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Tempo-spatial gait adaptations in stroke patients when approaching and crossing an elevated surface

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ABSTRACT

Background: In ambulatory stroke survivors, outdoor walking is important for participation, so adapting to heightened levels (e.g. curbs) is essential. This needs precise step regulation and foot positioning and has to be achieved despite impaired balance and motor regulation.
Research question: How do stroke patients approach and cross elevated surfaces?
Methods: Gait of 12 hemiparetic stroke patients (62.8 ± 10.3 years; Functional Ambulatory Category 3–5) and 13 controls (60.0 ± 12.4 years) was compared using a sensor carpet and 3D motion capturing to collect tempo-spatial parameters and foot trajectories in two conditions: flat walking vs. approaching to and stepping onto an elevated surface (height 15 cm) in a self-selected manner (6 trials each). Tempo-spatial adaptations were normalized to flat walking while trajectory analysis focused on foot clearance and placement. Complementary assessments included the Dynamic-Gait-Index, the Berg-Balance-Test and the Falls Efficacy Scale.
Results: Patients showed significantly worse Dynamic-Gait-Indices, less balance and more fear of falling. During the approach phase, patients slowed down, partly accompanied by shorter steps which controls did not. During crossing, no preference for a specific leading leg was detected. Clearance of the leading leg on average was not reduced but patients landed closer to the edge. Still clearance of the paretic leg was less than that of the non-paretic leg and the minimal clearance across all trials suggested an increased tripping risk, most evident for the trailing leg. In particular slower approaching caused difficulties to ensure sufficient leg clearance and to place the foot safely. Independent from that, better balance correlated with safer clearance.
Significance: When managing elevated levels, leading with the paretic leg causes more difficulties to safely clear the legs which is considerably dependent upon speed. Therapists should consider that slow walking may not increase safety while faster gait and aspects of postural control potentially facilitate crossing a curb.

1. Introduction

Stroke is the leading cause of disability with over 1 million new cases per year in Europe [1]. In patients that regain walking, outdoor mobility is an important aim [2]. However, activity in daily life is limited, since physical constrains and psychological factors like limited balance confidence [3] often cause patients to avoid environmental impediments. Training gait adaptability is therefore essential during advanced rehabilitation. Specifically, more complicated tasks, like managing curbs and adapting to different levels may provide hazards to falls [4] and can constrain community walking [5].

Elevated surfaces afford tempo-spatial regulation of gait, appropriate positioning of the feet before, over and onto the target [6]. In particular the last approaching step is critical [7]: the foot must be placed close enough to put the leading leg (first leg) safely onto the target, but far enough to allow clearance of the trailing leg (second leg). Previous studies on elevated surfaces compared young vs. elderly. Elderly, which are known for their sensory-motor decay, place their last step more distant from the target which likely limits the risk of trailing leg contact during swing [8], but also smaller clearances have been reported [9]. Others suggested a decline in anticipatory motor control, which does not allow elderly to increase their velocity towards a raised surface [7]. Faster speeds might be efficient while slowing down may reflect the need to plan an actual strategy.

Hemiparetic stroke patients face several constraints that may affect the ability to clear an elevated surface: e.g. balance deficits [11], disturbed joint kinematics and impaired tempo-spatial gait parameters, typically, with unequal step lengths [12] and a limited capacity to

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increase walking speed [14]. Also a decline in anticipatory feed-forward processing could be detrimental. It was moreover suggested that approaching to and stepping up a raised surface could reveal atypical perceptual-motor coupling [6]. Still, in the past, primarily crossing tasks of singular, thin obstacles have been assessed in stroke patients. By modifying their lead limb trajectory patients actually showed greater clearances thus reduced the potential risk of a trip for one leg, but reductions in toe clearance when the affected limb trails [15] and smaller post-obstacle distances were noted [15,16]. More importantly, failing to clear obstacles during laboratory settings is related with real life falling [17]. Next to potential physical damage, falls (or near falls) increase the fear of falling [18] and this can again provide barriers to mobility. Since tempo-spatial measures of unperturbed gait were not related to fear of falling in stroke patients [19], more complex task could be informative.

In sum, knowledge about surface height accommodation is limited and little information on the strategies and risks of stroke patients exists. This study therefore investigates how hemiparetic stroke patients adapt their gait when approaching and crossing an elevated surface. If they misinterpret the affordances, or non-adequately plan their approach, the task likely becomes less safe. We hypothesized that patients would show altered tempo-spatial regulations during the approach and display reduced clearance and foot placement close to the edge during and after crossing. Eventually, better balance and gait adaptability scores are thought to correlate to safer clearances.

