29</td>
<td>8</td>
<td>infarction</td>
<td>left</td>
<td>severely impaired</td>
<td>3</td>
<td>mildly impaired</td>
<td>occasionally present</td>
</tr>
<tr>
<td>S2 C</td>
<td>0.31</td>
<td>83</td>
<td>21</td>
<td>infarction</td>
<td>left</td>
<td>normal</td>
<td>5</td>
<td>mildly impaired</td>
<td>not present</td>
</tr>
<tr>
<td>S2 D</td>
<td>0.42</td>
<td>61</td>
<td>18</td>
<td>infarction</td>
<td>right</td>
<td>normal</td>
<td>6</td>
<td>normal</td>
<td>not present</td>
</tr>
<tr>
<td>S2 E</td>
<td>0.31</td>
<td>55</td>
<td>16</td>
<td>infarction</td>
<td>left</td>
<td>mildly impaired</td>
<td>3</td>
<td>mildly impaired</td>
<td>not present</td>
</tr>
</tbody>
</table>
Figure 1: Relation between the moment of obstacle presentation relative to the gait cycle, the available response time, and the amount of required foot displacement. Depicted are the ipsilateral leg in its predicted (i.e. unaltered) landing position (dashed), and its actual position at the moment of obstacle presentation, during (A) unperturbed walking (B) obstacle presentation during late swing, (C) obstacle presentation during early swing, and (D) obstacle presentation during late stance. Note that the moment of obstacle presentation relative to the gait cycle determines how much time is available to respond, and which stepping strategy (lengthening or shortening) requires the smallest amount of foot displacement. ART= Available Response Time.

In figure 1, it can be seen that if the obstacle was presented during late swing, the unaltered landing area of the foot would be on the near end of the obstacle Consequently, the amount of foot displacement required to avoid contact with the obstacle favors step shortening. Because the distance between foot position at the moment of obstacle presentation and the predicted landing area is small, the available response time (ART) is short (see figure 1b). In contrast, when
the obstacle was presented during late stance, the unaltered landing area would be on the far end of the obstacle, and the amount of foot displacement required to avoid the obstacle favors lengthening of the step. In this case, the distance between the foot and the predicted landing area is relatively large and the ART is long (see figure 1d).

In order to enhance estimation accuracy, subjects were instructed to walk at the same position on the treadmill and to maintain a constant distance from the obstacle of about 10 centimetres. The distance from the obstacle was monitored visually by one of the experimenters, and in case subjects did not conform to the prescribed distance they were warned verbally. The distance from the obstacle was monitored visually by one of the experimenters, and in case subjects did not conform to the prescribed distance they were warned verbally. In addition, marker data of all trials were inspected off line. In particular, it was checked whether the foot indeed would have landed on the obstacle if no avoidance reaction was initiated. Occasionally, the predicted foot landing area would be in front of the obstacle surface if the prescribed distance to the obstacle was not maintained. Such trials were identified off line and excluded from further analysis. This way, 6% of the trials had to be rejected. Trials were presented in randomised blocks to prevent the use of anticipatory strategies by subjects. Each block consisted of four trials, with each trial corresponding to a particular category of ART's (0-250 ms, 251-500, 501-750, and 751-1000 ms). Note that the exact ART of each trial was estimated off-line after completion of the experiment.

Procedure
For both controls and stroke patients, the default walking speed that had to be pursued was 0.56 ms\(^{-1}\). This speed compares well to the walking speeds that have been reported in the literature for hemiplegic stroke patients (0.23 to 0.73 ms\(^{-1}\), cf. Olney and Richards, 1996)). However, the selected speed is considerably slower than the speeds that have been reported for healthy elderly (0.70 to 1.38 ms\(^{-1}\), cf. Prince et. al, 1997). Nevertheless, this speed was chosen because we expected it to be feasible for most of the patients, without being experienced as abnormally low by healthy subjects. Prior to experimentation, all patients walked on the treadmill while the speed was gradually increased until the desired speed of 0.56 ms\(^{-1}\) was reached. However, if patients were unable to walk at the specified speed, or were presumably unable to maintain the required speed for the duration of the entire experiment, treadmill speed was adjusted until the maximum pace was reached at
which the minimum number of required trials could presumably be completed. For 5 of the 11 stroke subjects, the target speed of 0.56 ms\(^{-1}\) appeared to be unfeasible, and the treadmill was set to a slower speed to guarantee a sufficient number of trials under safe conditions. Each obstacle presentation was equivalent to one ‘trial’. For the stroke subjects, the total number of trials was set to 24 for each leg. During the experiment, four of the eleven patients reported to be too fatigued to continue the experiment and the experiment was halted. For these patients, a minimum of 18 trials could be obtained for each leg. For the control subjects, the experiment involved 28 presentations of the obstacle, to the left leg only. Treadmill speed for controls was always set at 0.56 ms\(^{-1}\). Between two obstacle presentations, subjects walked unperturbed for approximately 30 to 50 seconds.