2. Methods

2.1. Participants and protocol

12 stroke patients, recruited in a rehabilitation facility, participated (Table 1). They had hemiparesis, categorized in Functional Ambulatory Category 3–5 [20], were able to follow verbal instruction and had no major visual deficits. 13 healthy age-matched subjects, free of orthopedic or neurological deficits, served as controls. Ethical approval was granted (Project Nr.: 70-069, LMU Munich) and subjects gave informed written consent. Measurements consistent of instrumented gait assessments, questionnaires (Falls Efficacy Scale [FES-I] [21]), observational gait adaptability tests (Dynamic Gait Index [DGI] [22]) and the Berg balance scale test [BBS] [23].

2.2. Instrumented gait assessment

A 6.1 m long pressure-sensitive carpet (GAITRite, CIR Systems Inc., USA) and a 3D motion capture system (Simi Reality Motion Systems GmbH, Germany) were used. Gait analysis was performed at self-selected speed in two conditions (quasi-randomized balanced allocation): flat vs. approaching and crossing an elevated surface [6 trials each]. Subjects wore low top shoes, partly used orthotics or canes (N = 3 and 4) and were equipped with reflective markers according to the built-in model of Simi (comparable to a modified Plug-In Gait) sampled at 100 Hz. Preceding trials, the edges of the elevated surface (15 cm height x 90 cm width x 288 cm length) were digitized (Fig. 1). The height is typical for an upstanding curb, e.g. separating the driving surface from a sidewalk [31], thus a common impediment for ambulators, and has been similarly used in previous studies [8]. For condition b, the start position was fixed at the beginning of the carpet at a distance of 5 m. Participants incorporated the target in their natural gait [6] while an investigator potentially assisted in the event of unsteadiness.

2.3. Data analysis

During the approach, the feet were localized by the rearfoot centroid on the GAITRite carpet. Raw marker data were filtered with a 2nd order Butterworth Filter at 6 Hz, spline interpolated and exported to Matlab 2017b (Mathworks, USA). During flat walking, tempo-spatial parameters were extracted from the GAITRite software. The same applies for all steps prior to the elevated surface. During crossing, the data of the leading and trailing leg [LL and TL] (˜1 st and 2nd step to traverse) was based on marker data. The feet were then localized by the center of the ankle joint. For the distance parameters during the approach and crossing, the vector from the heel to the metatarsals marker was elongated according to the shoe length to locate the tip, as determined during standing trials (Fig. 1).

Trials were further grouped according the side of the LL. They were classified as fails and discarded when subjects lost balance or discontinued their maneuver. Contacts were counted separately. The side that was leaded in more trials was classified as preferred. In controls only this leg was analyzed. If trials were equally distributed, one leg was randomly chosen. For patients, both the paretic and non-paretic leg was analyzed. This resulted in 2 available crossing strategies for

Table 1
Subject characteristics, results of complementary assessments and gait parameters during flat walking. Values present group means (1SD) [range]. Statistical Significance: *different from controls, § difference between legs of patients, Statistical Significance: *,§ P < 0.05, ** P < 0.001.

Subject characteristics		Stroke patients (n = 12)	Controls (n = 13)
Demographics	Sex (f/m)	2 / 10	6 / 7
	Age (years)	62.8 (10.3) [43-82]	60.0 (12.4) [34-73]
	Height (cm)	177.3 (8.1)	173.8 (10.9)
	Weight (kg)	83.2 (18.3)	75.8 (12.7)
Type of stroke	hemorrhagic / ischemic	4 / 8	n.a.
Stage/ Acuteness	subacute (3w-6 m.) / chronic (6 m.) (n)	2 / 10	n.a.
	Elapsed time since insult (w)	21 (32) [3-112]	n.a.
	Side of hemiparesis (re/li)	2 / 10	n.a.
Walking aid	Cane (n) / AFO (n)	4 / 3	0/0
Complementary Assessments	Berg Balance Scale (BBS)	**42 (16)* [29-56]**	55 (1) [54-56]
	Dynamic Gait Index (DGI)	**15 (7)** [7–24]**	24 (1) [21–34]
	Falls Efficacy Scale (FES-I)	**29 (12)* [17-60]**	17 (2) [16–22]

Gait parameters during flat walking	paretic	non-paretic	preferred crossing leg
Veocity (m/sec)	**0.79(40)** **		1.37(0.16)
Step length (cm)	**53(16)** **	**52(20)** **	75(8)
abs. Step length asymmetry [%]	**4.2 (8.0)** **		0.7 (0.5)
Single stance duration (sec.)	**0.43(0.09)** §	**0.54 (0.13)** *	0.42(0.03)
Step width (cm)	**13.5(4.4)** *	**14.9(4.7)** *	10.0 (2.1)
Step time (sec.)	**0.84(0.33)** ** §	**0.69(23)** *	0.56(0.05)

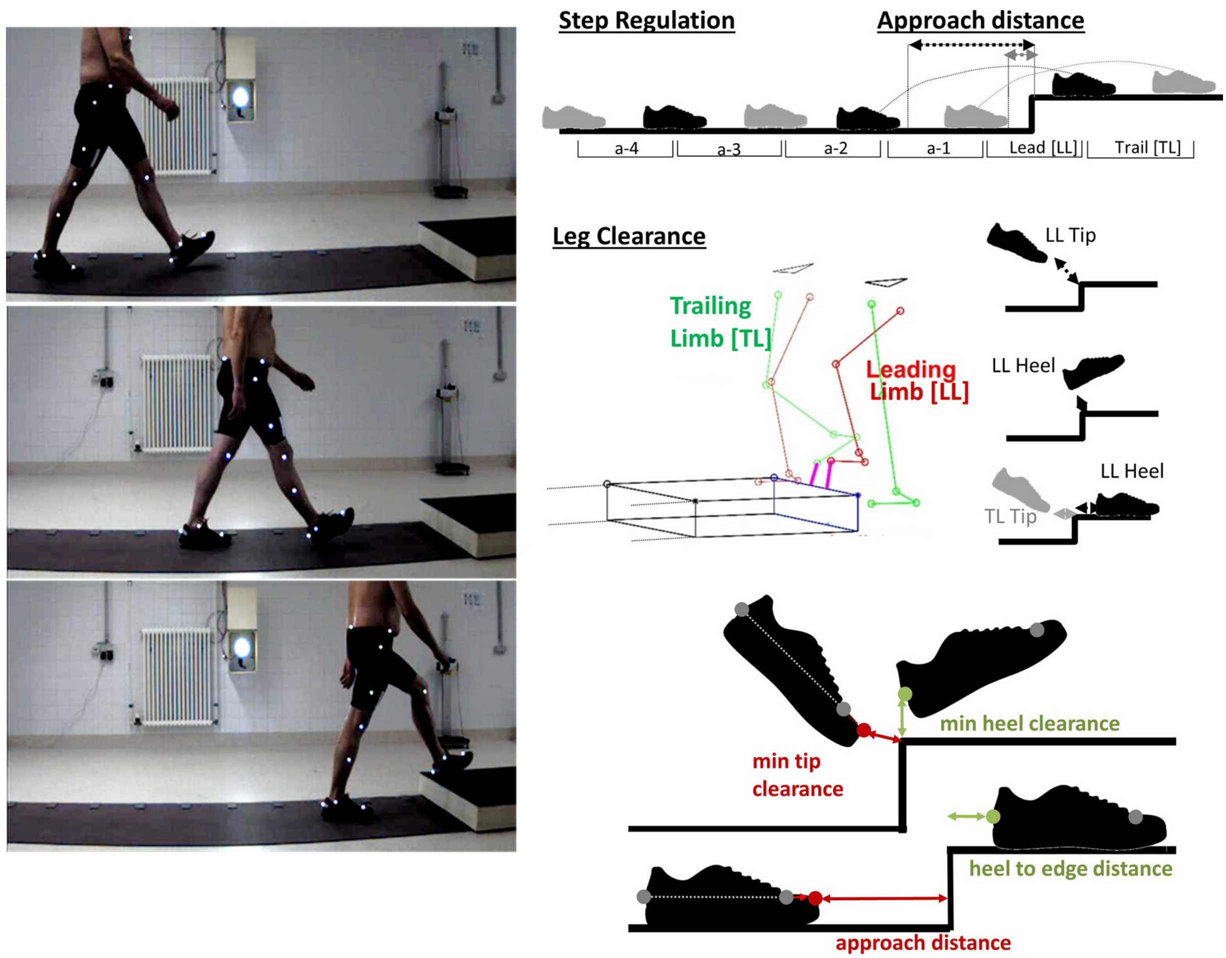

Fig. 1. Illustration of a control subject during the final approach and targeting of the elevated surface. Schematics of data extraction for the steps of the approaching phase (a-4 to a-1), as well as for the leading and trailing leg (LL and TL; first and second leg to clear the obstacle) concerning the approach distances and leg clearance. The lower part shows that the metatarsal marker was shifted anteriorly in the direction of a vector from the heel to the metatarsals to represent the end of the shoe as digitized during standing trials.

patients: leading paretic or non-paretic. For controls, the preferred leg strategy was included.