All subjects were instructed to avoid foot contact with the obstacle, and were informed that steps beside the obstacle were classified as failures. Patients were allowed to take a rest in between blocks of trials, if necessary. Although patients were encouraged to walk unsupported, they were allowed to hold on to a bar at the front end of the treadmill if they experienced problems maintaining dynamic balance. The height of the rail was adjusted for each individual patient and set to pelvis height. Therefore subjects could only use it for reference, not for body unloading. This was done to discourage the use of arm strategies, e.g. to prolong single stance phases during the crossing manoeuvre. For safety, all subjects wore a harness around the waist attached to a special suspension system. No body weight support was supplied.

Data analysis

Video recordings were made in order to classify each attempt to cross the obstacle as either a ‘success’ or a ‘failure’, and to further categorise the successful trials as a ‘lengthened step’ or as a ‘shortened step’. A trial was considered as a failure if the subject stepped on or beside the obstacle. In the case where foot contact was made in front of the obstacle prior to the actual crossing step, the trial was categorised as a ‘shortened step’ (see figure 2a). A successful trial was categorised as a ‘lengthened step’ if the step cycle in which the obstacle was presented was lengthened to cross the obstacle (see figure 2 b).

The individual failure rates were expressed as a percentage of the total number of trials completed by each subject. Similarly, individual strategy preference scores were obtained by calculating the frequency of occurrence of each strategy as a percentage of the total number of successful trials. Both the individual failure rates and the individual strategy scores were subsequently averaged to obtain mean
failure rates and strategy scores for the control group, and for presentations to the affected and unaffected leg in the patient group. Because the timing of obstacle presentation relative to the gait cycle is likely to affect the degree of difficulty of the obstacle avoidance task, failure rates were further categorised with respect to the phase of the gait cycle in which the obstacle was presented. Each trial was categorised as belonging to one of five categories: presentation between 1 – 20%, 21 – 40%, 41 – 60%, 61 – 80%, or 81 – 100% of the gait cycle. For stroke patients, a mean number of 4.1 trials (sd=0.38) within each of these categories could be obtained for the affected leg, and a mean number of 4.3 trials (sd= 0.46) for the unaffected leg. For controls subjects, the mean number of trials within each category was 5.2 (sd=0.52).

The gait cycle was defined as the time between two ipsilateral initial foot contacts, and was determined using speed distribution analysis of the heel marker data (Peham et al. 1999). This technique uses velocity data of the heel marker to create a distribution of speed values. The speed with the most frequent occurrence is assumed to correspond with the stance phase (i.e. no movement of the marker relative to the walking surface). Subsequently, this speed is used as a threshold for detection of the onset and termination of the stance phase.

In order to calculate the ART, first the normal landing time was predicted by

For young adults, it has been suggested that the amount of required foot displacement relative to the normal landing area plays an important role in determining the location of the alternative landing area (e.g. landing in front of the obstacle or behind it) (Patla et al. 1999). Therefore, we categorised the percentage of shortening and lengthening trials with respect to the amount of displacement required to employ a successful lengthened step or a successful shortened step. This was done by calculating the following value:

\[
\% \text{ in favour of lengthening} = \left( \frac{\text{required lengthening} (\text{mm}) - \text{required shortening}(\text{mm})}{\text{unperturbed step length}(\text{mm})} \right) \times 100
\]

This value represents the amount of foot displacement in favour of step lengthening, with negative values occurring if step shortening would be spatially more efficient. These values enabled us to categorize each trial as belonging to one of six categories: 0-25%, 26-50%, or more than 50% of unperturbed step length in favour of step lengthening; or 0-25%, 26-50%, or more than 50% of unperturbed
Figure 2. Schematic explanation of some key concepts: (A) Shortening strategy: additional foot contact is made in front of the obstacle prior to the actual crossing manoeuvre. (B) Lengthening strategy: the step during which the obstacle is presented is lengthened to cross the obstacle. (C) Available response time: the time between obstacle presentation and the predicted (unaltered) landing time of the foot. (D) Required foot displacement: minimum amount of foot displacement necessary to avoid stepping on the obstacle, relative to the unaltered landing area. Note that lengthening and shortening of the step usually require different amounts of foot displacement. Extrapolating the duration of the last unperturbed stride preceding obstacle presentation. The difference between the moment of obstacle presentation and the predicted normal landing time was the ART (see Figure 2c).
step length in favour of step shortening (see Figure 2d).

In order to obtain more detailed information on the spatial and temporal stride characteristics, stride length (mm), duration (ms), and velocity (ms⁻¹) were calculated for the pre-crossing, crossing, and post-crossing stride. Because of between subject differences in the length, duration, and velocity of the normal stride, the spatial and temporal variables for the crossing and post-crossing stride were normalised with respect to the last unperturbed stride preceding obstacle presentation. This was done in order to legitimate between subject comparisons on these variables. For example, the pre-crossing stride length was used to calculate the ‘percentage increase in crossing stride length’ as follows:

\[
\text{% increase in crossing step length} = \left(\frac{\text{crossing step length}}{\text{pre crossing step length}}\right) \times 100 - 100
\]

This measure expresses the percentage of extra stride length used during the crossing stride, relative to the stride length during normal, unperturbed walking.

Statistical analysis
During experimentation, 6 stroke subjects were able to walk at the target treadmill speed of 0.56 ms⁻¹, while 5 patients completed the experiment at slower treadmill speeds (see Table 1 for information on the actual walking speeds that were employed). These groups will be referred to as group S1 (0.56ms⁻¹) and S2 (< 0.56ms⁻¹). Because of the differences in walking speed, statistical comparisons between group S2 and the control group are questionable. Therefore, group S2 was excluded from statistical analysis. Nevertheless, the S2 results will be presented and discussed, because this group may still provide valuable information on obstacle avoidance in more slowly walking and more severely affected stroke patients.

Effects of the factor ‘Group’ (S1 vs. controls) on the percentage of failures and the percentage of shortened steps employed were tested non-parametrically using the Mann-Whitney test. Within the patient group, effects of the factor ‘Side’ (obstacle presentation to the affected side vs. presentations to the unaffected side) on the number of failures and the percentage of shortened steps were tested using a Wilcoxon matched pairs signed ranks test. We used Friedmans non parametric test for repeated measures to test whether the ART affected the percentage of failures, and whether the amount of required foot displacement affected the percentage shortening strategies. For each of these non-parametric tests the α-value was set to .05.
Group differences in normal stride length, duration, and velocity, and percentage increase in (post-) crossing stride length, duration, and velocity, were tested simultaneously using a one way multivariate analysis of variance (MANOVA) with ‘GROUP’ (S1 vs controls) as a between subjects factor. Within the patient group S1, effects of the factor ‘SIDE’ (obstacle presentation to the affected side vs. presentations to the unaffected side) on normal stride length, duration, and velocity, as well as percentage increase in (post-) crossing stride length, duration, and velocity, were tested simultaneously using a one way multivariate analysis of variance (MANOVA).

Results

Failure rate

The mean percentage of failed trials on the obstacle avoidance task was 0.5 % in control subjects, whereas it was 14% in stroke group S1. Nonparametric statistical testing revealed a significant group effect ($U=2; p=0.004$). The mean failure rate of the more slowly walking stroke group S2 was 21%, which is also substantially higher than the value found for controls. Within stroke group S1, the mean percentage of failed trials when the obstacle was presented to the affected side was 13% (range 0-46%) whereas the percentage of failures on the unaffected side was 14% (range 0-50%). This difference was not statistically significant ($z=-0.31; p=0.75$). In the more slowly walking stroke group S2, failure rates amounted to 18% (range 0-41%) when obstacles were presented to the affected side, and 24% (range 4-58%) when obstacles were presented to the unaffected side. As can be seen in figure 3, the failure rate in group S1 depended on the moment of obstacle presentation, when the obstacles were presented to the affected leg (Chi-square (df=4) = 18.81; $p=0.001$), as well as when the obstacles were presented to the unaffected leg (Chi-square (df=4) = 15.07; $p=0.005$). From this figure it becomes clear that the relative number of failed trials increases when obstacles were presented late in the gait cycle and the corresponding ART's were short. Similar behavior was upheld by subgroup S2 (not illustrated), in which the mean percentage of failed trial increased from 10.2% (affected side) and 8.3% (unaffected side) for ART’s longer than 750 ms, to 28.3% (affected side) and 31.2% (unaffected side) for ART’s shorter than 250 ms. The controls made errors only for the shortest ART’s. Because the failure rates for controls were zero for all but one ART/ % gait cycle category, statistical testing did not yield a significant result for this group (Chi-square (df=4) = 4; $p=0.41$).
Figure 3. The mean percentage of failures plotted as a function of the moment of obstacle presentation (% of gait cycle) and the available response time (ms.), for controls (white squares) and the faster stroke group S1 (unaffected side: black circles; affected side: grey diamonds).