2.4. Outcomes

Concerning the foot placement during the approach, the tip to edge distance of the final 2 contacts with respect to the surface was once quantified in absolute values and once in % of unperturbed step length. During crossing, the minimal 3D distance of the leading leg's tip and heel to the edge was calculated. For the trailing leg, only the clearance of the tip was calculated. Besides, the foot placement respect to the edge of the leading leg's heel on the surface was extracted. Analysis for these parameters was once done for the average and once for the minimum over all trials after pooling trials and legs.

Concerning tempo-spatial parameters, walking velocity [m/s], step length [cm], abs. step length asymmetry [%], step time [sec] and width [cm], as well as single support duration [sec] were chosen as outcomes. During the elevated surface 6 steps were analyzed (the last 4 approaching steps: a-4 to a-1; as well as the leading and crossing step). All values were normalized to their values during flat walking [expressed in %].

2.5. Statistics

Analysis was done in Matlab2017b (Mathworks, USA). Normality was tested with Shapiro Wilk's tests.

FES-I, DGI and BBS scores were compared between groups with Mann Whitney U-tests. During flat walking, tempo-spatial parameters were compared between paretic and non-paretic legs and with respect to controls with dependent t- or Wilcoxon signed-rank tests when comparing both limbs or with independent t-, Mann Whitney U test between groups. To analyze the adaptations of patients and controls during the elevated surface condition, we compared the normalized tempo-spatial parameters at each of the 6 steps with independent *t*-test or Mann Whitney *U* test. For patients, additional comparisons between both strategies were made with dependent *t*-test or Wilcoxon signed-rank test. Foot placement during the approach and the clearance parameters were evaluated similarly. To distinguish specific tempo-spatial regulations with respect to unperturbed walking, the a-4 step was set as baseline referenceand compared separately to each of the 5 following steps (a-3, a-2, a-1, LL, TL).

To analyze the associations between the scores and the clearance parameters, bi-variate Spearman's rank correlations (rho) were calculated. Since walking speed was expected to have an influence on clearance parameters [24], partial correlations were performed by using the approaching speed (average of the last 3 steps) as a co-variate. Unless indicated differently, group descriptives represent mean (1SD). Due to the exploratory nature of this study, alpha was set to 0.05.

3. Results

3.1. Demographics and complementary assessments

As summarized in Table 1, there was no group difference in age, height and weight ($P > 0.288$). The DGI, BBS and FES-I of patients showed significant deteriorations: Concerning the BBS, 5 of 12 patients scored lower than 45 and on the DGI, 6 scored below 19 which both indicate a high risk of falls [25]. Moreover, 7 showed a high concern (FES-I > 23) about falling [26].

3.2. Leg preference, fails and contacts

During the elevated surface condition, 57 (31)% of patients' trials were leaded with the paretic leg ($P = 0.459$ between legs). 3 patients failed during 1–2 trials and 3 contacted in up to 5 trials. Fails and contacts were distributed between both legs. The failure and contact rate was 6.3 (11.9)% [range: 0–33] and 13.8 (29.2)% [range: 0–83]. In controls, 53 (38)% of trials were leaded with the left leg and none failed or contacted the surface. Overall 73.6 (20.7)% and 83.3 (15.2)% of trials were leaded with a specific leg in patients and controls ($P = 0.096$).

3.3. Tempo-spatial gait analysis

During flat walking (Table 1) patients walked slower ($P < 0.001$) while taking shorter and wider steps compared to controls (both $P < 0.035$). They had an increased step length asymmetry ($P = 0.008$). Single limb support was increased on the non-paretic limb ($P = 0.024$). Comparing both limbs of patients showed that step time was greater on the paretic side ($P = 0.012$), while single limb duration was larger on the non-paretic limb ($P = 0.022$).