Stepping strategies
All successful trials were categorized as either a ‘shortening trial’ or a ‘lengthening trial’ (see figure 2). On average, stroke patients in group S1 preferred a lengthening of the step on 91.4% (sd=6.98) of the trials, whereas controls used the lengthened step on 74.8% of the trials (sd=14.53). The difference between controls and stroke group S1 was statistically significant (U=5; p=.035). The bias towards step lengthening was also found in the more slowly walking stroke group S2, showing a mean percentage of lengthening trials of 81.89 (sd=4.91). Within stroke group S1, the mean percentage of lengthened steps for presentations to the affected side was 89.20 (sd=9.17), whereas during presentations to the unaffected side this percentage was 93.7 (sd=10.11). This difference was not statistically significant (z=-.730; p=.465). Likewise, stroke group S2 did not show clear asymmetries between the two legs with regard to the stepping strategies that were employed. When the obstacle was presented to the affected leg, these patients used
a shortened step on 81.3% (sd=8.70) of the trials, against 82.4% (sd=8.25) when the obstacle was presented to the unaffected leg.

Figure 4 shows the percentage of shortening and lengthening trials for group S1 and controls, as a function of the amount of foot displacement required to execute either stepping strategy successfully (see figure 2d for an explanation). Again, group S2 was excluded from the figure to ensure comparability in terms of walking speed (see above). It can be seen that there was a strong bias towards
lengthening of the step, even in cases were shortening of the step would be spatially more efficient. For instance, control subjects used step lengthening in 53.17% of the trials even when it was 26-50% more advantageous spatially to shorten the step. The differences between the six categories that reflect the amount of required foot displacement, were statistically significant for stroke group S1 (Chi-square=27.01; p<.001) as well as for controls (Chi-square=31.73; p<.001).

Figure 4 further shows that the bias towards step lengthening is more pronounced in patients than in controls. In controls, shortening of the step became the dominant stepping strategy only in trials where this was over 50% more spatially efficient. In contrast, in stroke patients the shortening step never became the dominant strategy, neither at the affected nor at the unaffected side.

**Spatiotemporal step characteristics**

For the lengthening trials, a detailed analysis was made of the length, the duration, and the velocity of the normal, the crossing, and the post-crossing stride. Analysis of spatial and temporal characteristics was not possible for the shortening steps, because the number of trials in which the shortening strategy was performed, was insufficient. The absolute lengths (mm), durations (ms) and velocities (ms⁻¹) of the unperturbed steps were included in the analysis, in order to relate data of the crossing and post crossing stride to characteristics of the normal stepping pattern. Stride length, duration and velocity for all three groups are depicted in figure 5. The average stride length during normal walking was 785 mm in controls (sd=110) and 839 mm (sd=170) for stroke group S1, which was substantially larger than the average unperturbed stride length of patients in stroke group S2 (402 mm (sd=116). With regard to the crossing stride, stride length was increased by 37% (sd=17) and 27% (sd=13) with respect to unperturbed stepping, for controls and S1 respectively. The percentual increase in crossing length was substantially larger in stroke group S2, and amounted to a mean of 131% (sd=84). With regard to the post-crossing stride length, an overall decrease was found with respect to the pre crossing values. Differences in controls (-2%) (sd=9) were substantially smaller than the values found in stroke group S1 (-12%; sd=9). Again, deviations from the normal stride were largest in stroke group S2 (-29%; sd=14). Stride duration during unperturbed walking was 1482 msec (sd=188) and 1375 msec (sd=313) for stroke groups S1 and S2 respectively. These values compare quite well with the normal stride duration found in healthy controls (1388 msec; sd=294). However, during the crossing stride, stroke group S2 increased their stride duration on average by
51% (sd=35), which was substantially larger than the increases found for stroke group S1 (13%; sd=11) and controls (15%; sd=15). With respect to the percentage increase in post crossing stride duration, stroke patients increased their stride duration 29% (sd=14) and 9% (sd=6) for groups S2 and S1 respectively), whereas controls adopted a stride duration that was close to their normal stride duration (-1% (sd=5)).

The stride velocity for a particular trial was calculated by dividing the length of the stride by its duration During unperturbed walking, the mean stride velocity in stroke group S2 was \(0.301 \text{ms}^{-1}; \text{sd}=0.098\), which is lower than the velocity values found for stroke group S1 \(0.566 \text{ms}^{-1}; \text{sd}=0.007\) and controls \(0.564 \text{ms}^{-1}; \text{sd}=0.012\). During obstacle crossing, subjects increased their stride velocity. The percentage increase in stride velocity during the crossing stride was larger in stroke group S2 (mean increase 43%; sd =15) than in controls, whereas differences in crossing velocity between S1 (mean increase 14%; sd=10) and controls (mean increase 15%; sd=6) were negligible. During the post crossing stride, stride velocity was decreased
by 10% (sd=10) for subjects in S1, and by 12% (sd=7) in controls. Again, the largest deviations from normal stepping were found for group S2, were post crossing stride velocity was decreased by 47% (sd=14).

The one way MANOVA with the between subjects factor ‘GROUP’ (S1 vs. Controls) that was used to test all spatiotemporal variables simultaneously, did not yield a statistically significant effect. This implies that stroke group S1 and controls did not differ with respect to the length, duration, and velocity of the normal stride, or the percentual increase in length, duration and velocity of the crossing and the post crossing stride.

Discussion

Failure rates

In the present study, it was found that stroke patients were more likely to fail the obstacle avoidance task. Failure rates at the affected as well as at the unaffected side exceeded the values found in healthy controls. The very low mean failure rate that was found for controls indicates that healthy subjects are well capable of modifying their step trajectories within the time frame of one step, provided that these modifications are made in the line of progression (see also Patla et al., 1991). In contrast to the near perfect scores for controls in the present study, Chen et al. (1994) found success rates of about 70% at ART’s of 350 ms, dropping to a mere 15% at ART of 200 ms, in a group of healthy elderly. However, in Chen’s study the subjects walked at a speed of about 1.40 ms\(^{-1}\), which is substantially faster than the 0.56 ms\(^{-1}\) that was used in the present study. Stroke patients performed considerably worse on the obstacle avoidance task, which confirms the results previously found by Said et al (1999) for overground obstacle avoidance. However, in the present study, the mean overall failure rate for patients was 17.1%, which appears to be relatively high when compared to the approximate 9% that was found in the Said et al. study. However, it must be noted that a simple comparison between Said et al. (1999) and the present study is not entirely warranted. First, the two studies differ with respect to the type of obstacle that was used. Whereas the dimensions of the presently used obstacle (400 mm (l) * 300 mm (w) * 15 mm (h)) were chosen primarily to provoke adjustments in step length and posed no real threat to ambulatory safety, the obstacles used by Said and coworkers were 100, 400, and 800 mm high, and were possibly more related to unsafe gait or tripping. Second, the present study used treadmill walking, whereas subjects in the Said et. al study walked overground. In principle, this could have allowed subjects in the Siad et al.
study to adapt their walking speed in anticipation of the eventual crossing step. Because the present study was performed on a treadmill, such anticipatory strategies were not possible, which may partly explain the relatively high failure rates that were found in comparison to Said et al (1999).

However, is it likely the addition of time constraints that represents the main contribution to the relatively high failure rates that were found in the present study. Indeed, we found that the chance of contact with the obstacle increased when ART’s were short. Failure rates increased from about 7% for the longest ART’s (approximately 900 milliseconds), to about 27% for the shortest ART’s (approximately 180 milliseconds). These results confirm work by others, showing that time criticality is an important determinant of the success rate in obstacle avoidance tasks (Chen et al 1994, 1996; Patla et al. 1991; 1996 Weerdesteijn et al. 2001). Despite this, it is interesting to note that, even at ART’s of longer than 500 milliseconds, stroke patients still fail the avoidance task much more often than controls. This perhaps reflects a more general deficit in the ability of stroke patients to negotiate obstacles that is independent of the effects of time pressure. A further point that needs mentioning is that failure rates in the stroke group were high, despite the very slow walking speeds that were employed (0.17 to 0.56 ms\(^{-1}\)), implying that ‘slow’ walking cannot be equated with ‘safe’ walking for these patients. Even in the case of the slowest walking patient in this study (0.17 ms\(^{-1}\)), failure rates were as high as 41.7% at the affected side, and 21.4% at the unaffected side.