Focusing the tempo-spatial regulations (Fig. 2), controls did not change speed or step length during the approach but, two steps prior to the crossing maneuver, the step time and single support was significantly increased (both $P < 0.021$). During the trailing step, they slowed down ($P < 0.001$). In addition, the leading and trailing step length was reduced with respect to unperturbed walking and the corresponding step time and single support duration was increased (all $P < 0.017$). Eventually, only the trailing step width significantly increased ($P = 0.027$).

Concerning patients, for both strategies, they slowed down starting during a-2 (both $P < 0.039$). The decrease with respect to controls was significant for the last approaching (a-1) and leading step concerning the paretic ($P = 0.018$) and non-paretic leading leg strategy ($P = 0.045$), respectively. For the trailing step, the velocity was significantly decreased for both strategies ($P < 0.004$) and the decrease was larger than in controls (both $P < 0.016$).

Next, patients showed a considerable reduction in step length during the last approaching step (a-1), when leading with the non-paretic leg ($P = 0.039$) and minor reductions when leading with the paretic leg. Large standard deviations at a-1 display a variable modification. Normalized step length during the leading step was not different for patient and controls (Fig. 2) while the trailing step length was reduced for both strategies, but only the reductions of the paretic leading leg strategy turned out to be significant ($P = 0.005$ and 0.062). Significantly different adjustments with respect to controls were noted concerning trials leading with the paretic leg at a-2 ($P = 0.008$) and the trailing step ($P = 0.005$).

Similar to controls, step time was increased during a-2 and during the leading and trailing step (all $P < 0.045$). Noteworthy, the increase in leading leg's step time tended to be enlarged in patients for both strategies ($P = 0.065$ and 0.070).

Single support duration increased during the leading and trailing step (both $P = 0.024$) when crossing with the paretic limb. For the trailing limb, it was also increased when leading with the non-paretic leg ($P < 0.001$). However, when comparing patients and controls, the increase in single stance was significantly larger when leading or trailing (both $P < 0.011$) with the paretic limb (˜increased time spent on the non-paretic leg). Comparing both strategies, the increase was larger when the paretic limb was leading ($P = 0.011$). In addition, in contrast to controls, no adjustment in single stance duration were seen during a-2 ($P = 0.002$).

Concerning step width, the trailing step when leading with the non-paretic limb showed increased values ($P = 0.020$). Yet, with respect to controls, a significantly larger step width occurred for a-2 and a-1 when the paretic limb was used (all $P < 0.013$) and for both strategies during the leading step ($P < 0.033$).

3.4. Approach placement and foot clearance

Results are presented in Table 2. The last but one preparatory footfall of patients was placed closer to the edge for both strategies (both $P < 0.013$), while the distance of the final footfall was not significantly different (both $P > 0.125$). The relative distance [% step length] was kept rather consistent for the non-paretic leg, while distances of the paretic leg tended to be higher. Specifically, patients placed the trailing leg further away when leading with the paretic leg ($P = 0.039$).

Average foot clearance was not significantly different between groups. Only the clearance of the trailing paretic leg tended to be reduced ($P = 0.083$). When comparing paretic vs. non-paretic legs, reduced clearance of the paretic leg's tip when leading was noted ($P = 0.039$). The overall minimum values in patients were non-specifically distributed across legs. Both limbs were pooled and significant reductions concerning the minimum leading legs' heel ($P = 0.032$) and the trailing legs tip clearance ($P = 0.007$) were found.

Significant bi-variate correlations suggested that faster approaching speed induced larger clearances of the leading tip and larger heel to edge distances in patients upon foot placement (Fig. 3). For the paretic leading strategy, the trail limb clearance also increased. The only significant effect of walking speed for controls was a positive correlation with respect to the trailing tip distance.

When statistically controlling for these velocity effects (Table 3), a positive correlation between the BBS and the clearance of the leading tip ($r = 0.69$, $P < 0.001$) and the heel to edge distance ($r = 0.77$, $P = 0.005$) in patients was noted. The FES-I and DGI showed no significant correlations.

4. Discussion

We investigated how stroke patients approach and cross elevated surface. Overall, 25% (3 of 12) failed and if unsupported, 2 patients would have been fallen. Failures could not be linked to a specific leg but curbs apparently pose an important thread to stability [4]. Despite a slightly attenuated preference for a specific leg, patients showed no clear priority for the paretic or non-paretic leg [27]. More complex tasks may necessitate modification of motor programs after a stroke and induce issues with leg dominance.