Several mechanisms may account for the impaired ability to negotiate wide obstacles in stroke patients. First, animal experiments have pointed at the importance of the primary motor cortex for the production of visually controlled, voluntary gait modifications (Drew, 1988, 1996). Whereas the neurophysiological basis for human gait modification is less clear, damage to cerebrospinal pathways, e.g. following a cerebrovascular accident, may impair visuomotor coordination and result in a reduced ability to negotiate obstacles during gait. Indeed, the actual crossing manoeuvre may require real time modifications of swing limb flexor activity (Patla et al, 1991) and support limb extensor activity, as well as adjustments in ipsilateral and contralateral propulsive forces (cf. Varraine et al. 2000). This may be difficult to implement for persons with stroke, since knee flexion during the swing phase, hip extension during the stance phase (Knutson and Richards, 1979) and the amount of vertical push off force (Carsloo et al 1974) are often reduced in these patients.
Second, it has been shown that general slowness of information processing is one of the most prominent cognitive deficits associated with stroke (Hochstenbach et al., 1998) with up to 70% of the assessed patients showing signs of mental slowness. In addition, several reaction time studies have pointed out that the increased visuomotor decision time found in stroke patients forms a major component of the increased total response time observed for these subjects (Gerritsen et al., 2003, Dee and van Allen, 1971). Such cognitive impairments may have played a role in the impaired ability of hemiplegics to negotiate obstacles, especially when time pressure is high and fast locomotor responses are required.

An interesting observation in this study was that the number of failures at the unaffected side was relatively high, and did not differ significantly from the failure rate observed at the affected side. This result seems to be in accordance with Said et al. (1999) who failed to find a statistically significant difference in failure rates between the affected and the unaffected leg, despite a trend that was found for the affected, leading leg to show more failures. Several mechanisms may account for the high failure rates that were found on the unaffected side in stroke patients. First, when the obstacle is crossed with the unaffected leg, the impaired weight bearing capacity of the affected will be stressed. This possibly leads to problems in the maintenance of dynamic balance, particularly when stride duration has to be prolonged in order to step over the obstacle, resulting in increased failure rates for the unaffected leg. Second, muscle weakness may have been present on the unaffected side. There have been several reports in the literature showing that primary motor impairments are present on the so-called ‘unaffected’ side of hemiparetic stroke patients. For instance, muscular weakness has been reported for the unaffected lower limb (Watkins et al., 1984) as well as for the unaffected upper limb (Desrosiers et al., 1996). Finally, the coordinative reorganization that is required during unilateral obstacle avoidance may depend on bilateral cortical involvement. In a recent study by Debaere et. al (2001), it was shown that the performance of coordinated movements between the unaffected upper and lower extremity is impaired in stroke patients. This indicates that control of interlimb coordinative patterns may require the coupled activity of two intact hemispheres. This may be important with respect to spatiotemporal flexibility in walking, because successful adjustments of the stepping pattern can only be attained through a strong coordinative coupling of leg movements. Because the level of performance during adaptive gait tasks depends on the coupled neural control of the perturbed and the unperturbed leg, unilateral perturbations of gait will inevitably lead to a
bilateral reorganization of the movement pattern. Future analysis of electromyographic data may further clarify the changes in motor patterns involved in such adaptive reorganizations, and how neuromuscular strategies differ between healthy subjects and persons with hemiplegia.

**Stepping strategies**

With regard to the stepping strategies that were used to cross the obstacle, it was found that stroke patients as well as controls generally preferred a lengthening of the step to cross the obstacle. It has been suggested by Patla et al. (1999) that in young adults the preferred stepping strategy serves to minimize alterations in the normal gait trajectory and tries to secure dynamic equilibrium. When the alternative landing area of the foot has to be chosen in the line of progression, subjects are likely to choose the stepping strategy that minimizes the amount of foot displacement relative to the normal landing area, whereas for comparable amounts of foot displacement, lengthening is generally preferred over shortening of the step. The results from the present study generally confirm these ideas, showing that the choice of an alternate foot landing area is not random, and that there is a clear relation between the amount of required foot displacement and the preferred stepping strategy. However, in patients as well as in controls, the bias towards lengthening of the step was much stronger than would be expected on the basis of a minimal foot displacement criterion alone, i.e. the lengthened step was the dominant step even if this entailed a much larger amount of foot displacement.

The present findings on stepping strategies are in line with results obtained in healthy elderly. Weerdesteijn et al., (2001), showed that elderly subjects had a strong preference for lengthening of the step even if shortening of the step would be spatially more efficient. This suggests that minimisation of foot displacement may not be the sole principle for determination of the stepping strategy, and that this criterion is subordinate to a more general attempt to minimise the net perturbing effect of the obstacle. During shortening of the step, the foot is placed in front of the obstacle, while the center of mass continues to move forward over the base of support. Next, the displacement of the head-arm-trunk system requires quick initiation of the actual crossing step in order to lengthen the base of support, and to prevent the subject from falling. Such movements are motorically complex and pose a greater risk to dynamic balance than merely lengthening the perturbed step. This may explain why stroke subjects relied more on the lengthening strategy
in an attempt to reduce risk of contact with the obstacle or the tendency to fall, even at the cost of spatial efficiency.

Another potential explanation for the bias towards step lengthening, especially in stroke patients, is that, during the lengthened step, the crossing leg will be in a leading position and that visual information on the crossing leg will be available continuously. In contrast, shortening of the perturbed step will generally result in a situation in which the crossing leg will be in a trailing position, so that visual information will not, or only partly, be available. This will make a lengthened step possibly easier to implement, especially for subjects whose problems in postural control and movement regulation have made them more dependent on visual information.

In this context, it is important to note that a direct comparison between the Patla et. al study (1999) and the present study is rather difficult because of some important differences in the protocol and experimental setup between both studies. First, the present experiment was carried out on a treadmill, whereas the experiments of Patla et al. addressed overground walking. Indeed, the treadmill may have contributed to the bias that was found towards lengthening of the step, because during shortening of the perturbed step, the base of support is ‘pulled’ in the posterior direction by the moving treadmill surface, relative to the centre of mass. This makes the execution of a shortened crossing step more complex, which may partly explain why both patients and healthy subjects generally preferred lengthening of the step. In addition, the preference for step lengthening may also be related to the wider range of possibilities offered by stepping in the space behind the obstacle as compared to stepping inside the narrowing gap between the approaching obstacle and the ipsilateral foot. This is perhaps a less efficient strategy but it is easier in terms of precise planning of landing since the treadmill surface behind the obstacle is larger than it is in front of the obstacle. Second, the Patla et al study utilized light spots instead of a three dimensional object. The physical object that was used in the present study has different behavioral consequences (e.g. stumbling) than a two dimensional light spot. As a consequence, safety issues may have played a more prominent role in the present experiment, e.g. with respect to the preferred stepping strategies.

Spatiotemporal stride characteristics
As was expected, subjects showed an increase in stride length during successful lengthening trials. However, the relative amount of lengthening that was used for
the crossing stride differed between the three groups that were assessed. Whereas in healthy controls and subjects in stroke group S1 the amount of extra stride length that was used amounted to 27% en 37% respectively, for stroke group S2 the amount of lengthening was as high as 131%. Since this difference was found solely for the more slowly walking subgroup of patients, this raises the question whether it can be explained as a simple speed effect instead of an effect of stroke. Although characteristics of the crossing and post crossing stride were normalized with respect to pre crossing values, walking speed may have affected crossing and post crossing stride characteristics indirectly. Because lower walking speeds are generally associated with smaller stride lengths (Grieve & Gear, 1966), a potential explanation for the excessive increase in crossing stride length in S2 may be sought in the smaller stride length used by these subjects during normal, unperturbed gait. When faced with identical spatial constraints, the relative increase in stride length for a subject will be proportional to the stride length used during the unperturbed

stroke patient, ipsilateral leg (0.44 m/s)

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control subject, ipsilateral leg (0.56 m/s)

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Figure 6 Typical examples of the stepping pattern of a patient and a control subject. Length and duration, and the normalized length and duration (between brackets) are given for the normal stride (A), the crossing stride (B), and the post crossing stride (C). ART’s were comparable for both subjects (650 and 630 milliseconds for the patient and control subject, respectively).
stride preceding obstacle presentation. As a consequence, for people with smaller pre crossing stride lengths, the relative amount of lengthening required to cross the obstacle is likely to be larger. Indeed, the mean normal stride length in group S2 was 403 mm, which is substantially smaller than the 840 mm and 786 mm that was found for stroke group S1 and controls, respectively. Therefore, the relative magnitude of the required step modification was larger for patients in group S2. This may have urged patients in group S2 to increase the length of their stride by a substantially greater amount, in order to cross the obstacle successfully. This idea is illustrated in figure 6, where stride length and duration are plotted for a typical patient and a typical control. From this figure it becomes clear that, in the stroke subject, a smaller unperturbed stride length corresponds with a much larger percentual increase in crossing stride length and duration than in the control subject. However, the absolute crossing stride length and stride duration compare quite well between both subjects, possibly because the crossing stride length is strongly constrained by the length of the obstacle.