Concerning the approaching phase, the increased step times may reflect control adjustments and create time for visual sampling since footfall targets are usually fixated about two steps [28]. Next, as seen in elderly [29], the patients' lead foot (2 footfalls ahead of the surface) was placed closer to the edge to probably balance their shortened steps. The fact that the last approaching steps needed to be shortened in patients while being closer to the target proposes a lack of feed-forward control or competing requirements: a) reaching the target with the leading leg and b) achieving clearance of the trailing leg. Since the leading leg still landed closer to the edge or below (Fig. 2), trail clearance was prioritized. We did, on a group level, not find significant differences concerning trail foot placement before the surface. For singular thin obstacles, stroke patients also maintained pre-obstacle

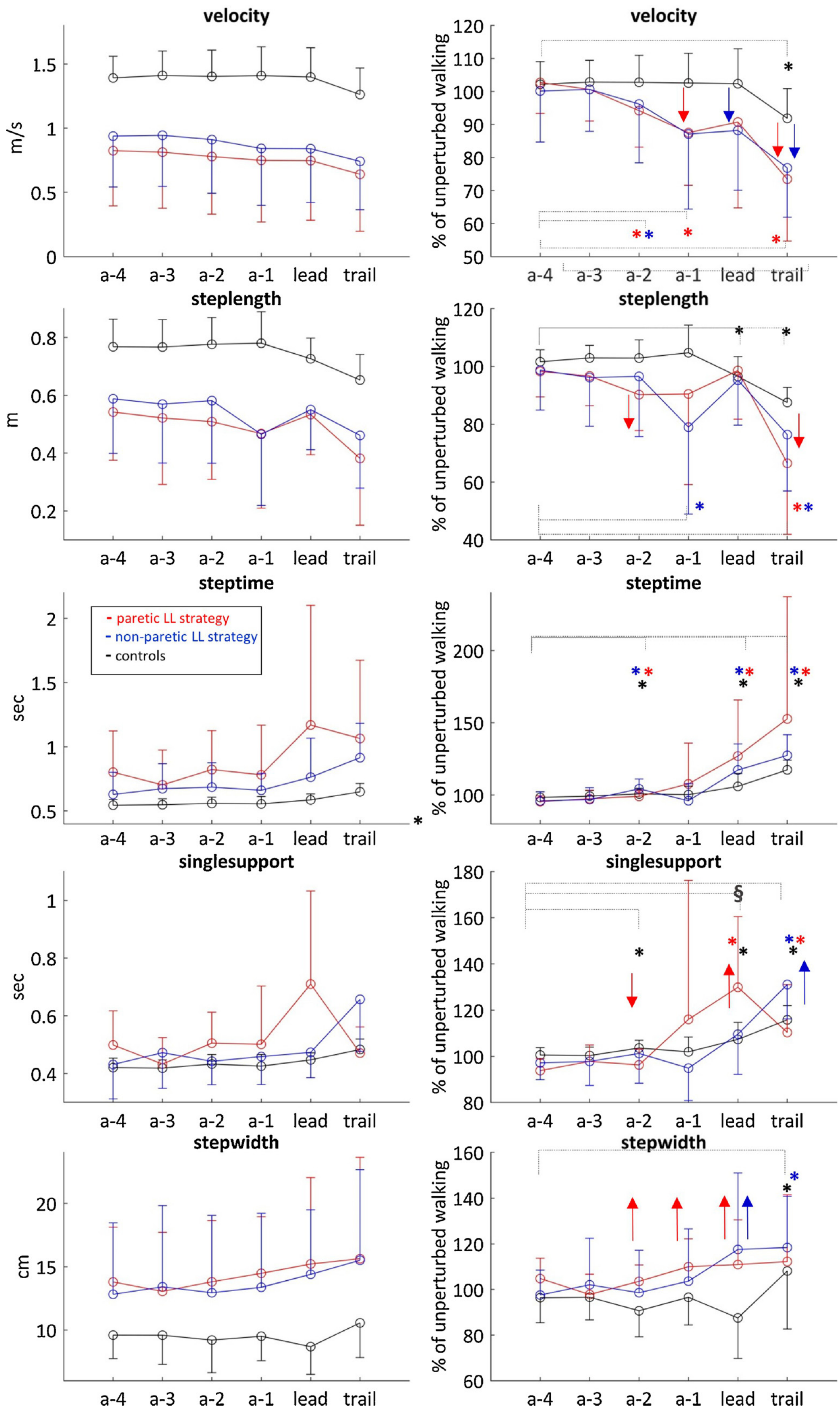

Fig. 2. Results of tempo-spatial regulations during the approach for the last 4 approaching steps, a-4 to a-1 and the step of the leading and trailing limb. Trials were grouped according to the leading leg. Error bars represent 1SD and, for clarity were only plotted in one direction. Left column: absolute values. Right column: normalized values in % of flat walking. Statistical Significance: *different from a-4 (˜baseline), ↑ different from controls, § difference between legs of CVA, all P < 0.05.

Table 2
Approach placement and clearance parameters. Trials were grouped according to the leading leg. Values present Means (1SD). The minimum over all trials was derived after pooling trials and legs. LL = leading leg, TL = trailing leg: Statistical Significance. *different from controls, § difference between legs of CVA, all P < 0.05.

Approach placement		Crossing strategy: Stroke paretic	Stroke non-paretic	Controls preferred
LL [cm]		**72.7(32.0)***	**70.6(31.6)***	107.0(21.6)
LL [% flat SL]		129.4(35.2)	118.7(40.4)	141.8(25.8)
TL [cm]		**26.6 (9.6)** §	23.0 (10.6)	31.3 (14.0)
TL [% flat SL]		67.4 (68.8)	40.0(16)	42.4 (19.5)
Clearance parameters [cm]				
LL Tip	Avg.	**9.8 (4.6)**§	12.6(3.0)	11.5 (2.2)
	Overall Min.	7.8(5.6)		10.6(2.4)
LL Heel	Avg.	7.6(2.5)	7.7(1.0)	7.5(2.6)
	Overall Min.	**4.0(2.8)***		6.3(2.0)
TL Tip	Avg.	5.4(2.5)	8.1(2.5)	7.5 (3.0)
	Overall Min.	**3.0(2.2)***		6.6(3.2)
LL Heel to Edge	Avg.	**0.8 (8.2)***	**3.3(6.6)***	16.1(13.3)
	Overall Min.	**−0.6(10.3)***		8.4(11.0)

Table 3
Partial Spearman‘s rho correlations between balance (BBS: Berg balance scale), gait adaptability (DGI: Dynamic gait Index), falls efficacy scale (FES-I) with clearance parameters in patients with stroke. LL = leading leg, TL = trailing leg. The approaching speed (m/s) was used as a co-variate. Statistical Significance: * P < 0.05, ** P < 0.001.

Partial Spearman‘s rho (Co-variate approaching speed) — Clearance parameters	Scores: BBS	DGI	FES-I
LL Tip	**0.69****	−0.17	0.04
LL Heel	0.31	−0.29	0.16
TL Tip	0.31	−0.26	0.04
LL Heel to Edge	**0.77***	−0.03	0.00

distances [16]. This could reveal preserved visuo-motor transformation [29]. However, for patients, larger approach distances when leading with the paretic leg likely limited the risk of a trailing limb contact, as any trip of the non-paretic leg reasonably is more challenging to recover. Moreover, for the trailing limb, visual control is not available and proprioception is generally limited in stroke patients [30].

Although the leading tip clearance on average was not significantly reduced with respect to controls, direct comparisons of legs in patients suggested that the paretic leading tip clearance was lower. Eventually, the minimal distances across all trials and legs hint to greater general