Apart from the relation between the unperturbed stride length and the length of the obstacle, these remarkable increases in crossing stride length may also reflect adaptations of a strategic nature. Excessive lengthening of the stride may have been used to achieve larger horizontal foot clearance during landing. This strategy can be used to reduce the risk of contact with the obstacle by persons that are not able to precisely control the landing position of their crossing foot. The percentage increase in duration of the crossing stride was not proportionate to the amount of increase in stride length. Increases in duration were observed of 51, 13, en 15% in S2, S1, and controls respectively. This finding is in line with results from Varraine et al., (1999) showing that, during voluntary changes made in the length of the stride, stride duration remains relatively constant. Together with the present results, these data seem to suggest that the rhythm of gait is a basic parameter which is kept as constant as possible (see also Dietz et. al 1994). Because the percentage increase in stride length exceeded the percentage increase in duration, an increase in crossing stride velocity could be observed. For the S2 group, the increase in stride velocity was 43%, which is substantially higher than the 14 and 15% that were found for group S1 and controls. Irrespective of whether these results can be ascribed to a direct effect of stroke or to an indirect effect of walking speed, they show that for the more slowly walking stroke group, obstacle avoidance required a proportionally high degree of instantaneous adjustments in their gait pattern.
Evidently, gait speed is an important determinant of task complexity in adaptive gait tasks. In order to enable us to match as many patients as possible without having to compromise gait speed too much for the control group, the default speed was set to 0.56 ms\(^{-1}\). In a review of the stroke literature Olney and Richards (1996) reported that the average speed in patients ranged from 0.23 ms\(^{-1}\) to 0.73 ms\(^{-1}\), so the currently used treadmill speed (0.56 ms\(^{-1}\)) represents the stroke population rather well. However, this speed is well below the average speeds that have been reported in healthy elderly (0.80 to 1.52 ms\(^{-1}\) in females, 0.81 to 1.61 in males; Perry, 1992) so that it may have been experienced as artificially slow by our controls. When walking speed is decreased, demands in terms of postural control increase, as well as the time is spent in the single support phase, especially during the lengthened crossing stride. Therefore, it can be argued that, in the present task, low walking speeds do not necessarily coincide with decreased task complexity. The very slow walking speeds that were employed by the more severely affected group S2 did in fact show a larger mean increase in the duration of the crossing stride (51% for S2, vs 13% en 15% for S1 and controls respectively). As a result, this may have increased the demands on postural control in this group, in addition to the problems in weight bearing capacity in the limb during the single support phase. This could explain the relatively high failure rates found for this group despite their very low gait speeds.

Walking on a treadmill requires that the distance traversed per time unit is kept more or less constant over subsequent steps. Therefore, changes made in the length of the stride (as in the lengthened crossing steps), may require spatial and/or temporal corrections during subsequent steps in order to maintain an approximately constant position on the moving treadmill surface. Arguably, the amount of spatiotemporal compensation that was observed in the post crossing stride (51% for S2, vs 13% en 15% for S1 and controls respectively). As a result, this may have increased the demands on postural control in this group, in addition to the problems in weight bearing capacity in the limb during the single support phase. This could explain the relatively high failure rates found for this group despite their very low gait speeds.

In controls and in stroke group S1, the post crossing stride length was almost instantaneously restored to normal values, indicating that for these persons stride length modifications are easily incorporated into the ongoing stepping pattern. Quite in contrast, in stroke group S2, the increases in length, duration, and velocity that were observed during the crossing stride, led to marked changes in the spatiotemporal organization of the post-crossing stride. The significantly smaller relative length and greater relative duration of the post crossing stride that was found shows that, in this subgroup of patients, the time window that was used to
settle into the normal walking rhythm was larger than in controls. Following excessive lengthening of the stride during obstacle crossing, forward momentum in the leading leg will be rapidly decreasing, especially given the very slow walking speeds employed by the patients in this subgroup. As a consequence, more mechanical work has to be delivered by both the trailing and the leading limb to progress the body over the leading stance limb. This may be too difficult a task to perform in the light of reduced muscular strength and problems in the maintenance of dynamic balance, commonly associated with hemiplegia.

Conclusions
Unilateral cortical damage results in an impaired ability to avoid obstacles at both sides of the body. During successful obstacle avoidance trials, stroke patients lengthen their steps more often than controls, which may reflect an attempt to reduce movement complexity, even when a shortening of the step would be spatially more efficient. For a subgroup of more severely affected and more slowly walking patients, the execution of these lengthened steps led to larger disturbances in the locomotor rhythm than in controls. These results suggest that the ability to adequately modify the stepping pattern in response to imposed spatiotemporal constraints, is impaired in persons with stroke, especially when modifications have to be performed under time pressure.

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Gait control after stroke


Obstacle avoidance after stroke


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