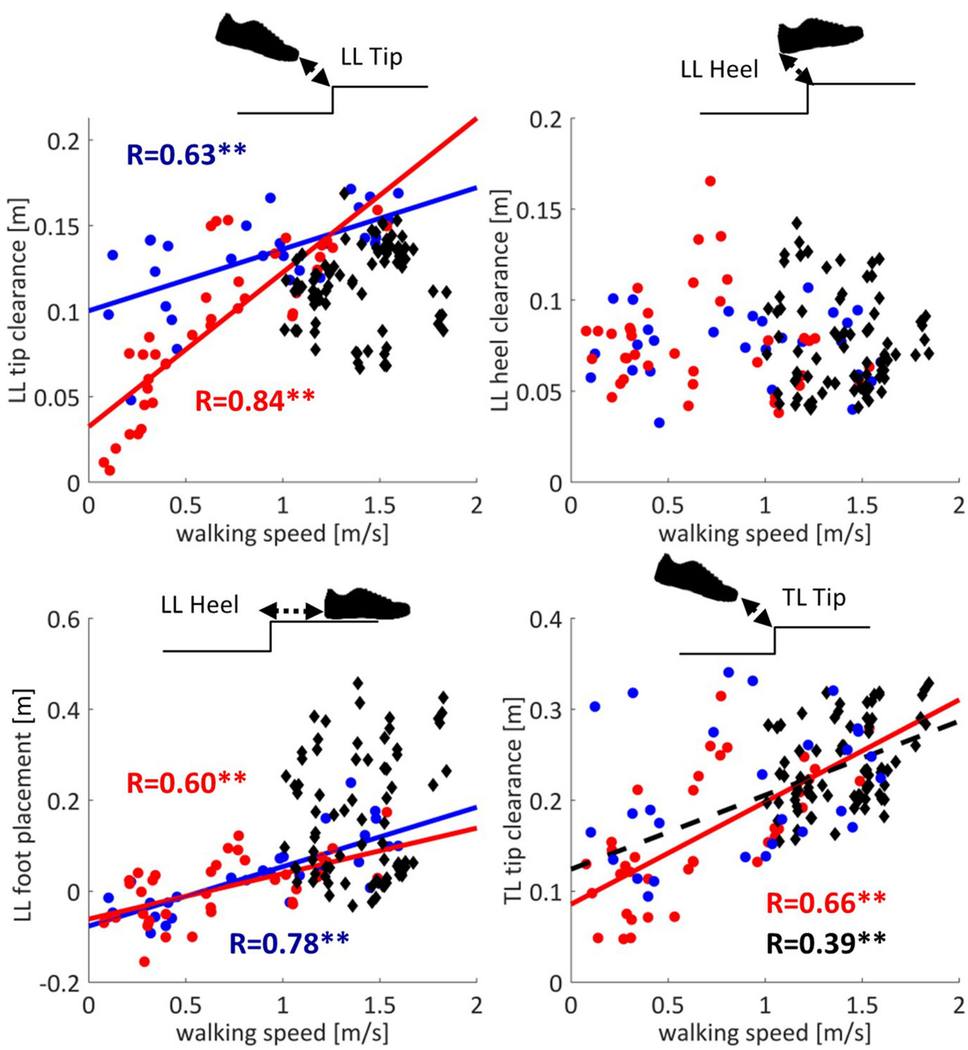

Fig. 3. Correlations of approaching speed and clearance parameters and placement of the leading foot with respect to the edge of the elevated surface. Statistical Significance: **P < 0.001, *P < 0.05. NB: trials were grouped according to the leading leg.

risk of contact in patients which was quite apparent for the trailing leg. Reductions in toe clearance when the affected limb trails have been reported earlier [15]. Current results contradict but this could be related to the impediment, as traversing a single thin obstacle on level ground [15] poses different requirements than surface adjustments. From a methodological perspective, due to the limited number of markers on the foot, the calculated clearance parameters may lack absolute accuracy but unlikely provide a systematic bias. Still, more reference points on the shoe could be used [32].

Slow approaching in patients seems to decrease clearance of the leading leg and reduces the distance to the edge upon landing. For the paretic leading strategy, it also decreases trail foot clearance. Slower walking naturally reduces ground clearance [24] and since gait typically becomes more variable at slower speed [13] that likely challenges balance, too [10]. Accordingly, slowing down was currently also joined by wider steps. By comparison, controls had no need to slow down perhaps due to intact anticipatory control.

Irrespective of walking slower, reduced balance had a negative impact on clearance of the leading tip and on the landing margins. So a stable support seems vital to control the mobile leg. In controls, the modifications in step width and single stance suggest that the primary demand on balance may be related to support the trailing leg. In stroke patients, increases in single stance duration peaked when the paretic foot (either leading or trailing) traversed. This requires good balance on the non-paretic side. The DGI was strongly related to the approaching speed itself but, beyond that, did not reflect foot control mechanisms during crossing. Finally, our results suggest that fear of falling was not closely associated with currently applied measures. It thus might have neither been beneficial, nor did it put the patients at an objectively quantified risk of tripping. Still, one potential faller had an inconspicuous FES-I score, thus underrated its risk.

5. Conclusion

Traversing an elevated surface provides a considerable thread to stability in stroke patients as minimal clearance parameters suggest an overall increased tripping risk. On average, leading with the paretic leg causes more difficulties which in turn seems to considerable depend upon the approaching speed. A causal relationship between walking speed, postural control and clearance parameters in patients has yet to be confirmed experimentally. Alternatively, slowing down may reflect a decline in anticipatory motor control. During rehabilitation, therapists could explore if a faster (maybe more confident) approach and better postural control improves the patients performance.

Declaration of Competing Interest

All authors do not have any financial and personal relationship with other people or organizations that inappropriately influence the work performed.

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